BSC

Design Calculation or Analysis Cover Sheet

Complete only applicable items.

1. QA: QA
2. Page 1

3. System	4. Document Identifier
Wet Handling Facility	050-PSA-WH00-00200-000-00B

5. Title
Wet Handling Facility Reliability and Event Sequence Categorization Analysis

6. Group
Preclosure Safety Analyses

7. Document Status Designation
☐ Preliminary ☒ Committed ☐ Confirmed ☐ Cancelled/Superseded

8. Notes/Comments

This revision addresses the following condition reports (CRs): 11966, 11982, 11989, 12002, 12024, 12025, 12103, 12105, 12167, 12176, 12185, 12188, 12226, 12227, 12228, 12229, 12245, 12250, and 12310, It also incorporates calculation/analysis change notice (CACN) 050-PSA-WH00-00200-000-00A-CACN001. The table on page 3 provides detailed descriptions and page or section numbers of changes between Revision 00A and Revision 00B. In addition, editorial changes (including updating headers and footers) have been made throughout and affect every page.

Attachments		Total Number of Pages
Attachment A.	Event Trees	232
Attachment B.	System/Pivotal Event Analysis – Fault Trees	~~562~~ 561 DB 1/7/09
Attachment C.	Active Component Reliability Data Analysis	58
Attachment D.	Passive Equipment Failure Analysis	96
Attachment E.	Human Reliability Analysis	300
Attachment F.	Fire Analysis	178
Attachment G.	Event Sequence Quantification Summary Tables	116
Attachment H.	SAPHIRE Model and Supporting Files	4 + CD

RECORD OF REVISIONS

9. No.	10. Reason For Revision	11. Total # of Pgs.	12. Last Pg. #	13. Originator (Print/Sign/Date)	14. Checker (Print/Sign/Date)	15. EGS (Print/Sign/Date)	16. Approved/Accepted (Print/Sign/Date)
00A	Initial Issue	1,375	H-2	Howard Lambert/See Page 2	See Page 3	Michael Frank	Mark Wisenburg
00B	The purpose of this revision is to respond to the condition reports calculation/analysis change notices noted in Box 8.	~~1830~~ 1829 DB 1/7/09	H-4	David Bradley [signature] 11/25/08	Norman Graves for Daniel Christman [signature] for Dan Christman 11/25/08	Sen-Sung Tsai for Michael Frank [signature] for M. Frank 11/26/08	Michael Frank [signature] 1/9/09

NOTICE OF OPEN CHANGE DOCUMENTS - THIS DOCUMENT IS IMPACTED BY THE LISTED CHANGE DOCUMENTS AND CANNOT BE USED WITHOUT THEM.

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1) CACN-001, DATED 03/23/2009

DISCLAIMER

The analysis contained in this document was developed by Bechtel SAIC Company, LLC (BSC) and is intended solely for the use of BSC in its work for the Yucca Mountain Project.

Summary of Changes between Revision 00A and Revision 00B		
CR/CACN Action	**Location of Change**	**Description of Change**
CR 11966-004	Section C1.3, Table C4-1, pages C-24 and C-25	More reliable data for the jib crane drop rate was gathered, resulting in a new drop rate figure of 6.41E-5 that was incorporated in the text (Section C1.3, Paragraph 8 and Table C4-1, entry CRJ-DRP). A new paragraph was inserted in Section C1.3, Paragraph 7 to reflect the issue addressed in the CR.
CR 11982-001, -002, -004	Table 6.9-1, Section 6.2.2.7.4, Section B7.4.1.6, Figures B7.4-1 and B7.4-2, Table B7-4.3, Section 6.0.3 Table 6.0-2	-001 -- "EP-WHF-COOL-1 and EP-WHF-COOL-2" was added to the "Source" column for item 79 (not item 81) in Table 6.9-1, which had no entry. In Section 6.2.2.7.4, correction was made to the 1st and 2nd bullet, Attachment B, Section B7.4.1.6 - Figure B7.4-1 and Figure B7.4-2, pp. B7-17, B7-18, Section B7.4.1.7. Table B7-4.3, p B7-20, was modified to provide the correct result (3.6E-2) from the HVAC 720 hour mission time fault tree quantification. The 3rd and 4th bullet in Section 6.2.2.7.4 was modified to provide the correct result (1E-3) from the HVAC 24 hour mission time fault tree quantification. Figure B7.4-1A contains the results for the same fault trees using a 24-hour mission time Attachment B, Section B7.4.1.6, was modified to include a discussion on the quantification of the HVAC-PREP fault tree (24 hour mission time) result. "050-JIBCRANE-JIB-DRP" was changed in the "Source" column for items 73 and 74 (not items 75 and 76) in Table 6.9-1 to "050-JIBCRANE-CRN-DRP." -002 -- A discussion on the screening of the "drop of cask in pool leading to pool structural damage" initiating event was added in Section 6.0.8 of the calculation. -004 -- Changes to Table 6.0-2 as follows: the Initiating Event Description Column entry of the row of the table on page 107 that read "Explosion of site prime mover fuel tank" was changed to read "Fuel tank explosion involving site transporter, cask tractor, cask transfer trailer, or site prime mover." The Screening Basis Column entry of this row of the table was changed to read "Fuel tank design for equipment used to move casks or aging overpacks containing high-level waste shall include a requirement for the tank construction to use a low-temperature melt material. The low-temperature melt material precludes tank explosion as an initiating event; therefore, fuel tank explosions for these movers are not analyzed further for categorization." Added a row to the end of the table after the revisions described above for events involving punctures of casks and canisters by the cask transfer trailer.
CR 11989-004	Section 1, page 17	The pertinent portion of the text identified in this CR was changed from "are not addressed in this analysis" to "were considered in a separate safeguards and security analysis performed by others." Revised text dealing with intentional malevolent acts.
CR 12002-004	Table 6.3-1 (2 occurrences), Section C1.3, Table C4-1	CR stated that data for drop rate was based on 110 very heavy load lifts when in fact there were 109 very heavy load lifts involving single-failure proof cranes at nuclear power plants. Changing the denominator of the drop rate caused a slight increase. Incorporated the latest drop rate data for the cask handling crane, 3.16E-5 drops per lift.
CR 12024-005	Sections B8.4.1.4 and B8.4.2.4	According to the CR, text shall be added in the electrical portion of the fault tree documentation to explain the exclusion of bus ducts, cable trays, etc, from the fault trees. Revised rationale for exclusion of ducts, etc., from fault tree in sections B8.4.1.4 (Load Center Train A) and B8.4.2.4. (Load Center Train B).
CR 12025-003	Sections B7.2, B7.3, B7.4	Major revisions to HVAC model and related discussion based on comments in the CR. Extensive revision to ensure consistency with design information.

