current *Qualified and Controlled Software Report*, and was obtained from Software Configuration Management. The SAPHIRE software is specifically designed for PRA simulation and analyses and has been verified to show that this software produces precise solutions for encoded mathematical models within the defined limits for each parameter employed (Ref. 2.2.36). Therefore, SAPHIRE version 7.26 is suitable for use in this analysis.

The SAPHIRE project files for this analysis are listed in Attachment H. They are contained on a compact disc, which is included as part of Attachment H. SAPHIRE project files contain all of the inputs that SAPHIRE requires to produce the outputs that are documented in this analysis.

4.2.2 Level 2 Software

This section addresses software used in this analysis that are classified as Level 2 software, as defined in *Software Management* (Ref. 2.1.3, Attachment 12). The software is used on personal computers running either Windows XP Professional or Windows 2000 operating systems.

- Word 2003, a component of Microsoft Office Professional 2003, and Visio Professional 2003 are listed in the current Level 2 Usage Controlled Software Report. Word 2003 and Visio 2003 are used in this analysis for the generation of graphics and text. The accuracy of the resulting graphics and text is verified by visual inspection. The precise means of verification is left to the discretion of the checker in compliance with applicable procedures.

- Excel 2003, a component of Microsoft Office Professional 2003, and Mathcad version 13.0 and 14.0 are listed in the current Level 2 Usage Controlled Software Report. Crystal Ball version 7.3.1, a commercial, off-the-shelf, Excel-based risk analysis tool, is listed on the Controlled Software Report and is registered for Level 2 usage. Excel 2003 is used for this analysis to produce noncomplex reliability models (described in Section 6), to calculate probability distributions for selected SAPHIRE inputs, and to graphically display information. Mathcad 13.0 and 14.0 and Crystal Ball 7.3.1 are also used for calculating probability distributions for SAPHIRE and for graphics. Graphical representations are verified by visual inspection. The calculations are documented in sufficient detail to allow an independent replication of the computations. The user-defined formulas and inputs are verified by visual inspection. The results are in some cases verified by independent replication of the computations; however, in some cases (e.g., for some Excel calculations and Mathcad 13.0 and 14.0 calculations), the results are verified by visual inspection. The precise means of verification is left to the discretion of the checker in compliance with applicable procedures.

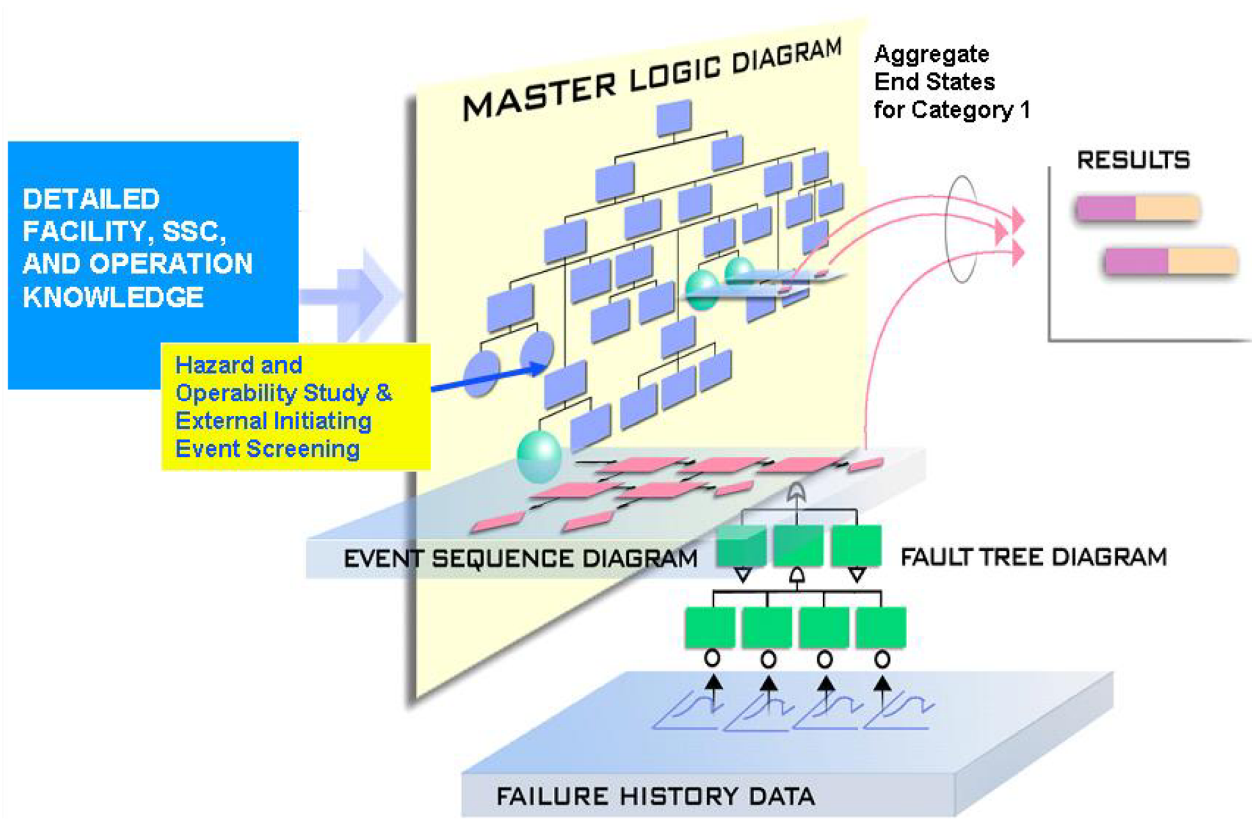
- WinZip 9.0, a file compression utility for Windows, is listed in the current Level 2 Usage Controlled Software Report. WinZip 9.0 is used in this analysis to compress files for presentation on compact disc in Attachment H.

4.3 DESCRIPTION OF ANALYSIS METHODS

This section presents the PCSA approach and analysis methods in the context of overall repository operations. As such, it includes a discussion of operations that may not apply to Intra-Site Operations and balance of plant (BOP) facilities. Specific features and operations of Intra-Site Operations are not discussed until Section 6, where the methods described here are applied. The PCSA uses the technology of PRA as described in references such as *Standard for Probabilistic Risk Assessment for Nuclear Power Plant Applications* (Ref. 2.2.6). The PRA answers three questions:

1. What can go wrong?
2. What are the consequences?
3. How likely is it?

PRA may be thought of as an investigation into the responses of a system to perturbations or deviations from its normal operation or environment. The PCSA is a simulation of how a system acts when something goes wrong. Relationships between the methodological components of the PCSA are depicted in Figure 4.3-1. Phrases in ***bold italics*** in this section indicate methods and ideas depicted in Figure 4.3-1. Phrases in normal *italics* indicate key concepts.



Source: Modified from Ref. 2.2.79

Figure 4.3-1. Event Sequence Analysis Process

The PCSA starts with analysts obtaining sufficient knowledge of the designs and operations of facility, equipment, and SSCs to understand how the YMP waste handling is conducted. This is largely performed and documented in the precedent event sequence development analysis (Ref. 2.2.29). An understanding of how a facility operates is a prerequisite for developing event sequences that depict how it would fail. *Success criteria* are important additional inputs to the PCSA. A success criterion states the minimum functionality that constitutes acceptable, safe performance. For example, a success criterion for a crane is to pick-up, transport, and put-down a cask without dropping it. The complementary statement of a success criterion is a failure mode (e.g., crane drops cask).

The basis of the PCSA is the development of ***event sequences***. An event sequence may be thought of as a string of events beginning with an *initiating event* and eventually leading to potential consequences (*end states*). Between initiating events and end states within a scenario, are *pivotal events* that determine whether and how an initiating event propagates to an end state. An event sequence answers the question "What can go wrong?" and is defined by one or more initiating events, one or more pivotal events, and one end state. Initiating events are identified by MLD development, cross-checked with an evaluation based on applied HAZOP evaluation techniques. Event sequences unfold as a combination of failures and successes of pivotal events. An end state, the termination point for an event sequence, identifies the type of radiation exposure or potential criticality, if any, that results. In this analysis, the following eight mutually exclusive end states are of interest:

1. "OK"–Indicates the absence of the other end states.

2. Direct Exposure, Degraded Shielding–Applies to event sequences where an SSC providing shielding is not breached, but the shielding function is jeopardized. An example is a lead-shielded transportation cask that is dropped from a height great enough for the lead to slump toward the bottom of the cask at impact, leaving a partially shielded path for radiation to stream. This excludes radionuclide release from containment and an indication of a reactivity increase.

3. Direct Exposure, Loss of Shielding (LOS)–Applies to event sequences where an SSC providing shielding fails, leaving a direct path for radiation to stream. For example, this end state applies to a breached transportation cask, with the dual-purpose canister (DPC) or transportation, aging, and disposal (TAD) canister inside maintaining its containment function. In another example, this end state applies to shield doors inadvertently opened. This excludes radionuclide release from containment and an indication of a reactivity increase.

4. Radionuclide Release, Filtered–Indicates a release of radioactive material from its containment, through a filtered path, to the environment. The release is filtered when it is confined and filtered through the successful operation of the heating, ventilation, and air conditioning (HVAC) system over its mission time. This excludes nuclear reactivity increases.

5. Radionuclide Release, Unfiltered–Indicates a release of radioactive material from its confinement, through an unfiltered path, to the environment. This excludes nuclear reactivity increases.

6. Radionuclide Release, Filtered, Also Important to Criticality–For dry operations with canistered SNF, this end state refers to a situation in which a breach of a canister has occurred (resulting in a radionuclide release), and a moderator, such as unborated water, has entered the canister. For dry operations with uncanistered commercial spent nuclear fuel (UCSNF), this end state refers to a situation in which a breach of a transportation cask has occurred (resulting in a radionuclide release), and a moderator, such as unborated water, has entered the cask. The release of the radioactive material to the environment is through a filtered path.

7. Radionuclide Release, Unfiltered, Also Important to Criticality–This end state refers to a situation in which an unfiltered radionuclide release occurs and (unless the associated event sequence is beyond Category 2) a criticality investigation is indicated.

8. Important to Criticality–This end state refers to a situation in which there has been no radionuclide release and (unless the associated event sequence is beyond Category 2) a criticality investigation is indicated.