Summary of Changes between Revision 00A and Revision 00B		
CR/CACN Action	**Location of Change**	**Description of Change**
CR 12103-008	Table 6.3-1, various tables and figures of Attachment B (see list in next column), and selected basic events in the SAPHIRE model	Resolved inconsistencies found between Table 6.3-1, Attachment B, and the SAPHIRE model. The following tables and figures in Attachment B are affected: Tables: B2.4-2, B2.4-5, B3.4-5, B4.4-1, B4.4-4, B4.4-5, B4.4-6, B4.4-8, B4.4-13, B5.4-4, B6.4-3, B6.4-5, B6.4-9, B7.4-1, B8.4-1, B8.4-3, B8.4-5, B8.4-8, B9.4-1. Figures: B2.4-1, B2.4-2, B2.4-3, B2.4-8, B3.4-7 thru B3.4-9, B4.4-1, B4.4-2, B4.4-15, B4.4-17, B4.4-18, B4.4-20 thru B4.4-23, B4.4-26, B4.4-49, B4.4-50, B6.4-9.
CR 12105-004	Tables	"N/A" or "–" was inserted in each table to indicate that information was not applicable. There are no blanks in tables.
CR 12185-001	Attachments E, pp. E-60 thru E-68 and Table E6.2-1	Text has been modified to ensure consistent reference to the 20-ton auxiliary hook on the 200-ton crane. In Attachment E, the term 'cask handling crane' was changed to '20-ton auxiliary crane.'
CR 12167-001	Table G-4, p.G-219 event name ESD22-FUEL-SEQ2P-GRRC	Change to correct typo in event sequence name, and transcription errors in the Mean, Median, Std Dev, and Event Sequence Cat.
CR 12176-001	Section 6.9.1	Added text to the end of the section to clarify the meaning of and improve the traceability of the entries in the seventh column of the table.
CR 12188-001	Section 6.2.2.10.2, Table 6.3-9, Figure B10.5-1	In Section 6.2.2.10.2, rounded 9.4E-05 to 9E-05. In Table 6.3-9, changed cross references for the following basic event: 50-OIL-MODERATOR. Updated Figure B10.5-1.
CR 12226-001	Section B1.4.4.3	Revised description of precautions during movement of SPMTT in the Entrance Vestibule and Cask Preparation Room.
CR 12227-001	Section A4.3.1	Revised description of site transporter rollover event.
CR 12228-001	Sections A4.5.1 and A4.6.1	Added references to basic event table provided in these two sections.
CR 12229-001, -003	Throughout Section in A4, A4.1, .2, .3, .4, .5, .6, .7, .8, .9, .10, .11, .12, .13, .14, .17, .31	Clarified text describing initiating events and link to fault trees.
CR 12245-004	SAPHIRE model, Section 4.3.3.3, Table 6.3-1, Section 6.3.1.3, figures and tables in Attachment B, Sections B2, B3, B4, B6, B7, B8 and B9, Section C3	Revised the descriptions of the treatment of common-cause failures in Section 4.3.3.3 and Section C3. For each common-cause failure basic event, used the embedded SAPHIRE function enabling CCF probability distribution evaluation, resulting in minor changes to CCF basic event values. Revised values associated with common-cause failure events in Table 6.3-1 and throughout Attachment B.
CR 12250-001	Table 6.9-2	Corrected text to "90 atom% B10."
CR 12310-004	Table 6.8-3, Tables G-1 through G-4	Updated results tables to reflect changes to the SAPHIRE model made as a result of other CRs. Ensure that new results are generated and saved after all inputs to the WHF model have been updated, such as in response to other Condition Reports. Ensure that the results documented in Section 6, Table 6.3-8, and in Attachment G, Table G-1 through G-4, reflect the final results in SAPHIRE consistent with all inputs.
Incorporated 050-PSA-WH00-00200-000-00A-CACN001	Table 6.9-1, Items 11 and 79	Corrected two representative event sequence numbers. Item 11 changed WHF-ESD03-TAD to WHF-ESD03-AODPC item 79 changed WHF-ESD13-TAD to WHF-ESD16-CSNF

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FIGURES

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TABLES

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TABLES (Continued)

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ACRONYMS AND ABBREVIATIONS

Acronyms

ATHEANA	a technique for human event analysis
BSC	Bechtel SAIC Company, LLC
CCF	common-cause failure
CREAM	Cognitive Reliability and Error Analysis Method
CRCF	Canister Receipt and Closure Facility
CTM	canister transfer machine
CTT	cask transfer trolley
CSNF	commercial spent nuclear fuel
DOE	U.S. Department of Energy
DPC	dual-purpose canister
EDGF	Emergency Diesel Generator Facility
EFC	error forcing context
ESD	event sequence diagram
FTA	fault tree analysis
GROA	geologic repository operations area
HAZOP	hazard and operability
HCTT	horizontal cask tractor and trailer
HEART	Human Error Assessment and Reduction Technique
HEP	human error probabilities
HEPA	high-efficiency particulate air
HFE	human failure event
HLW	high-level radioactive waste
HRA	human reliability analysis
HVAC	heating, ventilation, and air conditioning
IET	initiator event tree
IHF	Initial Handling Facility
ITC	important to criticality
ITS	important to safety
LLNL	Lawrence Livermore National Laboratory
LOSP	loss of offsite power
MCC	motor control centers
MCO	multicanister overpack
MLD	master logic diagram

ACRONYMS AND ABBREVIATIONS (Continued)