The end states Radionuclide Release (filtered or unfiltered), also Important to Criticality and Important to Criticality segregate event sequences for which some of the conditions leading to a criticality event have been met. This does not imply, however, that a criticality event is inevitable.

The answer to the second question, “What are the consequences?” requires consideration of radiation exposure and the potential for criticality for Category 1 and Category 2 event sequences. Consideration of the consequences of event sequences that are beyond Category 2 is not required by 10 CFR Part 63 (Ref. 2.3.2). Radiation doses to individuals from direct exposure and radionuclide release are addressed in a companion consequence analysis by modeling the effects of bounding event sequences related to the various waste forms and the facilities that handle them.

The radiological consequence analysis develops a set of bounding consequences. Each bounding consequence represents a group of like event sequences. The group (or bin) is based on such factors as characteristics of the waste form involved, availability of HEPA filtration, location of occurrence (in water or air), and characteristics of the surrounding material (such as transportation cask or waste package). Each event sequence is mapped to one of the bounding consequences, for which conservative doses have been calculated.

Criticality analyses are performed to ensure that any Category 1 and Category 2 event sequences that terminate in end states that are ITC would not result in a criticality. In order to determine the criticality potential for each waste form and associated facility and handling operations, criticality sensitivity calculations are performed. These calculations evaluate the impact on system reactivity of variations in each of the parameters ITC during the preclosure period. The parameters are: waste form characteristics, reflection, interaction, neutron absorbers (fixed and soluble), geometry, and moderation. The criticality sensitivity calculations determine the sensitivity of the effective neutron multiplication factor to variations in any of these parameters as a function of the other parameters. The deterministic sensitivity analysis covers all reasonably achievable repository configurations that are ITC. Section 4.3.9 provides a detailed discussion of the treatment of criticality in event sequences.

The third question, "How likely is it?" is answered by the estimation of event sequence frequencies. The PCSA uses ***failure history*** records (for example, *Nonelectronic Parts Reliability Data 1995* (Ref. 2.2.35) and *Nuclear Computerized Library for Assessing Reactor Reliability (NUCLARR)* NUREG/CR-4639 (Ref. 2.2.48)), structural reliability analysis, thermal stress analysis, and engineering and scientific knowledge about the design as the basis for estimation of probabilities and frequencies. These sources coupled with the techniques of probability and statistics, for example, *Handbook of Parameter Estimation for Probabilistic Risk Assessment*, NUREG/CR-6823 (Ref. 2.2.8), are used to estimate frequencies of initiating events and event sequences and the conditional probabilities of pivotal events.

The PCSA uses ***event sequence diagrams*** (ESDs), *event trees*, and ***fault trees*** to develop and quantify event sequences. The ESDs and event trees are described and developed in the event sequence development analyses (Ref. 2.2.29). The present analysis uses fault trees to disaggregate an SSC or equipment item to a level of detail that is supported by available reliability information from failure history records. Various techniques of probability and statistics are employed to estimate failure frequencies of mechanical, electrical, electro-mechanical, and electronic equipment. Such frequencies, or *active component* unreliabilities, provide inputs to the fault tree models of equipment items. Fault trees are used to model initiating events and, in some instances, to model pivotal events.

Some pivotal events are related to structural failures of containment (e.g., canisters) and others are related to shielding (e.g., transportation casks). In these cases, probabilistic structural reliability analysis methods are employed to calculate the mean conditional probability of containment or shielding failure, given a defined initiating event (e.g., a drop from a crane). Other pivotal events require knowledge of system response to a thermal challenge (e.g., fire). Calculation of failure probabilities given a thermal challenge is accomplished by the appropriate analysis using applicable material properties and traditional methods of heat transfer analysis, structural analysis, and fire dynamics. The probabilities so derived are called *passive equipment* failure probabilities.

All pivotal events in the PCSA are characterized by *conditional probabilities* because their values rely on the conditions set by previous events in an event sequence. For example, the failure of electrical or electronic equipment depends on the operating temperature. Therefore, if a previous event in a scenario is a failure of a cooling system, then the probability of the electronic equipment failure would depend on the operation (or not) of the cooling system.

The frequency of occurrence of an event sequence is the product of the frequency of its initiating event and the conditional probabilities of its pivotal events. This is true whether or not the frequency and probabilities are expressed as single points or probability distributions. The frequencies of event sequences within the same ESD that result in the same end state are summed to group together event sequences for the purpose of categorization. The concept of ***aggregating event sequences*** to obtain aggregated end state results is depicted in Figure 4.3-1.

The PCSA is described above as a system simulation. This is important in that any simulation or model is an approximate representation of reality. Approximations may lead to uncertainties regarding the frequencies of event sequences. The event sequence quantification presented in this document propagates input uncertainties to the calculated frequencies of event sequences using Monte Carlo techniques. Figure 4.3-1 illustrates the ***results*** as horizontal bars to depict the uncertainties that give rise to potential ranges of results.

As required by the performance objectives for the GROA through permanent closure in 10 CFR 63.111 (Ref. 2.3.2), each aggregated event sequence is categorized based on its frequency. Therefore, the focus of the analysis in this document is to:

1. Quantify the frequency of each initiating event that is identified in the event sequence development analysis (Ref. 2.2.29).

2. Quantify the conditional probability of the pivotal events in each event sequence.

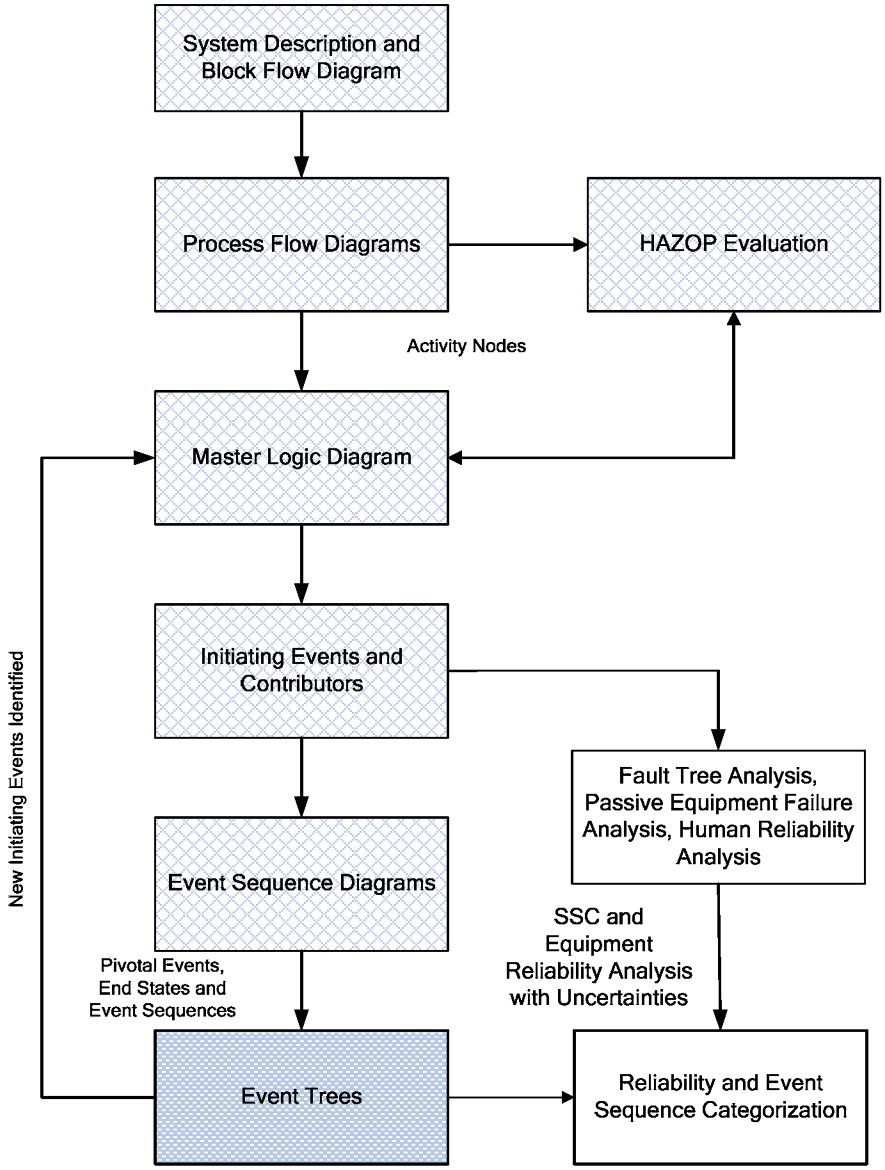
3. Calculate the frequency of each event sequence (i.e., calculate the product of the initiating event frequency and pivotal event conditional probabilities).

4. Calculate the frequencies of the aggregated event sequences.

5. Categorize the aggregated event sequences for further analysis.

The activities required to accomplish these objectives are illustrated in Figure 4.3-2. The cross-hatched boxes review the process steps performed for the event sequence development analysis (Ref. 2.2.29). The interface between the event sequence development analysis and this categorization analysis is the set of event trees, as represented by the darkly shaded box. The event trees from the event sequence development analysis are passed as input into this analysis. The unshaded boxes represent the analysis performed in this study, the methods of which are described later in Section 4.

The event sequences that are categorized in this analysis can be more fully understood by consulting the event sequence development analysis (Ref. 2.2.29). The remainder of this subsection presents a brief overview of the event sequence development process.