NARA	Nuclear Action Reliability Assessment
NRC	U.S. Nuclear Regulatory Commission
PCSA	preclosure safety analysis
PEFA	passive equipment failure analysis
PFD	process flow diagram
PLC	programmable logic controller
PRA	probabilistic risk assessment
PSC	procedural safety controls
PSF	performance shaping factors
RF	Receipt Facility
SFTM	spent fuel transfer machine
SLS	steel/lead/steel
SNF	spent nuclear fuel
SPM	site prime mover
SPMRC	site prime mover railcars
SPMTT	site prime mover truck trailers
SRET	system response event tree
SSC	structure, system, or component
SSCs	structures, systems, and components
STC	shielded transfer cask
TAD	transportation, aging, and disposal
TEV	transport and emplacement vehicle
THERP	Technique for Human Error Rate Prediction
TYP-FM	type and failure mode
WHF	Wet Handling Facility
WPTT	waste package transfer trolley
YMP	Yucca Mountain Project

ACRONYMS AND ABBREVIATIONS (Continued)

Abbreviations

AC	alternating current
B	Boron
°C	degrees Celsius
DC	direct current
°F	degrees Fahrenheit
ft	foot, feet
ft/min	foot, feet/minute
ft/sec	foot, feet/second
g	gram
gpm	gallons per minute
Hg	mercury
hp	horsepower
hr, hrs	hour, hours
in.	inch
J	joule
K	degrees Kelvin
kV	kilovolt
L	liter
lb	pound
m	meter
mg	milligram
min	minute, minutes
mm	millimeter
MPa	megapascal
mph	miles per hour
sec	second
Torr	a unit of pressure equal to 1.316 × 10-3 atmospheres
V	volt
W	watt

ACRONYMS AND ABBREVIATIONS (Continued)

yr, yrs	year, years

1. PURPOSE

This document on the Wet Handling Facility (WHF) and its companion document entitled *Wet Handling Facility Reliability and Event Sequence Development Analysis* (Ref. 2.2.37) constitute a portion of the preclosure safety analysis (PCSA) that is described in its entirety in the safety analysis report that will be submitted to the U.S. Nuclear Regulatory Commission (NRC) as part of the Yucca Mountain Project (YMP) license application. These documents are part of a collection of analysis reports that encompass all waste handling activities and facilities of the geologic repository operations area (GROA) from the beginning of operations to the end of the preclosure period. The *Wet Handling Facility Event Sequence Development Analysis* (Ref. 2.2.37) describes the identification of initiating events and the development of potential event sequences that emanate from them. This analysis uses the resulting event sequences to perform a quantitative analysis of the event sequences for the purpose of categorization per the definition provided by 10 CFR 63.2 (Ref. 2.3.2).

The PCSA uses probabilistic risk assessment (PRA) technology derived from both nuclear power plant and aerospace methods and applications in order to perform analyses to comply with the risk informed aspects of 10 CFR 63.111 and 63.112 (Ref. 2.3.2) and to be responsive to the acceptance criteria articulated in the *Yucca Mountain Review Plan, Final Report* (Ref. 2.2.71). The PCSA, however, limits the use of PRA technology to identification and development of event sequences that might lead to direct exposure of workers or onsite members of the public; radiological releases that may affect the workers or public (onsite and offsite) and criticality.

The radiological consequence assessment relies on bounding inputs with deterministic methods to obtain bounding dose estimates. These were developed using broad categories of scenarios that might cause a radiological release or direct exposure to workers and the public, both onsite and offsite. These broad categories of scenarios were characterized by conservative meteorology and dispersion parameters, conservative estimates of material at risk, conservative source terms, conservative leak path factors, and filtration of releases via facility high-efficiency particulate air (HEPA) filters when applicable. After completion of the event sequence development and categorization in this analysis, each Category 1 and Category 2 event sequence was conservatively matched with one of the categories of dose estimates. The event sequence analyses also serve as input to the PCSA criticality analyses by identifying the event sequences and end states where conditions leading to criticality are in Category 1 or 2.

An event sequence is defined in 10 CFR 63.2 (Ref. 2.3.2) as:

> A series of actions and/or occurrences within the natural and engineered components of a geologic repository operations area that could potentially lead to exposure of individuals to radiation. An event sequence includes one or more initiating events and associated combinations of repository system component failures, including those produced by the action or inaction of operating personnel. Those event sequences that are expected to occur one or more times before permanent closure of the geologic repository operations area are referred to as Category 1 event sequences. Other event sequences that have at least one chance in 10,000 of occurring before permanent closure are referred to as Category 2 event sequences.

As an extrapolation of the definition of 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. Consequence analyses are not required for those event sequences.

10 CFR 63.112, Paragraph (e) and Subparagraph (e)(6) (Ref. 2.3.2) require analyses to identify the controls that are relied upon to limit or prevent potential event sequences or mitigate their consequences. Subparagraph (e)(6) specifically notes that the analyses should include consideration of "means to prevent and control criticality." The PCSA criticality analyses employ specialized deterministic methods that are beyond the scope of the present analysis. However, the event sequence analyses serve as input for the PCSA criticality analyses by identifying the event sequences and end states where conditions leading to criticality are in Category 1 or 2. Some event sequence end states include the phrase "important to criticality." This indicates that the event sequence has a potential for reactivity increase that should be analyzed to determine if reactivity can exceed the upper subcriticality limit.

In order to determine the criticality potential for each waste form, associated facility, and handling operations, criticality sensitivity calculations are performed. These calculations evaluate the impact on system reactivity to variations in each of the parameters important to criticality during the preclosure period. The parameters are waste form characteristics, reflections, interactions, neutron absorbers (fixed and soluble), geometry, and moderation. The criticality sensitivity calculations determine the sensitivity of the effective neutron multiplication factor (k_{eff}) to variations in any of these parameters as a function of the other parameters. The PCSA criticality analyses determined the parameters that this event sequence analysis includes. The presence of a moderator in association with a path to exposed fuel was required to be explicitly modeled in the event sequence analysis because such events could not be deterministically found to be incapable of exceeding the upper subcriticality limit. Other situations treated in the event sequence analysis for similar reasons are multiple U.S. Department of Energy (DOE) spent nuclear fuel (SNF) canisters in the Canister Receipt and Closure Facility (CRCF) in the same general location and the presence of sufficient soluble boron in the pool in the WHF.

The initiating events considered in the PCSA define what could occur within the GROA, and are limited to those events that constitute a hazard to a waste form while it is present in the GROA. Initiating events include internal events occurring during waste handling operations conducted within the GROA and external events (e.g., seismic, wind energy, or flood water events) that impose a potential hazard to a waste form, waste handling systems, or personnel within the GROA. Such initiating events are included when developing event sequences for the PCSA. However, initiating events that are associated with conditions introduced in structures, systems, and components (SSCs) before they reach the site are not within the scope of the PCSA. The offsite conditions that are excluded from consideration include: drops of casks, canisters, or fuel assemblies during loading at a reactor site; improper drying, closing, or inerting at the reactor site; rail or road accidents during transport; tornado or missile strikes on a transportation cask; or nonconformances during cask or canister manufacture that result in a reduction of containment strength. Such potential precursors are subject to deterministic regulations such as 10 CFR Part 50 (Ref. 2.3.1), 10 CFR Part 71 (Ref. 2.3.3), 10 CFR Part 72 (Ref. 2.3.4), and associated quality assurance (QA) programs. As a result of compliance to such regulations, the SSCs are deemed to pose no undue risk to health and safety. Although the analyses do not address quantitative probabilities to the aforementioned excluded precursors, it is clear that the use of conservative design criteria and the implementation of QA controls result in unlikely exposures to radiation.

Other boundary conditions used in the PCSA include:

- Plant operational state — The initial state of the facility is normal with each system operating within its vendor-prescribed operating conditions.

- No other simultaneous initiating events — It is standard practice to not consider the occurrence of other initiating events (human-induced or naturally occurring) during the time span of an event sequence because: (a) the probability of two simultaneous initiating events within the time window is small and, (b) each initiating event will cause operations of the waste handling facility to be terminated, which further reduces the conditional probability of the occurrence of a second initiating event, given that the first has occurred.

- Component failure mode — The failure mode of a structure, system, or component (SSC) corresponds to that required to make the initiating or pivotal event occur.

- Fundamental to the basis for the use of industry-wide reliability parameters within the PCSA, such as failure rates, is the use of SSCs within the GROA that conform to NRC accepted consensus codes and standards, and other regulatory guidance.

- Intentional malevolent acts, such as sabotage and other security threats, were considered in a separate safeguards and security analysis performed by others.

As stated, the scope of the preclosure safety analysis is limited to internal initiating events originating within the GROA boundary and external initiating events that have their origin outside the GROA boundary, but can affect buildings and/or equipment within the GROA. External event analyses are documented in *External Events Hazards Screening Analysis* (Ref. 2.2.29) and *Frequency Analysis of Aircraft Hazards for License Application* (Ref. 2.2.18). Internal event identification (using a master logic diagram (MLD) and a hazard and operability (HAZOP) evaluation), event sequence development and grouping, and related facility details are provided in the *Wet Handling Facility Event Sequence Development Analysis* (Ref. 2.2.37), which also documents the methodology and process employed and initiates the analysis that is completed here.

This document uses event trees from the *Wet Handling Facility Event Sequence Development Analysis* (Ref. 2.2.37) to quantify the event sequences for each waste form. Quantification refers to the process of obtaining the mean frequency of each event sequence for the purpose of categorization. This document shows the categorization of each event sequence based on:

- Mean frequency associated with the event sequence frequency distribution

- Uncertainty associated with the event sequence frequency distribution

- Material at risk for each Category 1 and 2 event sequence for purposes of dose calculations

- Important to safety (ITS) SSCs

- Compliance with the nuclear safety design bases

- Procedural safety controls required for operations.

Other PCSA documents which are not referenced here cover the reliability and categorization of external events and summarize procedural safety controls and nuclear safety design bases. The main documents that will emanate from Volume I (Ref. 2.2.37) and the current analyses are:

- *ITS SSC/Non-ITS SSC Interactions Analysi*s (Ref. 2.4.1)
- *Preclosure Nuclear Safety Design Bases* (Ref. 2.4.2)
- *Preclosure Procedural Safety Controls* (Ref. 2.4.3)
- *Seismic Event Sequence Quantification and Categorization* (Ref. 2.4.4).

2. REFERENCES

2.1 PROCEDURES/DIRECTIVES

2.1.1 EG-PRO-3DP-G04B-00037, Rev. 14. *Calculations and Analyses*. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20081114.0008.

2.1.2 EG-PRO-3DP-G04B-00046, Rev. 13. *Engineering Drawings*. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG. 20081114.0009.

2.1.3 IT-PRO-0011, REV 10. *Software Management*. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20080923.0003.

2.1.4 LS-PRO-0201, REV 7. *Preclosure Safety Analysis Process*. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20081119.0007.

2.2 DESIGN INPUTS

The PCSA is based on a snapshot of the design. The reference design documents are appropriately documented as design inputs in this section. Since the safety analysis is based on a snapshot of the design, referencing subsequent revisions to the design documents (as described in EG-PRO-3DP-G04B-00037, *Calculations and Analyses* (Ref. 2.1.1, Section 3.2.2.F)) that implement PCSA requirements flowing from the safety analysis would not be appropriate for the purpose of this document. There are no superseded or cancelled documents associated with the modifications that led to the issuance of this revision. Cancelled or superseded documents associated with the portions of this document for which the snapshot has not yet been updated are designated herein with a dagger (†).

Design Inputs are listed in this section and the Attachment sections listed in Section 2.5.

The inputs in this Section noted with an asterisk (*) indicate that they fall into one of the designated categories described in Section 4.1, relative to suitability for intended use.

2.2.1 *Ahrens, M. 2000. *Fires in or at Industrial Chemical, Hazardous Chemical and Plastic Manufacturing Facilities, 1988-1997 Unallocated Annual Averages and Narratives*. Quincy, Massachusetts: National Fire Protection Association. TIC: 259997.

2.2.2 *Ahrens, M. 2007. *Structure Fires in Radioactive Material Working Facilities and Nuclear Energy Plants of Non-Combustible Construction*. Quincy, Massachusetts: National Fire Protection Association. TIC: 259983.