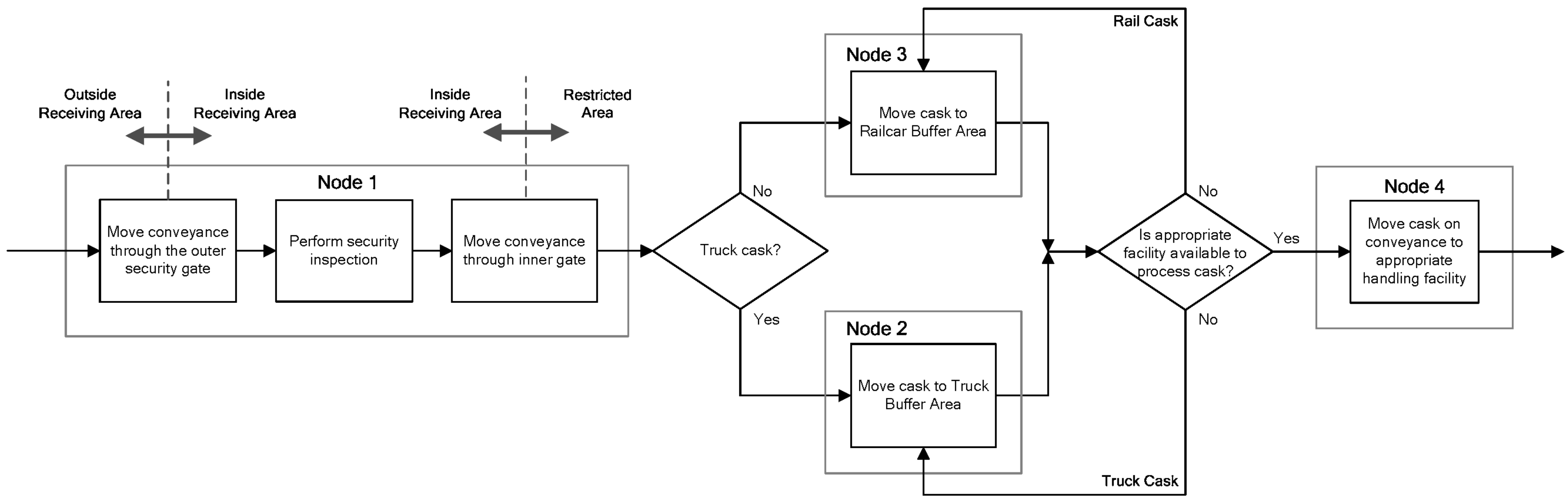


NOTE: HAZOP = hazard and operability; SSC = structure, system, or component.

Source: Modified from Ref. 2.2.29, Figure 2

Figure 4.3-2. Preclosure Safety Assessment Process

A simplified process flow diagram (PFD) is developed to clearly delineate the process and sequence of operations to be considered within the analysis. An excerpt from an example PFD is shown in Figure 4.3-3. The PFD guides development of the MLD and the conduct of the HAZOP evaluation. The PFD uses nodes to identify specific processes and operations that are evaluated with both a MLD and HAZOP evaluation to identify potential initiators.



NOTE: This diagram illustrates a small portion of the overall handling operations for typical site transportation operations.
TC = transportation cask.

Source: Original

Figure 4.3-3. Portion of a Simplified Example Process Flow Diagram for Typical Intra-Site Operations

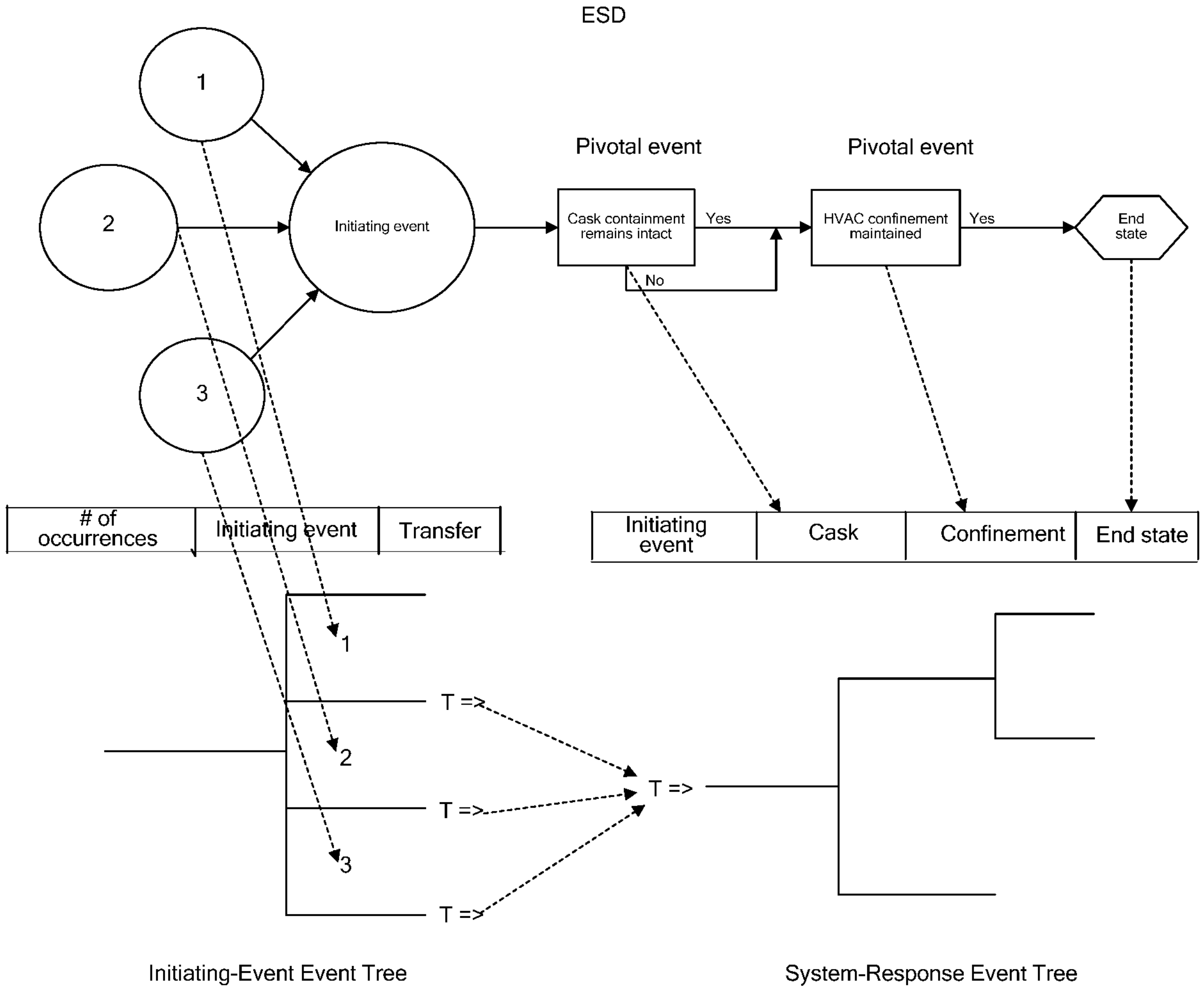
Development of the MLD is accomplished by deriving specific failures from a generalized statement of the undesired state. As a "top-down" analysis, the MLD starts with a top event, which represents a generalized undesired state. The top event includes direct exposure to radiation or exposure as result of a release of radioactive material. The basic question answered by the MLD is "How can the top event occur?" Each successively lower level in the MLD hierarchy divides the identified ways in which the top event can occur with the aim of eventually identifying specific initiating events that may cause the top event. In the MLD, the initiating events are shown at the next-to-lowest level. The lowest level provides an example of contributors to the initiating event. This process for the PCSA is presented in detail in the event sequence development analysis (Ref. 2.2.29, Section 4.3.1.2).

The HAZOP evaluation focuses on identifying potential initiators that are depicted in the lower levels of the MLD. It is a "bottom-up" approach that supplements the "top-down" approach of the MLD. Based on the PFD, the HAZOP evaluation includes a systematic study of repository operations during the preclosure phase. As an early step in the performance of the HAZOP evaluation, the intended function, or intention, of each node in the PFD is defined. The intention is a statement of what the node is supposed to accomplish as part of the overall operation. The HAZOP analysts work their way through the PFD, node by node, and postulate deviations from normal operations. A deviation is any out-of-tolerance variation from the normal values of parameters specified for the intention.

Although the repository is to be the first of its kind in some ways, the planned operations are based on established technologies, such as transportation cask movement by truck and rail; crane transfers of casks and canisters; rail-based trolleys; air-based conveyances; robotic welding; and SNF pool operations. The team assembled for the HAZOP evaluation (and available on call as questions arose) had experience with such technologies and was well equipped to perform the evaluation.

The MLD and HAZOP evaluation are strongly interrelated. The MLD is cross-checked to the HAZOP evaluation. That is, the MLD is modified to include any initiators and contributors identified in the HAZOP evaluation that are not already included in the MLD. The entire process (Figure 4.3-2) is iterative in nature with insights from succeeding steps often feeding back to predecessors. The top-down MLD and the bottom-up HAZOP evaluation provide a diversity of viewpoints that add confidence that no important initiating events have been omitted. Details on implementation of the HAZOP evaluation are presented in the event sequence development analysis (Ref. 2.2.29, Section 4.3.1.3).

An overview of the pertinent human and SSC responses to an initiating event is depicted in an ESD. As shown in Figure 4.3-4, an ESD represents event sequences in terms of initiating events, pivotal events, and end states. Because the future is uncertain, the analyst does not know which of the alternative scenarios might occur. The ESD depicts the alternative scenarios as paths that can be traced through the diagram. Each alternative path from initiating event to an end state represents an event sequence. The events that may occur after the initiating event are identified by asking and answering the question "What can happen next?" Typically, questions about the integrity of radionuclide containment (e.g., cask, canister, or waste package) and confinement (e.g., HVAC) become pivotal events in the ESD.



Source: Original

Figure 4.3-4. Event Sequence Diagram to Event Tree Relationship

The initiating events that are represented in the MLD are transferred to events depicted as "little bubbles" (Figure 4.3-4, "1", "2", "3") in the ESDs. One or more initiating events identified on the MLD may be included in a single little bubble, but all of the initiating events included in the little bubble must have the same pivotal events (i.e., human and SSC responses) and the same conditional probability for each pivotal event. Initiating events represented by little bubble may be aggregated further into larger circles, as depicted in Figure 4.3-4. The big bubble represents the failures associated with a major function in a specific location depicted in the PFD and establishes the level of aggregation for the categorization of the event sequence (as Category 1, Category 2, or beyond Category 2).

For example, all initiating events that challenge the containment function of a cask would include pivotal events that question the containment integrity of the cask and the shielding integrity. The knowledge to develop such ESDs and appropriately group the initiating events comes from a detailed knowledge of the SSCs and operations derived from developing the PFD, MLD, and HAZOP evaluation. The pivotal event conditional probabilities are the same for all initiating events grouped in a little bubble. All initiating events represented by the big bubble have the same human and SSC responses and, therefore, may be represented by the same event sequences. However, the conditional probability for each pivotal event is not necessarily the same for each little bubble.