2.2.3 *A.M. Birk Engineering 2005. *Tank-Car Thermal Protection Defect Assessment: Updated Thermal Modelling with Results of Fire-Testing: Summary Report*. TP 14367E. Ontario, Canada: Transportation Development Centre of Transport Canada. ACC: MOL.20071113.0095.

2.2.4 *ANSI/ANS-58.23-2007. *Fire PRA Methodology*. La Grange Park, Illinois: American Nuclear Society. TIC: 259894.

2.2.5 *Apostolakis, G. and Kaplan, S. 1981. "Pitfalls in Risk Calculations."*Reliability Engineering, 2,* 135-145. Barking, England: Applied Science Publishers. TIC: 253648.

2.2.6 ASCE/SEI 7-05. 2006. *Minimum Design Loads for Buildings and Other Structures*. Including Supplement No. 1. Reston, Virginia: American Society of Civil Engineers. TIC: 258057. ISBN: 0-7844-0809-2.

2.2.7 ASME RA-S-2002. *Standard for Probabilistic Risk Assessment for Nuclear Power Plant Applications.* New York, New York: American Society of Mechanical Engineers. TIC: 255508. ISBN: 0-7918-2745-3.

2.2.8 ASME (American Society of Mechanical Engineers) 2004. *2004 ASME Boiler and Pressure Vessel Code.* 2004 Edition. New York, New York: American Society of Mechanical Engineers. TIC: 256479. ISBN: 0-7918-2899-9.

2.2.9 ASME NOG-1-2004. 2005. *Rules for Construction of Overhead and Gantry Cranes (Top Running Bridge, Multiple Girder).* New York, New York: American Society of Mechanical Engineers. TIC: 257672. ISBN: 0-7918-2939-1.

2.2.10 *Atwood, C.L.; LaChance, J.L.; Martz, H.F.; Anderson, D.J.; Englehardt, M.; Whitehead, D.; and Wheeler, T. 2003. *Handbook of Parameter Estimation for Probabilistic Risk Assessment*. NUREG/CR-6823. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20060126.0121.

2.2.11 *Benhardt, H.C.; Eide, S.A.; Held, J.E.; Olsen, L.M.; and Vail, R.E. 1994. *Savannah River Site Human Error Data Base Development for Nonreactor Nuclear Facilities (U).* WSRC-TR-93-581. Aiken, South Carolina: Westinghouse Savannah River Company, Savannah River Site. ACC: MOL.20061201.0160.

2.2.12 *Brereton, S.J.; Alesso, H.P.; Altenbach, T.J.; Bennett, C.T.; and Ma, C. 1998. *AVLIS Criticality Risk Assessment.* UCRL-JC-130693. Livermore, California: Lawrence Livermore National Laboratory. ACC: MOL.20080102.0002.

2.2.13 BSC (Bechtel SAIC Company) 2005 *Thermal Performance of Spent Nuclear Fuel During Dry Air Transfer-Initial Calculations.* 000-00C-DSU0-03900-000-00B. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20050110.0003.

2.2.14 †BSC 2007. *Basis of Design for the TAD Canister-Based Repository Design Concept.* 000-3DR-MGR0-00300-000-001. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071002.0042. (DIRS 182131)

2.2.15 *BSC 2007. *Canister Receipt and Closure Facility 1 Fire Hazard Analysis.* 060-M0A-FP00-00100-000-00B. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071129.0032.

2.2.16 BSC 2007. *CRCF-1 and IHF WP Transfer Trolley Mechanical Equipment Envelope Plan & Elevations-Sh 1 of 2.* 000-MJ0-HL00-00101-000 REV 00B. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071027.0015.

2.2.17 BSC 2007. *Emplacement and Retrieval Transport and Emplacement Vehicle Mechanical Equipment Envelope.* 800-MJ0-HE00-00101-000 REV 00B. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20070918.0041.

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2.3 DESIGN CONSTRAINTS

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2.3.2 10 CFR 63. 2007. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada.

2.3.3 10 CFR 71. 2007. Energy: Packaging and Transportation of Radioactive Material. ACC: MOL.20070829.0114.

2.3.4 10 CFR 72. 2007. Energy: Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste.

2.4 DESIGN OUTPUTS

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2.4.2 BSC 2008. *Preclosure Nuclear Safety Design Bases*. 000-30R-MGR0-03500-000-000. Las Vegas, Nevada: Bechtel SAIC Company. ENG.20080312.0036

2.4.3 BSC 2008. *Preclosure Procedural Safety Controls*. 000-30R-MGR0-03600-000-000 Las Vegas, Nevada: Bechtel SAIC Company.ENG.20080311.0017

2.4.4 BSC 2008. *Seismic Event Sequence Quantification and Categorization*. 000-PSA-MGR0-01100-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ENG.20080311.0032

2.5 ATTACHMENT REFERENCES

2.5.1 Attachment A: Design Input references are listed in Section 2.2 of the main report.

2.5.2 Attachment B: Design Input references are listed in Sections B1.1; B2.1; B3.1; B4.1; B5.1; B6.1; B7.1; B8.1; B9.1.

2.5.3 Attachment C: Design Input references are listed in Section C1.2.

2.5.4 Attachment D: Design Input references are listed in Section D4

2.5.5 Attachment E: Design Input references are listed in Section E9.

2.5.6 Attachment F: Design Input references are listed in Section F2.

2.5.7 Attachment G: This attachment does not contain Design Input references.

2.5.8 Attachment H: This attachment does not contain Design Input references.

3. ASSUMPTIONS

3.1 ASSUMPTIONS REQUIRING VERIFICATION

There are no assumptions requiring verification.

3.2 ASSUMPTIONS NOT REQUIRING VERIFICATION

3.2.1 General Analysis Assumptions

Assumption—Equipment and SSCs designed and purchased for the Yucca Mountain repository are of the population of equipment and SSCs represented in United States industry-wide reliability information sources. Furthermore, the uncertainty in reliability is represented by the variability of reliabilities across this population.