4.3.1 Event Tree Analysis and Categorization

Also illustrated in Figure 4.3-4 is the relationship of the YMP ESDs to their equivalent event trees. Event trees contain the same information as ESDs but in a form suitable to be used by software such as SAPHIRE (Ref. 2.2.36), which ultimately stores event trees, fault trees, and reliability data, and can be used to quantify complex event sequences. (SAPHIRE was used on for fault tree quantification of initiating events for Intra-Site Operations and Subsurface Operations, because the systems and operations involved were not as complex as those in the waste handling facilities.)

Event tree depiction of ESDs provides little new information. In an event tree, each event sequence has its separate line so that the connections between initiating events and end states is more explicit than in ESDs (Ref. 2.2.64, Section 3.4.4.2). Any path from left to right that begins with the initiating event and terminates with an end state is an event sequence. Every path must ultimately terminate at an end state. As illustrated in the event tree portion of Figure 4.3-4, each intersection of a horizontal and vertical line is a node (or branch point). Each node is associated with a conditional probability of following the vertical (downward) branch. The complement is the probability of taking the vertical (upward) branch, that is, the probability of success. By convention, the description of each branch is stated as a success, and the downward branch indicates a failure. To quantify the event sequence, the initiating event frequency (or expected number of occurrences) is multiplied by the conditional probability of each subsequent pivotal event node in the event sequence until an end state is reached.

The YMP PCSA uses the concept of linked event trees (Ref. 2.2.64). Each facility has its own set of event trees. The first event tree simply represents the little bubbles, one horizontal line per little bubble. This is called the initiator event tree (IET). The second event tree contains the pivotal events and end states. This is called the system response event tree (SRET). An event sequence starts with each of the horizontal lines as if it were the initiating event on the SRET, as indicated in Figure 4.3-4. Each set of event trees is quantified for each waste container type (e.g., DPCs, TAD canisters, or DOE SNF) handled by the YMP. The event in the IET labeled "# of occurrences" represents the number of handlings (i.e., demands) for that initiating event. For example, each movement of an aging overpack between a handling facility and the Aging Facility provides an opportunity for a drop or collision. An event sequence quantification includes: the frequency (or number of occurrences) of each end state (e.g., radionuclide release), associated with a single lift, and multiplies it by the number of lifts to obtain the expected number of drops over the preclosure period. This approach is consistent with a binomial model of reliability.

Categorization of event sequences is based on the aggregated "big bubble" initiating event. Each line on the IET coupled with the SRET is quantified separately. Using Figure 4.3-4, this would mean three quantifications, corresponding to the three initiating event frequencies and three corresponding sets of pivotal event probabilities. (By SAPHIRE convention, the top line is a dummy initiating event.) Each event sequence, therefore, would have three values. In order to obtain the total frequency of an event sequence for purposes of categorization, per 10 CFR 63.111 (Ref. 2.3.2), the three frequencies are probabilistically summed. Doing this summation is equivalent to basing categorization on the big bubble. If an event sequence has only one little bubble in the ESD, then only the SRET is used, with the initiating event in the place so denoted. In this case, summation of event sequences is not necessary and is not performed.

Because each event sequence is associated with a mean number of occurrences over the preclosure period, categorization is straightforward. Those event sequences that are expected to occur one or more times before permanent closure of the GROA are Category 1 event sequences. Other event sequences that have at least one chance in 10,000 of occurring but less than one occurrence before permanent closure are Category 2 event sequences. Sequences that have less than one chance in 10,000 of occurring before permanent closure are identified as beyond Category 2. As described in Section 4.3.6, event sequence quantification considers uncertainties, and categorization is performed on the basis of an event sequence mean value of the underlying probability distribution. The preclosure period lasts 100 years but actual emplacement operations occupy 50% of this time (Ref. 2.2.16, Section 2.2.2.7).

An initiating event for an event sequence may have the potential to affect several waste form types, such as a high-level radioactive waste (HLW) canister and a DOE standardized canister, or a TAD canister and a DPC. For example, the seismically induced event sequence leading to a collapse of a surface facility could cause the breach of all the waste containers inside that facility. Similarly, a large fire affecting an entire facility affects all the waste containers inside the facility. The number of occurrences over the preclosure period of an event sequence that affects more than one type of waste container is equal to the number of occurrences of the event sequence, evaluated for one of the waste form types, multiplied by the probability that the other waste form types are present at the time the initiating event occurs. Because a probability is less than or equal to one, the resulting product is not greater than the number of occurrences of the event sequence before multiplication by the probability. The number of occurrences of an event sequence is calculated for a given waste form type, without adjustment for the probability of presence of other waste form types.

The results of the event sequence categorization (Section 6.8.3) show that the event sequences that have the potential to cause personnel exposure to radiation from more than one type of waste form are either Category 2 event sequences resulting in a direct exposure, or beyond Category 2 event sequences resulting in a radionuclide release. In the first case, doses from direct radiation after a Category 2 event sequence have no effect on the public because of the great distances from the locations of offsite receptors. In the second case, beyond Category 2 event sequences do not require a consequence calculation. Thus, the demonstration that the performance objectives of 10 CFR 63.111 (Ref. 2.3.2) are met is not dependent on the waste form at risk in the event sequences that may involve more than one type of waste form. It is appropriate, therefore, to evaluate event sequences separately for each relevant type of waste form.

Although event trees were developed in the event sequence development analysis (Ref. 2.2.29), detailed event tree analysis using SAPHIRE software was not carried out. Instead, the event sequence logic is extracted from the set of IETs and SRETs and modeled in an Excel spreadsheet. Subsequently, data for initiating event frequencies and pivotal event conditional probabilities obtained via fault tree analysis (FTA) or derived from empirical data are incorporated into the spreadsheet. FTA is performed using SAPHIRE. When the spreadsheet is fully populated, event sequence quantification begins, followed by event sequence grouping and categorization. The method for obtaining the initiating and pivotal event data is described in Section 4.3.2. How the Excel spreadsheet is used for quantification is described in Section 4.3.1.1.

4.3.1.1 Quantification using Excel

This section presents a summary of how the quantification is performed for Intra-Site Operations using a combination of Excel (for event tree and event sequence quantification) and SAPHIRE fault tree quantification (to produce probability and uncertainty values for the calculation).

Internal event sequences that are based on the event trees presented in Attachment A and fault trees presented in Section 6.2 and Attachment B are quantified using Excel and SAPHIRE (refer also to discussion on software usage in Section 4.2). The quantification of an event sequence consists of calculating its number of occurrences over the preclosure period, which is generated by combining a frequency for each initiating event with the conditional probabilities of pivotal events that comprise the sequence. The quantification results are presented as an expression of the mean number of occurrences of each event sequence over the preclosure period and the uncertainty for the number of occurrences (i.e., standard deviation). The frequency of occurrence is the product of the following:

- *Number of times the waste handling operation or activity that gives rise to the event sequence is performed over the preclosure period*: An example of this value would be the total number of TAD canisters in aging overpacks to be sent to the Aging Facility combined with the number of transfers between a waste handling facility and the Aging Facility over the preclosure period.

- *Probability of occurrence of the initiating event, per waste handling operation, for the event sequence considered*: Continuing with the previous example, this could be the probability of dropping an aging overpack containing a TAD canister being conveyed by a site transporter between a surface facility and the Aging Facility. The initiating event probability is entered into Excel as parameters of the distribution (mean, median, and standard deviation), which are either produced from a fault tree in SAPHIRE or are based on a basic event value (e.g., empirical data on forklift collisions).

- *Conditional probability of each of the pivotal events of the event sequence (shown graphically in the SRET for each ESD)*: The conditional probabilities used in this analysis are point values that represent a passive failure (Section 6.3.2), for example, breach of a TAD canister inside an aging overpack due to a drop.

Uncertainties in the initiating event probabilities are propagated through the event sequence logic to quantify the uncertainty in the event sequence quantification. The uncertainty associated with the initiating event probabilities provided by the fault trees are produced by SAPHIRE using the built-in Monte Carlo method. Each fault tree top event was analyzed using 10,000 trials and a seed value of 1234. The number of trials is considered sufficient to ensure accurate results for the distribution parameters.

The event sequence logic (graphically shown in Attachment A, Section A5) follows a transfer to a SRET, which provides the basis for quantifying the rest of the sequence through the use of the pivotal events. (The pivotal events are detailed in Attachment A, and the values used for them are presented in Section 6.3.) The IETs and the SRETs developed in SAPHIRE for the event sequence development analysis (Ref. 2.2.29) provide a graphical representation for model development in the Excel spreadsheet. An example of the Excel spreadsheet is provided in Figure 4.3-5.

TADs	Event Tree / Sequence No.													
	ISO-ESD02-TAD	No. of AOs	No. of moves (each)	IE mean	IE median	IE std dev	TRANSCASK	CANISTER	SHIELDING	MODERATOR	Calc'd Mean	Calc'd Median	Calc'd StdDev	End State
ST collision	2-1	8,143	2	5.00E-03	2.00E-03	1.00E-03	N/A	1.00E+00	1.00E+00		8.E+01	3.E+01	2.E+01	OK
sm. bub1	2-2							1.00E+00	1.00E-05		8.E-04	3.E-04	2.E-04	DEL
	2-3							1.00E-08		1.00E+00	8.E-07	3.E-07	2.E-07	RRU
	2-4							1.00E-08		0.00E+00	0.E+00	0.E+00	0.E+00	RUC
ST drops AO	3-1	8,143	2	4.00E-08	2.00E-08	1.00E-07	N/A	1.00E+00	1.00E+00		6.5E-04	3.3E-04	1.6E-03	OK
sm. bub2	3-2							1.00E+00	5.00E-06		3.3E-09	1.6E-09	8.1E-09	DEL
	3-3							1.00E-05		1.00E+00	6.5E-09	3.3E-09	1.6E-08	RRU
	3-4							1.00E-05		0.00E+00	0.0E+00	0.0E+00	0.0E+00	RUC

	Total TAD Sequence ID	Mean	Median	StdDev	Initial Categ.
OK	**ISO02-TAD-SEQ1-OK**	**8.1E+01**	**3.3E+01**	**1.6E+01**	
DE-SHIELD	**ISO02-TAD-SEQ2-DEL**	**8.1E-04**	**3.3E-04**	**1.6E-04**	*Cat2*
RR-UNFILT	**ISO02-TAD-SEQ3-RRU**	**8.2E-07**	**3.3E-07**	**1.6E-07**	*BC2*
RR-UNFILT	**ISO02-TAD-SEQ4-RUC**	**0.0E+00**	**0.0E+00**	**0.0E+00**	*BC2*

NOTE: Blank cells in this table are intentional and have been verified.