Rationale—Although the repository features some unique pieces of equipment at the system level (such as the waste package transfer trolley (WPTT) and the cask transfer trolley (CTT)), at the component level, the repository relies on proven and established technologies. The industry-wide information sources include historical reliability information at the component level. Such experience is relevant to the repository because the repository relies on components that are similar to the ones represented in the information sources. In some cases, system-level information, such as crane load-drop rates, from industry-wide information sources are used. It is appropriate to use such information because it represents similar pieces of equipment at the system level. In addition, drawing from a wide spectrum of sources takes advantage of many observations, which yield better statistical information regarding the uncertainty associated with the resulting reliability estimates.

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4. METHODOLOGY

4.1 QUALITY ASSURANCE

This analysis has been prepared in accordance with *Calculations and Analyses* (Ref. 2.1.1) and *Preclosure Safety Analysis Process* (Ref. 2.1.4). Therefore, the approved version is designated as "QA: QA."

In general, input designated "QA: QA" is used. However, some of the inputs that are cited are designated "QA: N/A." The suitability of these inputs for the intended use is justified as follows:

Documentation of suitability for intended use of "QA: N/A" drawings: Engineering drawings are prepared using the "QA: QA" procedure *Engineering Drawings* (Ref. 2.1.2). They are checked by an independent checker and reviewed for constructability and coordination before review and approval by the engineering group supervisor and the discipline engineering manager (Ref. 2.1.2, Section 3.2.2 and Attachments 3 and 5). The check, review, and approval process provides assurance that these drawings accurately document the design and operational philosophy of the facility. For this reason, they are suitable for their intended use as sources of input to this analysis.

Documentation of suitability for intended use of sketches (which are "QA: N/A"): In a few instances, sketches are used as inputs to this analysis. The use of sketches is acceptable for committed analyses, such as the present analysis, provided that the results are not used for procurement, fabrication, or construction purposes. Because the present analysis is not used for procurement, fabrication, or construction purposes, the use of sketches is acceptable. Therefore, the sketches that are used as inputs are suitable for their intended uses.

Documentation of suitability for intended state descriptions were changed on pages 49-5 1ed use of "QA: N/A" engineering calculations or analyses: Engineering calculations and analyses are prepared using the "QA: QA" procedure *Calculations and Analyses* (Ref. 2.1.1). They are checked by an independent checker and reviewed for coordination before review and approval by the engineering group supervisor and the discipline engineering manager. The check, review, and approval process provides assurance that these calculations and analyses accurately document the design and operation of the facility. For this reason, they are suitable for their intended use as sources of input to this analysis.

Documentation of suitability for intended use of engineering studies (which are "QA: N/A"): In a few instances, studies are used as inputs to this analysis. The uses of inputs from studies are made clear by the context of the discussion at the point of use. The use of studies is acceptable for committed analyses, such as the present analysis, provided that the results are not used for procurement, fabrication, or construction purposes. Because the present analysis is not used for procurement, fabrication, or construction purposes, the use of studies is acceptable. Therefore, the studies that are used as inputs are suitable for their intended uses.

Documentation of suitability for intended use of BSC design guides (which are "QA: N/A"): The uses of inputs from design guides are made clear by the context of the discussion at the point of use. Design guides are used as inputs only when specific design documents, such as drawings, calculations, and design reports are not available at the present level of design development. Therefore, the design guides that are used as inputs are suitable for their intended uses.

Documentation of suitability for intended use of BSC engineering standards (which are "QA: N/A"): Engineering standards are used in this analysis as the basis for the numbering system for basic events. The uses of inputs from BSC engineering standards are made clear by the context of the discussion at the point of use. Therefore, the design guides that are used as inputs are suitable for their intended uses.

Documentation of suitability for intended use of BSC Interoffice memorandum: Due to the early nature of the design of some systems, the only available sources for the information used are interoffice memorandum. The information used from these sources is conservative estimates and appropriate for their intended use.

Documentation of suitability for intended use of inputs from outside sources: The uses of inputs from outside sources are made clear by the context of the discussion at the point of use. These uses fall into the following categories and are justified as follows (in addition to the justifications provided at the point of use).

1. Some inputs are cited as sources of the methods used in the analysis. These inputs are suitable for their intended uses because they represent commonly accepted methods of analysis among safety analysis practitioners or, more generally, among scientific and engineering professionals.

2. Some inputs are cited as examples of applications of analytical methods by others. These inputs are suitable for their intended uses because they illustrate applicable methods of analysis.

3. Some inputs are cited as sources of historical safety-related data. These inputs are suitable for their intended uses because they represent historical data that is commonly accepted among safety analysis practitioners.

4. Some inputs are cited as sources of accepted practices as recommended by codes, standards, or review plans. These inputs are suitable for their intended uses because they represent codes, standards, or review plans that are commonly accepted by practitioners of the affected professional disciplines.

5. Some inputs provide information specific to the Yucca Mountain repository that was produced by organizations other than BSC. These inputs are suitable for their intended uses because they provide information that was developed for the Yucca Mountain repository under procedures that apply to the organization that produced the information.

4.2 USE OF SOFTWARE

4.2.1 Level 1 Software

This section addresses software used in this analysis as Level 1 software, as defined in *Software Management* (Ref. 2.1.3). SAPHIRE Version 7.26 STN 10325-7.26-01 (Ref. 2.2.77) is used in this analysis for PRA simulation and analyses. The SAPHIRE software is used on a personal computer running Windows XP inside a VMware virtual machine; it is also listed in the 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. 2.2.43). 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). 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 version of *Globally Registered Controlled Software for Level 2 Usage*. Visio 2003 and Word 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 versions 13.0 and 14.0 are listed in the current version of *Globally Registered Controlled Software for Level 2 Usage*. Crystal Ball version 7.3.1 (a commercial, off-the-shelf, Excel-based risk-analysis tool) is also listed on the in the current version of the report *Globally Registered Controlled Software for Level 2 Usage* and is registered for Level 2 usage. Excel 2003, Mathcad 13.0 and 14.0, and Crystal Ball 7.3.1 are used in this analysis to calculate probability distributions for selected SAPHIRE inputs and to graphically display information. 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, for example, 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.