AO = aging overpack; BC2 = beyond Category 2; Cat2 = Category 2; DEL = direct exposure, loss of shielding; ESD = event sequence diagram; IE = initiating event; RRU = unfiltered radionuclide release, not important to criticality; RUC = unfiltered radionuclide release, important to criticality; SEQ = sequence; ST = site transporter; StdDev = standard deviation; TAD = transportation, aging, and disposal.

Source: Original

Figure 4.3-5. Excel Spreadsheet Example Emphasizing ISO-ESD02-TAD, Sequence 3-3 for a TAD Canister Drop Resulting in an Unfiltered Radiological Release

The calculation is illustrated in Figure 4.3-5 as an event sequence (Event Tree/Sequence No. 3-3) initiated by a drop of a TAD canister in an aging overpack during a transfer to the Aging Facility via a site transporter, followed by the breach of the canister, without potential for moderator entry into the canister.

The event sequence, which leads to an unfiltered radionuclide release that is not ITC (RRU), starts with an IET that depicts the number of TAD canisters in aging overpacks that are transported to and from the Aging Facility over the preclosure period. Based on *Waste Form Throughputs for Preclosure Safety Analysis* (Ref. 2.2.23, Table 4), there are 16,286 such movements (i.e., 8,143 waste forms × 2 trips each). The branch on the IET that deals with the drop of a canister is followed. Multiplying the number of TAD canister movements by the probability of a drop yields the number of occurrences of this initiating event over the preclosure period.

The breach of the canister given a drop (Event Tree/Sequence No. 3-3), is first evaluated under the pivotal event called "CANISTER" (data labeled in spreadsheet as "CANISTER_AO_IMPACT"), which has a failure probability of 1E-08. The next pivotal event is "MODERATOR", which has a probability value of "1", indicating that moderator is not present. In the event sequence analyzed, no moderator entry occurs; that is, the success branch is followed.

The parameters to define a distribution are calculated for each event sequence by multiplying each parameter (mean, median, and standard deviation) by the scalar values for the number of occurrences, the number of movements, and the conditional probability point estimates. This method is valid because multiplying a distribution by one or more constants is a linear operation. That is, it is simply a translation of the moments of the distribution. An additional check of this method was made to ensure the results generated were consistent with the other PCSA analyses, which required complex modeling in SAPHIRE. Test cases were run in SAPHIRE, and the results were the same as those generated in the Excel spreadsheet.

For categorization, the single-line event sequences are aggregated (summed) for each end state, as described previously in Section 4.3. After multiplying the distribution parameters by the applicable scalar values as described above, the single-line event sequences still represent a probability distribution, for which the mean values can be directly summed, as described in Equation 1 (Ref. 2.2.89):

Summing mean values for a given distribution:

$$\mu_{X+Y} = \mu_X + \mu_Y \tag{Eq. 1}$$

where

X and Y are independent variates

μ_X is the mean value for one distribution

μ_Y is the mean value for a second distribution

The standard deviation (σ) for the aggregated event sequence is calculated as the square root of the sum of the squares, based on the following property for combining variance, σ^2, of two distributions in Equation 2 (Ref. 2.2.89):

$$\sigma_{X+Y}^2 = \sigma_X^2 + \sigma_Y^2 \quad \text{(Eq. 2)}$$

where

X and Y are independent variates

σ_X^2 is the variance for one distribution

σ_Y^2 is the variance for the second distribution

Therefore, taking the square root of the variance to obtain the standard deviation, results in Equation 3:

$$\sqrt{\sigma_{X+Y}^2} = \sqrt{\sigma_X^2 + \sigma_Y^2} \quad \text{(Eq. 3)}$$

That is, the standard deviation for the combined distribution is the square root of the sum of the squares of each distribution's value for standard deviation.

The median for each aggregated sequence is calculated based on the mean and variance using Equation 4 (reordered to solve for the median) (Ref. 2.2.51, Table 11.2).

$$\sigma^2 = \mu^2\left[\left(\frac{\mu}{m}\right)^2 - 1\right] \quad \text{(Eq. 4)}$$

$$m = \mu^2\left[\frac{1}{\sqrt{\mu^2 + \sigma^2}}\right]$$

where

σ^2 is the variance (standard deviation squared)

μ is the mean

m is the median

The resulting values are the parameters that define the estimated probability distributions for each aggregated event sequence. The mean value for each aggregated sequence is compared to the performance objectives for categorization (Ref. 2.3.2). Figure 4.3-6 shows an example of the aggregated event sequence frequencies. The aggregated event sequence that results in direct exposure (DE-SHIELD-LOSS) has a mean value of 8.1E-04. This is greater than 1E-04 but less than 1, therefore, this is a Category 2 event sequence. The event sequence that ends in a non-ITC unfiltered radiological release (RR-UNFILTERED) is less than 1E-04 and is thus beyond

Category 2. The event sequence that ends in an unfiltered radiological release ITC (RR-UNFILTERED-ITC) is "0", because moderator is not present in this event; therefore, the potential for criticality cannot exist.

	Total TAD Sequence ID	Mean	Median	StdDev	Initial Categ.
OK	ISO02-TAD-SEQ1-OK	8.1E+01	3.3E+01	1.6E+01	
DE-SHIELD-LOSS	ISO02-TAD-SEQ2-DEL	8.1E-04	3.3E-04	1.6E-04	Cat2
RR-UNFILTERED	ISO02-TAD-SEQ3-RRU	8.2E-07	3.3E-07	1.6E-07	BC2
RR-UNFILTERED-ITC	ISO02-TAD-SEQ4-RUC	0.0E+00	0.0E+00	0.0E+00	BC2

NOTE: DEL = direct exposure due to shield loss; RRU = unfiltered radionuclide release; RUC = unfiltered radionuclide release also important to criticality; SEQ = sequence; StdDev = standard deviation; TAD = transportation, aging, and disposal.

Source: Original

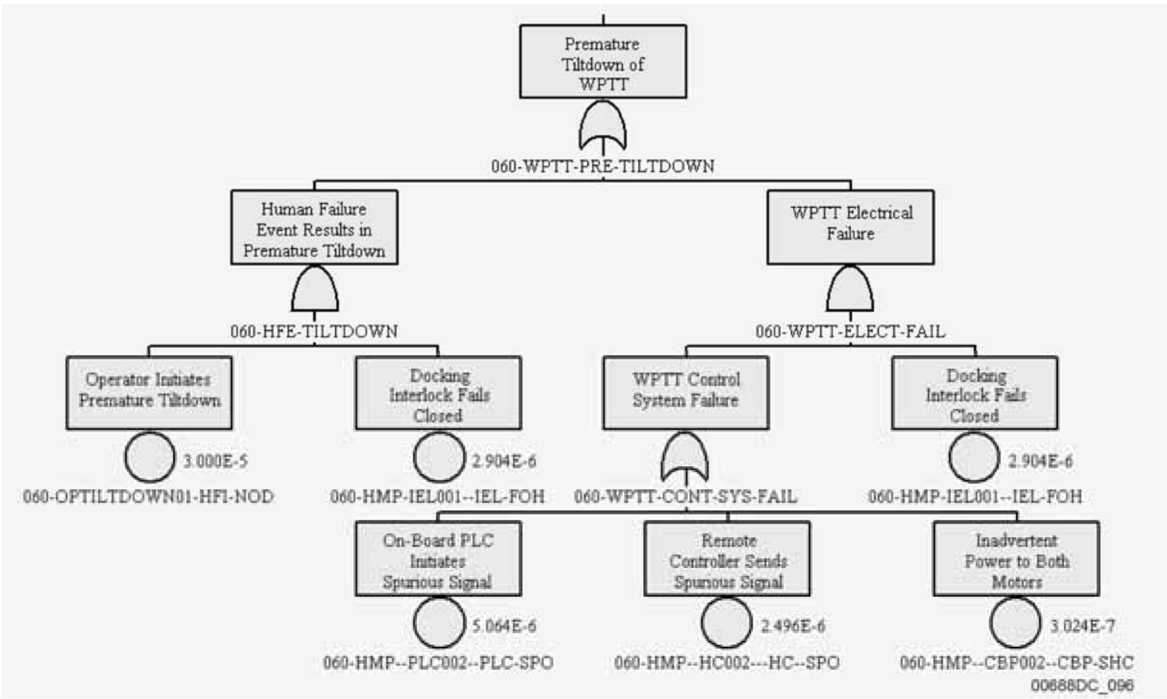
Figure 4.3-6. Grouped Event Sequences for ESD-02, TAD Canisters

4.3.2 Initiating and Pivotal Event Analysis

The purpose of this categorization analysis is to develop the frequency (i.e., expected number of occurrences over the 50-year operating lifetime for the facilities or during the preclosure period, as appropriate) for each event sequence, in order to categorize the event sequences in accordance with 10 CFR 63.2 (Ref. 2.3.2). (In this document, the term frequency is used interchangeably with the expected number when discussing event sequence quantification.) This involves developing the frequency of each initiating event and conditional probability of each pivotal event. Some pivotal events in this analysis are associated with structural or thermal events. In these cases, passive equipment failure analyses (PEFAs) are performed. The PEFAs include probabilistic structural or thermal analyses as summarized later in this section to develop mean conditional probabilities of failure directly associated with pivotal events. Often, however, the events depicted in ESDs or event trees cannot be mapped easily to such a calculation or to reliability data (e.g., failure history records). This is because large aggregates of components (e.g., systems or complicated pieces of equipment such as the transport and emplacement vehicle (TEV) used in Subsurface Operations) may be unique to the YMP facility with little or no prior operating history. However, the components of which unique equipment are composed have often been used before, and an adequate set of reliability data exists for these components. The PCSA uses fault trees for this mapping. As a result, the PCSA disaggregates or breaks down the initiating events and pivotal events, when needed, into a collection of simpler components. Most initiating events analyzed for Intra-Site Operations use fault trees. In effect, the use of fault trees creates a map between ESD or event tree events and the available reliability data.

4.3.2.1 Fault Tree Analysis

Construction of a fault tree is a deductive reasoning process that answers the question "What are all combinations of events that can cause the top event to occur?" Figure 4.3-7 demonstrates this:



NOTE: This fault tree is presented for illustrative purposes only and is not intended to represent results of the present analysis.

PLC = programmable logic controller; WPTT = waste package transfer trolley.

Source: Original

Figure 4.3-7. Example Fault Tree

This top-down analytical development defines the combinations of causes for the initiating or pivotal events into an event sequence in a way that allows the probability of the events to be estimated.

As the name implies, fault tree events are typically failures or faults. Fault trees use logic or Boolean gates. Figure 4.3-7 shows the two types of gates: the AND gate (mound-shaped symbol with a flat bottom) and the OR gate (mound-shaped symbol with a concave bottom). An AND gate flows output up the tree if *all* events immediately attached to it occur. An AND gate is often used to represent components or system features that back each other up, that is, if one fails then the other continues to adequately perform the function. An OR gate flows output up the tree if *any one or more* events immediately attached to it take place. The success criterion of the SSC or equipment being analyzed is important in determining the appropriate use of gates.

The bottom level of the fault tree contains events with circles beneath them indicating a *basic event*. Basic events are associated with frequencies from industry-wide active equipment reliability information, PEFA, or human reliability analysis (HRA).

Fault trees are Boolean-reduced to "minterm" form, which expresses the top event in terms of the union of minimal cut sets. Minimal cut sets, which are groups of basic events that must all occur to cause the top event in the fault tree, result from applying the Boolean Idempotency and Absorption laws. FTA, as used in the PCSA, is well described in the *Fault Tree Handbook* NUREG-0492 (Ref. 2.2.87). Each minimal cut set represents a single basic event or a combination of two or more basic events (e.g., a logical intersection of basic events) that could result in the occurrence of the event sequence. Minimal cut sets are minimal in the sense that they contain no redundant basic events (i.e., if any basic event were removed from a minimal set, the remaining basic events together would not be sufficient to cause the top event). Section 4.3.6 continues the discussion about utilization of minimal cut sets in the quantification of event sequences.

The organization of the fault trees in the PCSA is developed to emphasize two primary elements, which together result in the occurrence of the top event: (1) human failure events (HFEs), and (2) equipment failures. The HFEs include postulated unintended crew actions and omissions of crew actions. Identification and quantification of HFEs are performed in phases. Initial identification of HFEs lead to design changes either to eliminate them or to reduce the probability that they would cause the fault tree top event. For example, adding an electro-mechanical interlock to a piece of equipment would make it so a crew error of commission and failure of the interlock must both take place for an initiating event to occur.

Event trees and fault trees are complementary techniques. Often used together, they map the system response from initiating events through damage levels. Together, they delineate the necessary and sufficient conditions for the occurrence of each event sequence (and end state). Because of the complementary nature of using both inductive and deductive reasoning processes, combining event trees and fault trees allow more comprehensive, concise, and clearer event sequences to be developed and documented than using either one exclusively. The selection of and division of labor among each type of diagram depends on the analyst's opinion. In the PCSA, the choice was made to develop event trees along the lines of major functions such as crane lifts, waste container containment, HVAC, and building confinement, and introduction of moderator. Fault trees disaggregate these functions into equipment or component failure modes for which unreliabilities or unavailabilities were obtained.

4.3.2.2 Passive Equipment Failure Analysis

Passive equipment (e.g., transportation casks, storage canisters, waste packages) may fail from manufacturing defects, material variability, defects introduced by handling, long-term effects such as corrosion, and normal and abnormal use. Industry codes such as *Minimum Design Loads for Buildings and Other Structures* (Ref. 2.2.5) and "General Requirements for Division 1 and Division 2" Section III, Subsection NCA of *2004 ASME Boiler and Pressure Vessel Code* (Ref. 2.2.7) establish design load combinations for passive structures (such as building supports) and components (such as canisters). These codes specify design basis load combinations and provide the method to establish allowable stresses. Typical load combinations for buildings involve snow load, dead (mass) load, live occupancy load, wind load, and earthquake load. Typical load combinations for canisters and casks are found in *2004 ASME Boiler and Pressure Vessel Code* (Ref. 2.2.7) and would include, for example, preloads or pre-stresses, internal pressurization and drop loads, which are specified in terms of acceleration. Design basis load combinations are purposefully specified to conservatively encompass anticipated normal operational conditions as well as uncertainties in material properties and analysis. Therefore, passive components, when designed to codes and standards and in the absence of significant aging, generally fail because of load combinations or individual loads that are much more severe than those anticipated by the codes. Fortunately, the conservative nature of establishing the design basis coupled with the low probability of multiple design basis loads occurring concurrently often means a significant margin or factor of safety exists between the design point and actual failure. The approach used in the PCSA takes advantage of the design margins (or factor of safety).

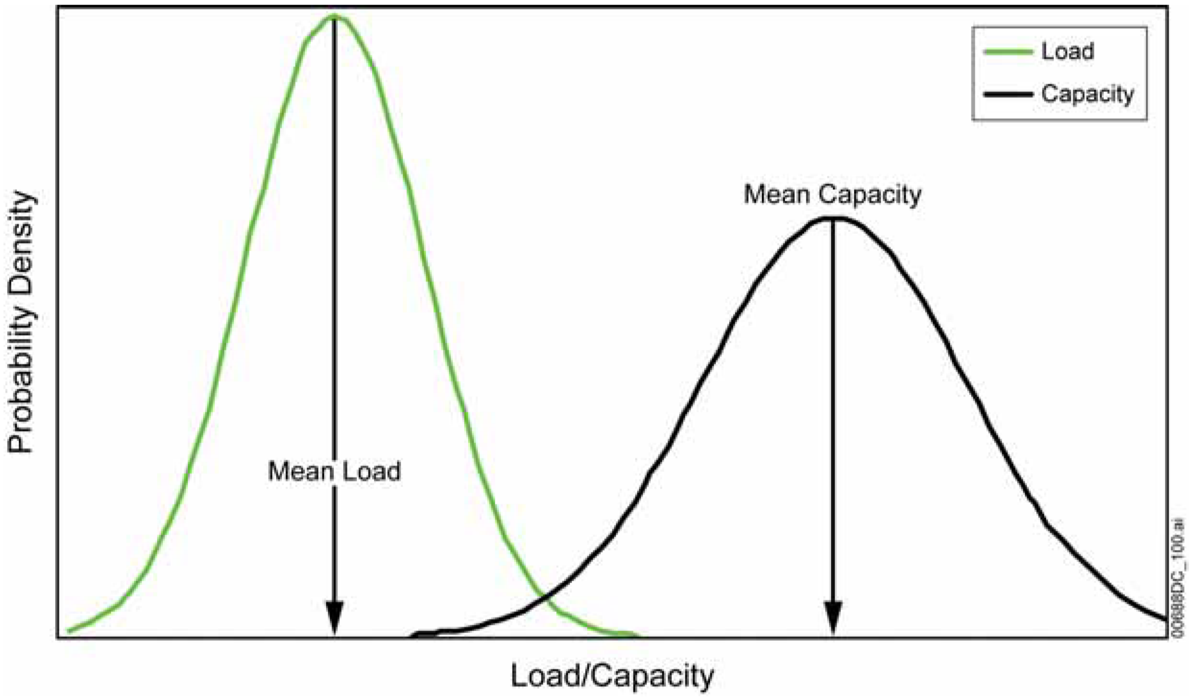
The development of code requirements for minimum design loads in buildings and other structures in the late 1970s considered multiple loads. A probabilistic basis for structural reliability was developed as part of the development of *Development of a Probability Based Load Criterion for American National Standard A58, Building Code Requirements for Minimum Design Loads in Buildings and Other Structures* (Ref. 2.2.41). This document refers to classic structural reliability theory. In this theory, each structure has a limit state (e.g., yield or ultimate), such that, loads and resistances are characterized by Equation 5:

$$g(x_1,x_2,\ldots x_i,\ldots x_n) = 0 \qquad \text{(Eq. 5)}$$

In Equation 5, g is termed the limit-state variable where failure is defined as $g < 0$ and the x_i are resistance (sometimes called capacity or fragility) variables or load (sometimes called stress or demand) variables. The probability of failure of a structure is given, in general, by Equation 6:

$$P_f = \int \ldots \int f_x(x_1, x_2, \ldots x_i \ldots x_n) dx_1 dx_2 \ldots dx_n \qquad \text{(Eq. 6)}$$

Where f_x is the joint probability density function (PDF) of x_i and the integral is over the region in which $g < 0$. The fact that these variables are represented by probability distributions implies that absolutely precise values are not known. In other words, the variable values are uncertain. This concept is illustrated in Figure 4.3-8. Codes and standards such as *Minimum Design Loads for Buildings and Other Structures* (Ref. 2.2.5) guide the process of designing structures such that there is a factor of safety between the load and capacity. The factor of safety is established in recognition that quantities, methods used to evaluate them, and tests used to ascertain material strength give rise to uncertainty. A heuristic measure of the factor of safety is the distance between the mean values of the two curves.



Source: Original

Figure 4.3-8. Concept of Uncertainty in Load and Resistance

In the case in which Equations 5 and 6 are approximated by one variable representing capacity and the other representing load, each of which is a function of the same independent variable y, the more familiar load-capacity interference integral results as shown in Equation 7.

$$P_f = \int F(y)h(y)dy \qquad \text{(Eq. 7)}$$

P_f is the mean probability of failure and is appropriate for use when comparing to a probability criterion such as one in a million. In Equation 7, *F(y)* represents the cumulative density function of structural capacity and *h(y)* represents the PDF of the load. The former is sometimes called the fragility function and the later is sometimes called the hazard function.