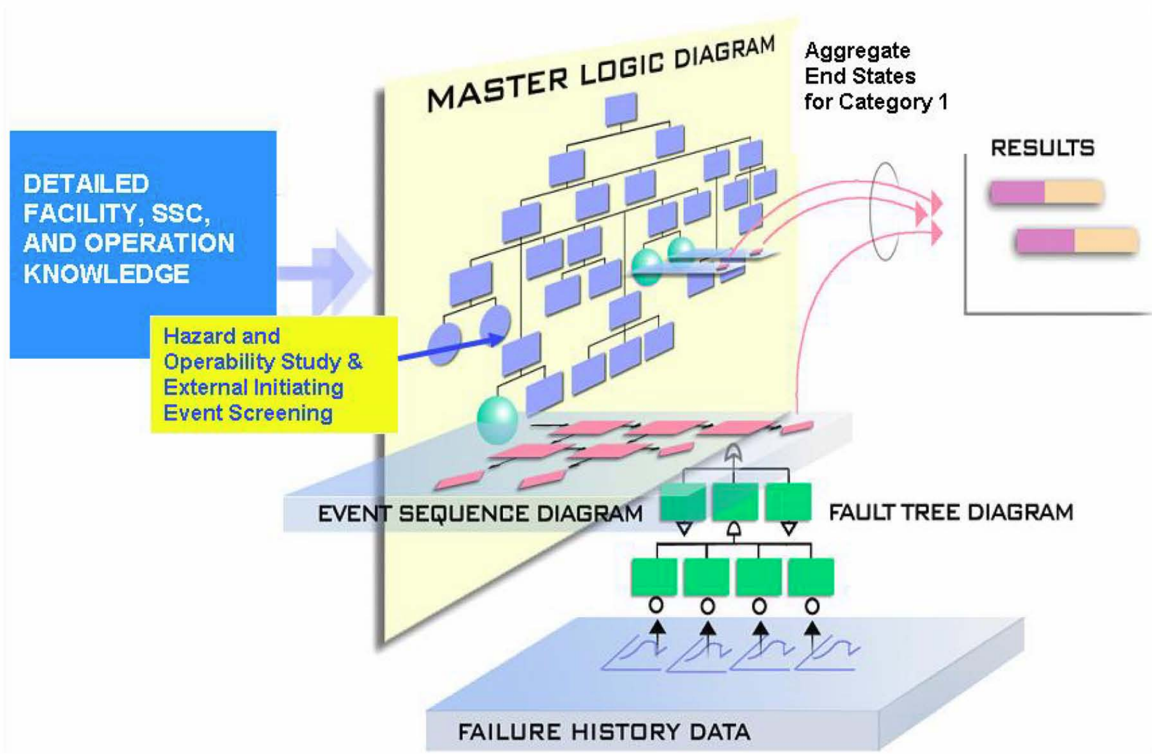
- WinZip 9.0, a file compression utility for Windows, is listed in the current version of *Globally Registered Controlled Software for Level 2 Usage*. WinZip 9.0 is used in this analysis to compress files for presentation on compact disc in Attachment H.

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 the WHF. Specific features of the WHF and its operations are not discussed until Section 6, where the methods described here are applied to the WHF. The PCSA uses the technology of PRA as described in references such as *Standard for Probabilistic Risk Assessment for Nuclear Power Plant Applications* (Ref. 2.2.7). 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 this 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.



NOTE: SSC = structure, system, or component.

Source: Modified from Ref. 2.2.80

Figure 4.3-1. Event Sequence Analysis Process

The PCSA starts with analysts obtaining sufficient knowledge of the design and operations of facility, equipment, and SSCs to understand how the YMP waste handling is conducted. This is largely performed and documented in the *Wet Handling Facility Event Sequence Development Analysis* (Ref. 2.2.37). 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, eight mutually exclusive end states are of interest:

1. "OK"—Indicates the absence of radiation exposure and potential for criticality.

2. Direct Exposure, Degraded Shielding—Applies to event sequences where a SSC providing shielding is not breached, but its 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 end state excludes radionuclide release.

3. Direct Exposure, Loss of Shielding—Applies to event sequences where a SSC providing shielding fails, leaving a direct path for radiation to stream. For example, this end state applies to a breached transportation cask, with a canister inside maintaining its containment function. In another example, this end state applies to shield doors inadvertently opened. This end state excludes radionuclide release.

4. Radionuclide Release, Filtered—Indicates a release of radioactive material from its confinement, 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 end state excludes moderator intrusion.

5. Radionuclide Release, Unfiltered—Indicates a release of radioactive material from its confinement, through the pool of the WHF or through an unfiltered path, to the environment. This end state excludes moderator intrusion.

6. Radionuclide Release, Filtered, Also Important to Criticality—This end state refers to a situation in which a filtered radionuclide release occurs and (unless the associated event sequence is Beyond Category 2) for which a criticality investigation is indicated.

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) for which 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) for which a criticality investigation is indicated.

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 important to criticality 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 important to criticality 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 important to criticality. Refer to Section 4.3.9 for 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. 2.2.42) and *Nuclear Computerized Library for Assessing Reactor Reliability (NUCLARR): Data Manual, Part 4: Summary Aggregations* (Ref. 2.2.53)), 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* (Ref. 2.2.10), 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. The present analysis uses fault trees to disaggregate a SSC or item of equipment 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* unreliability's, provide inputs to the fault tree models of items of equipment. Fault trees are used in some instances to model initiating events and in other 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 the initiating event (e.g., a drop from a crane). Other pivotal events require knowledge of response to fires. Calculation of failure probabilities given a fire 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. To group together event sequences for the purpose of categorization, the frequencies of event sequences within the same ESD that result in the same end state, are summed. The concept of ***aggregating event sequences*** to obtain aggregated end-state results is depicted in Figure 4.3-1.