To analyze the probability of breach of a dropped canister, y is typically in units of strain, *F* is typically a fragility function, which provides the conditional probability of breach given a strain, and *h* is the PDF of the strain that would emerge from the drop. For seismic risk analysis, *h* represents the seismic motion input, *y* is in units of peak ground acceleration, and *F* is the seismic fragility. The seismic analysis of the YMP structures is documented in a separate PCSA analysis. Degradation of shielding owing to impact loads uses a strain to failure criterion within the simplified approach of Equation 8, described below. For analysis of the conditional probability of breach owing to fires, *y* is temperature, *F* is developed from fire data for non-combustible structures, and *h* is developed using probabilistic heat transfer calculations.

If load and capacity are known, then Equations 6 and 7 provide a single valued result, which is the mean probability of failure. Each function in Figure 4.3-8 is characterized by a mean value, $\overline{L}$ (for load) and $\overline{C}$ (for capacity), and a measure of the uncertainty, generally the standard deviation, usually denoted by σ_L and σ_R for L and C, respectively. The spread of the functions may be expressed, alternatively, by the corresponding coefficient of variation (V) given by the ratio of standard deviation to mean, or $V_L = \sigma_L/\overline{L}$ and $V_R = \sigma_R/\overline{C}$ for load and capacity, respectively. The coefficient of variation may be thought of as a measure of dispersion expressed in terms of the number of means.

In the PCSA, the capacity curve for developing the fragility of casks and canisters against drops was constructed by a statistical fit to tensile elongation to failure tests (Ref. 2.2.32). The load curve may be constructed by varying drop height. A cumulative distribution function may be fit to a locus of points each of which is the product of drop height frequency and strain given drop height.

4.3.2.2.1 Impact Events Associated with Containment Breach

A simplification of Equation 7, consistent with *Staff Guidance HLWRS-ISG-02, Preclosure Safety Analysis – Level of Information and Reliability Estimation* (Ref. 2.2.70) and shown in Equation 8, is used in the PCSA. It is illustrated in Figure 4.3-9.

$$P_f = \int_0^h F(y)dy \qquad \text{(Eq. 8)}$$

In Equation 8, *h* is a single value conservative load.

The load is a single value estimated by performing a calculation for a condition more severe than the mean. For example, if the normal lift height of the bottom of a canister in a handling facility is 23 feet, a drop height of 32.5 feet is more severe and may be conservatively applied to all drop heights equal to or below this height. This can be conservatively applied to all drop heights equal to or below this height, such as for the maximum drop heights for railcars, truck trailers, or cask transfer trailers used during Intra-Site Operations. The conditional probability of breach is an increasing function of drop height. Strain resulting from drops is calculated by dynamic finite element analysis (FEA) using LS-DYNA for canisters and transportation cask drops (Ref. 2.2.32). Therefore, use of a higher than mean drop height for the load for all drop heights results in a conservative estimate of breach probability. As an additional conservatism, a lower limit of breach probability of 1E-05 was placed on drops of casks, canisters, and waste packages. To perform the analyses, representative canisters and casks were selected from the variety of available designs in current use which were relatively thin walled on the sides and bottom. This added another conservative element.

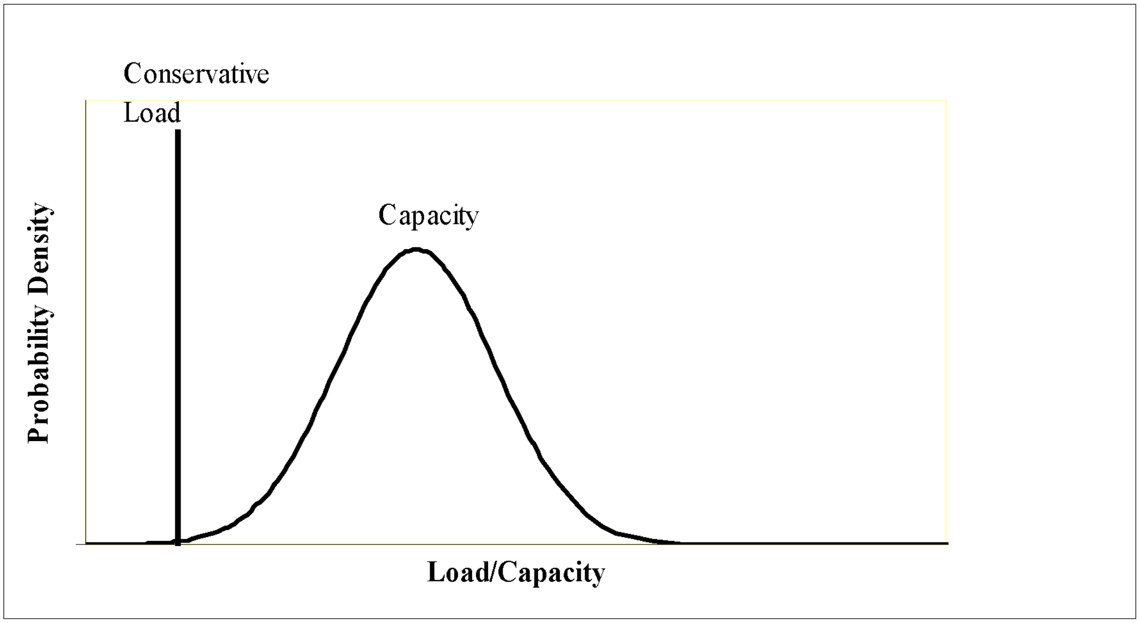


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Figure 4.3-9. Point Estimate Load Approximation Used in PCSA

The PCSA applies PEFAs to a wide variety of event sequences including those associated with:

- Canister drops
- Canister collisions with other objects and structures
- Other objects dropped on canisters
- Transportation cask drops and subsequent slapdowns (analyzed without impact limiters)
- Conveyance derailments and collisions when carrying transportation casks and canisters (conveyances would be trucks, railcars, cask transfer trailers, and site transporters)
- Other objects dropped on transportation casks
- Waste package drops
- Waste package collisions with other waste packages
- TEV collisions with structures or another TEV when carrying a waste package
- Objects dropped on waste packages
- Objects dropped on TEV.

Many of these, such as collisions, derailments, and objects dropped onto casks/canisters, involve far lower energy loads than drop events. For impact loads that are far less energetic than drops, the drop probability is ratioed by impact energy to estimate the less energetic situation.

4.3.2.2.2 Shielding Degradation Events

Impact loads (such as drops) may not be severe enough to breach a transportation cask, but might lead to degradation of shielding such that onsite personnel are exposed.

The shielding degradation analysis is based primarily on results of finite element modeling (FEM) performed for four generic transportation cask types for transportation accidents, as reported in *Reexamination of Spent Fuel Shipment Risk Estimates,* NUREG/CR-6672 (Ref. 2.2.82). The results of the FEM analysis were used to estimate threshold drop heights and thermal conditions at which LOS may occur in repository event sequences. The four cask types include one steel monolith rail cask, one steel/depleted uranium truck cask, one steel/lead/steel (SLS) truck cask, and one SLS rail cask. The study performed structural and thermal analyses for both failure of containment boundaries and LOS for accident scenarios involving rail and truck casks impacting unyielding targets at various impact speeds from 30 mph to greater than 120 mph. Impact orientations included side, corner, and end. The study also correlated the damage to impacts on real targets, including soil and concrete.

NUREG/CR-6672 (Ref. 2.2.82) addresses two modes of shielding degradation in accident scenarios: deformations of lid and closure geometry that permit direct streaming of radiation; and/or reductions in cask wall thickness or relocation of the depleted uranium or lead shielding. The shielding degradation due to lid/closure distortion can be accompanied by airborne releases if the inner shell of the cask is also breached.

The structural analyses do not credit the energy absorption capability of impact limiters. Therefore, the results are deemed applicable to conservatively approximate the structural response of transportation and similar casks in drop scenarios for Intra-Site Operations.

Principal insights reported in *Reexamination of Spent Fuel Shipment Risk Estimates.* NUREG/CR-6672 (Ref. 2.2.82) include the following:

- Monolithic steel rail casks do not exhibit any shielding degradation, but there may be some radiation streaming through gaps in closures in any of the impact scenarios.
- Steel/depleted uranium/steel truck cask exhibited no shielding degradation, explained by modeling that included no gaps between forged depleted uranium segments so that no displacement of depleted uranium could occur.
- The SLS rail and truck casks exhibit shielding degradation due to lead slumping. Lead slump occurs mostly on end-on impact, with a lesser amount in corner orientation. For side-on orientation, there is no significant reduction in shielding.

Therefore, this analysis focuses on SLS casks to estimate the drop or collision conditions that could result in shielding degradation from lead slumping. Since it is not possible to predict at this time the fraction of casks to be delivered during the preclosure period that will be of the steel-lead-steel type, all transportation casks are analyzed as described below.

The document *Shipping Container Response to Severe Highway and Railway Accident Conditions*, NUREG/CR-4829 (Ref. 2.2.45) defines three levels of cask response, characterized by the maximum effective plastic strain within the inner shell of a transportation cask. Of these, level S3 has strain levels between 2.0% and 30% which produces large distortions, seal leakage likely and lead slump likely. The minimum strain level associated with S3 was applied to the strain versus impact speed results from the FEM (Ref. 2.2.82) to establish a median threshold impact speed for the onset of shielding degradation. The threshold speeds are translated into equivalent drop heights, using calculated bottom corner drops for impact loads onto real concrete targets, not idealized rigid targets. Use of a conservative coefficient of variation, coupled with the median, allowed a lognormal fragility curve as a function of drop height (or equivalently impact speed), to be developed. Each event sequence may be characterized by a conservative impact speed. For example, the maximum speed of onsite vehicles involved in moving and handling waste forms is 2.5 mph by design (except for the site prime mover (SPM) which is limited to 9 mph), and a cask drop height of 15 feet is unlikely, by design, to be exceeded. Using Equation 8, the fragility curve was combined with the maximum, or a conservative estimate of, impact speed (or equivalent drop height).

4.3.2.2.3 Fire Events Associated with Possible Containment Breach

Fire initiated events are included in the PCSA, which probabilistically analyzes the full range of possible fires that can occur, as well as variations in the dynamics of the heat transfer and uncertainties in the failure temperature of the target. This analysis focuses on fires that might directly impact the integrity of cask, canister, and waste package containment. Equation 7 is used for this purpose. The fragility analysis includes the uncertainty in the temperature that containment will be breached, and the uncertainty in the thermal response of the canister to the fire. In calculating the thermal response of the canister, variations in the intensity and duration of the fire are considered along with conditions that control the rate of heat transfer to the container, e.g., convective heat transfer coefficients, view factors, emissivities, etc. In calculating the failure temperature of the canister, variations in the material properties of the canister are considered, along with, variations in the loads that lead to failure. The load or demand is associated with uncertainty in the fire severity.

Fire severity is characterized by the fire temperature and duration, since these factors control the amount of energy that the fire could transfer to a cask, canister, or waste package. (In this analysis, these are referred to as targets.) The duration of the fire is taken to be the amount of time a particular container is exposed to the fire, and not necessarily the amount of time a fire burns. Probability distributions of the fire temperature and fire duration are based on the unavailability of manual or automatic suppression, which leads to an assessment that significantly overstates the risk of fires.

4.3.2.2.4 Uncertainty in Fire Severity

An uncertainty distribution for the fire duration is developed by considering test data and analytical results reported in several different sources; some specific to the YMP facilities and some providing more generic information. In general, the fire durations are found to depend upon the amount, type, and configuration of the available combustible material.

Based on a review of the available information, it is determined that two separate uncertainty distributions would be needed: one for conditions without automatic suppression and one for conditions with automatic suppression. The derivation of these two distributions is discussed below.

Uncertainty in fire duration was developed from:

- *Utilisation of Statistics to Assess Fire Risks in Buildings* (Ref. 2.2.84)
- *Heat and Mass Release for Some Transient Fuel Source Fires: A Test Report.* NUREG/CR-4680 (Ref. 2.2.61)
- *Quantitative Data on the Fire Behavior of Combustible Material in Nuclear Power Plants: A Literature Review.* NUREG/CR-4679 (Ref. 2.2.62).

The derivation of the distribution of fire duration is described in Attachment D, Sections D2.1.1.2 and D2.1.1.3.

The fire temperature used in this calculation is the effective blackbody temperature of the fire. This temperature implicitly accounts for the effective emissivity of the fire, which for large fires approaches a value of 1.0 (Ref. 2.2.77, p. 2-56). Fires inside a YMP facility may involve both combustible solid and liquid materials. A probability distribution for the fire temperature was derived by combining fire severity information for compartment fires discussed in *SFPE Handbook of Fire Protection Engineering* (Ref. 2.2.77, Section 2, Chapter 2) with information about liquid hydrocarbon pool fires. The derivation of this distribution is described in Attachment D, Section D2.1.2. The fire temperature distribution is normally distributed with a mean of 1,072 K (799°C) and a standard deviation of 172 K. The mean of this distribution is approximately equal to the transportation cask design basis fire temperature of 800°C specified in 10 CFR 71.73 (Ref. 2.3.3).

Fire temperature and duration are negatively correlated. Intense fires with high fire temperatures tend to be short-lived because the high temperature results from very rapid burning of the combustible material. In determining the joint probability distribution of fire duration and temperature, a negative correlation coefficient of -0.5 was used (Attachment D, Section D2.1.3).

The thermal response of the canister is calculated using simplified radiative, convective, and conductive heat transfer models, which have been calibrated to more precise models. The simplified models are found to accurately match predictions for heating of the canister in either a cask or waste package. The heat transfer models are simplified in order to allow a probabilistic analysis to be performed using Monte Carlo sampling. The models consider radiative and convective heat transfer from the fire to the canister, cask, waste package, or shield bell. This analysis conservatively models the fire completely engulfing the container.

When calculating the heat load on the target for a fully engulfing fire, radiation is the dominant mode of heat transfer between the fire and the target. The magnitude of the radiant heating of the container depends on the fire temperature, the emissivity of the container, the view factor between the fire and the container, also the duration of the fire.

The total radiant energy deposited in the container can be roughly estimated using Equation 9:

$$Q_{rad} = \varepsilon F_{cf} \sigma (T_{fire})^4 At \qquad \text{(Eq. 9)}$$

where

Q_{rad}	=	incident radiant energy over the fire duration (J)
ε	=	emissivity of the container
F_{cf}	=	container-to-fire view factor
σ	=	Stefan-Boltzmann constant ($W/m^2\ K^4$)
T_{fire}	=	equivalent blackbody fire temperature (K)
A	=	container surface area (m^2)
t	=	duration of the fire (s).

The following variables in this equation are treated as uncertain: fire temperature, view factor, and fire duration. In the case of a canister inside a waste package, cask, or shield bell, a more complicated set of equations is used to simulate outer shell heat up and subsequent heat transfer to layers of containment or shielding and then to the canister itself. The model also includes heating of the canister by decay heat from the SNF or HLW.

To estimate the uncertainty associated with target fragility, two failure modes were considered:

1. *Creep-Induced Failure*. Creep is the plastic deformation that takes place when a material is held at high temperature for an extended period under tensile load. This mode of failure is possible for long duration fires.

2. *Limit Load Failure*. This failure mode occurs when the load exerted on a material exceeds its structural strength. As the temperature of the canister increases, its strength decreases. Failure is generally predicted at some fraction (usually around 70%) of the ultimate strength.

Failure is considered to occur when either of the failure thresholds is exceeded.

Equation 7, along with the heat transfer equations, are solved using Monte Carlo simulation (described in Section 4.3.6) with the above described fragility and target fire severity probability distributions, and distributions for the uncertain heat transfer factors. For each Monte Carlo trial, the calculated maximum canister temperature is compared to the sampled target failure temperature. If the maximum temperature of the target exceeds the sampled failure temperature, then target failure is counted. The failure probability in this method is equal to the fraction of the samples for which failure is calculated.

Uncertainty in the calculated canister failure probability is given by a calculated mean and standard deviation, where the mean is simply the number of failures divided by the total number of samples and the standard deviation is given by Equation 10 for the standard deviation of a binomial distribution:

$$\sigma = \sqrt{\frac{\frac{n_{fail}}{N}\left(\frac{N - n_{fail}}{N}\right)}{N}} \qquad \text{(Eq. 10)}$$

where n_{fail} is the number of trials in which failure occurs and N is the total number of Monte Carlo trials.

4.3.2.2.5 Fire Event Associated with Shielding Degradation

The thermal analyses in NUREG/CR-6672 (Ref. 2.2.82) indicates that the probability of shielding degradation in a fire scenario should be based on the probability of having a fire equivalent to a 1,000°C engulfing fire lasting more than a half-hour. However, shielding degradation does not occur unless there is a coincident puncture or breach in the cask that allows a pathway for melted lead to flow out of its usual configuration. These threshold conditions apply to all cask types and would result in radiation streaming from the cask.

The transportation cask is present within the YMP facilities in only three areas: vestibules, preparation rooms, and unloading rooms. Transportation casks are also present outside of buildings within the GROA. The fire ignition frequencies of these areas are summed up in Section 6.5 and Attachment F, Section F4.3. Furthermore, the method described above for obtaining the probability distribution of fire severity from input distributions of fire temperature and fire duration, resulted in an estimate of the conditional probability of the threshold fire given a fire ignition. The joint frequency of having a fire in these areas that is at or above the threshold was obtained and found to be very small (described in Attachment D). This is a conservative calculation because it did not include the conditional probability that a puncture or failure through the wall to the lead shielding must also occur for shielding degradation.

4.3.2.2.6 Other Thermal Events Associated with Possible Breach

The PCSA focuses on the potential of cask, canister, and waste package breach associated with fires. As described above, the fires of most interest were those that surround the target containment. However, one heat-up associated with loss of building cooling is also considered. Such events are not relevant to the Intra-Site Operations analysis, but discussion is included here to show continuity of the methods used.

The analysis of loss of building cooling on containment integrity takes a conservative, analytical approach. A bounding set of conditions and configurations are postulated, and then using the ANSYS code (Ref. 2.2.12), the maximum steady state temperature is compared to the temperature at which the component would be expected to fail. In no case is a containment barrier found to be near its failure threshold from loss of building cooling.

4.3.2.2.7 Fires that Occur Outside of Building Structures (Intra-Site Operations Only)

Fires associated waste forms for Intra-Site Operations occur outside of the main process buildings. With regard to the frequency of such fires, based on historical fire ignition frequencies from other facilities, the fire frequency across the site is proportional to the number of main process buildings on the site. That is, the number of opportunities for fires outside buildings is affected by the number of main process buildings being serviced. There are six main process buildings in the GROA: Initial Handling Facility (IHF), Receipt Facility (RF), WHF, and three CRCFs).

The frequency of outside fires at the YMP is expected to be similar to those from other industrial facilities. The specific type of facility, the type of construction of the buildings, and other features are not considered relevant to the frequency of outside fires because the ignition sources that exist outside of the buildings are considered to be generic to any industrial facility. The assessment of fire severity is performed as already described. Fire severity is addressed in Attachment D, Section D2.1.

Outside fire initiating events are considered for the potential to directly affect one or more waste forms, causing a breach or shield degradation that would result in a release. The fire analysis, therefore, focuses on this potential. The steps of this process include identifying areas onsite where waste forms can be present, correlating these areas with historical industry-wide databases, and defining the initiating events.

In order to assess the total fire frequency, two pieces of information are required from the industry-wide databases: the number of facilities and the number of fires at these facilities. The assessment of this data yields the fire frequencies for outside areas, which is then used as input to the fire initiating event frequency analysis.

The frequency is expressed in terms of facility-year. Therefore, the overall frequency of outside fires for the GROA will be the frequency per facility-year times the number of main process buildings (six): IHF, WHF, RF, and three CRCFs.

A suitable uncertainty distribution is applied to the results of the initiating event frequency analysis to represent the significant uncertainty that results from the application of this methodology.

4.3.3 Utilization of Industry-Wide Reliability Data

4.3.3.1 Use of Population Variability Data

The quantification of event sequence probabilities via event tree and fault tree modeling requires information on the reliability of active equipment and components, as usually represented in fault tree basic events. The PCSA attempts to anticipate event sequences before they happen, which means that associated equipment reliabilities are uncertain.

As presented in NUREG-0492 (Ref. 2.2.87), the typical model of failure probability for a component is depicted as a “bathtub curve” illustrated in Figure 4.3-10. The curve is divided into three distinct phases. Phase I represents the component failure probability during the “burn-