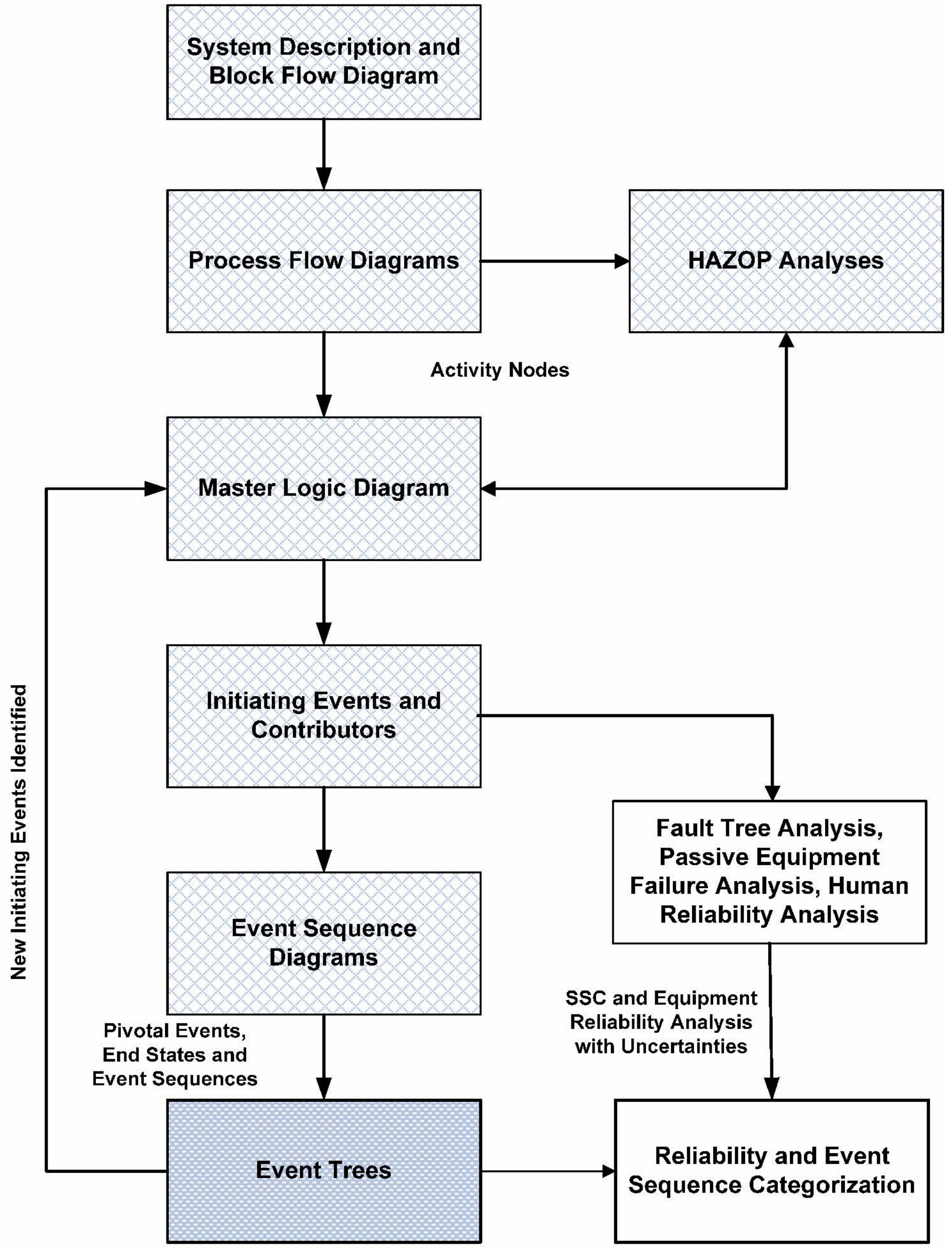
The PCSA is described above as a system simulation. This is important in that any simulation or model is an approximate representation of reality. Approximations may lead to uncertainties regarding the frequencies of event sequences. The event sequence quantification presented in this document propagates 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 *Wet Handling Facility Event Sequence Development Analysis* (Ref. 2.2.37).
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 and described below.

The cross-hatched boxes in Figure 4.3-2 serve as a review of the analysis performed for the Wet Handling Facility Event Sequence Development Analysis (Ref. 2.2.37). The interface between the event sequence development analysis and the present 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 the present analysis. The unshaded boxes represent the analysis performed in this study, the methods of which are described later in Section 4.



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

Source: Modified from Wet Handling Facility Event Sequence Development Analysis (Ref. 2.2.37DIRS 185738, Figure 2)

Figure 4.3-2. Preclosure Safety Assessment Process

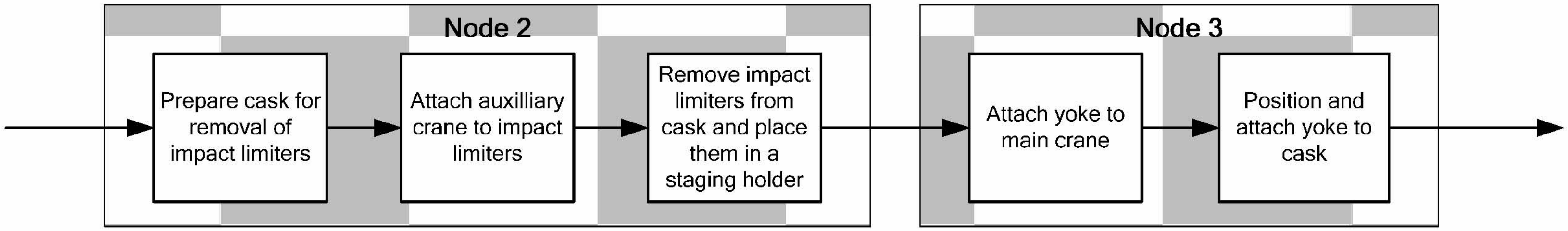
The event sequences that are categorized in the present analysis can be more fully understood by consulting the event sequence development analysis (Ref. 2.2.37). The remainder of this subsection presents a refresher of the event sequence development process.

A simplified process flow diagram (PFD) is developed to clearly delineate the process and sequence of operations to be considered within the analysis of the facility. 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 is broken down into nodes to identify specific processes and operations that are evaluated with both a MLD and HAZOP evaluation to identify potential initiators.

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 and 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 detailed in *Wet Handling Facility Event Sequence Development Analysis* (Ref. 2.2.37, 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. The HAZOP evaluation is also a systematic analysis 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 in some ways to be the first of its kind, the operations are based on established technologies: for example, 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 that are identified in the HAZOP evaluation but not already included in the MLD. The entire process is iterative in nature (Figure 4.3-2, iteration not shown) 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 *Wet Handling Facility Event Sequence Development Analysis* (Ref. 2.2.37, Section 4.3.1.3).

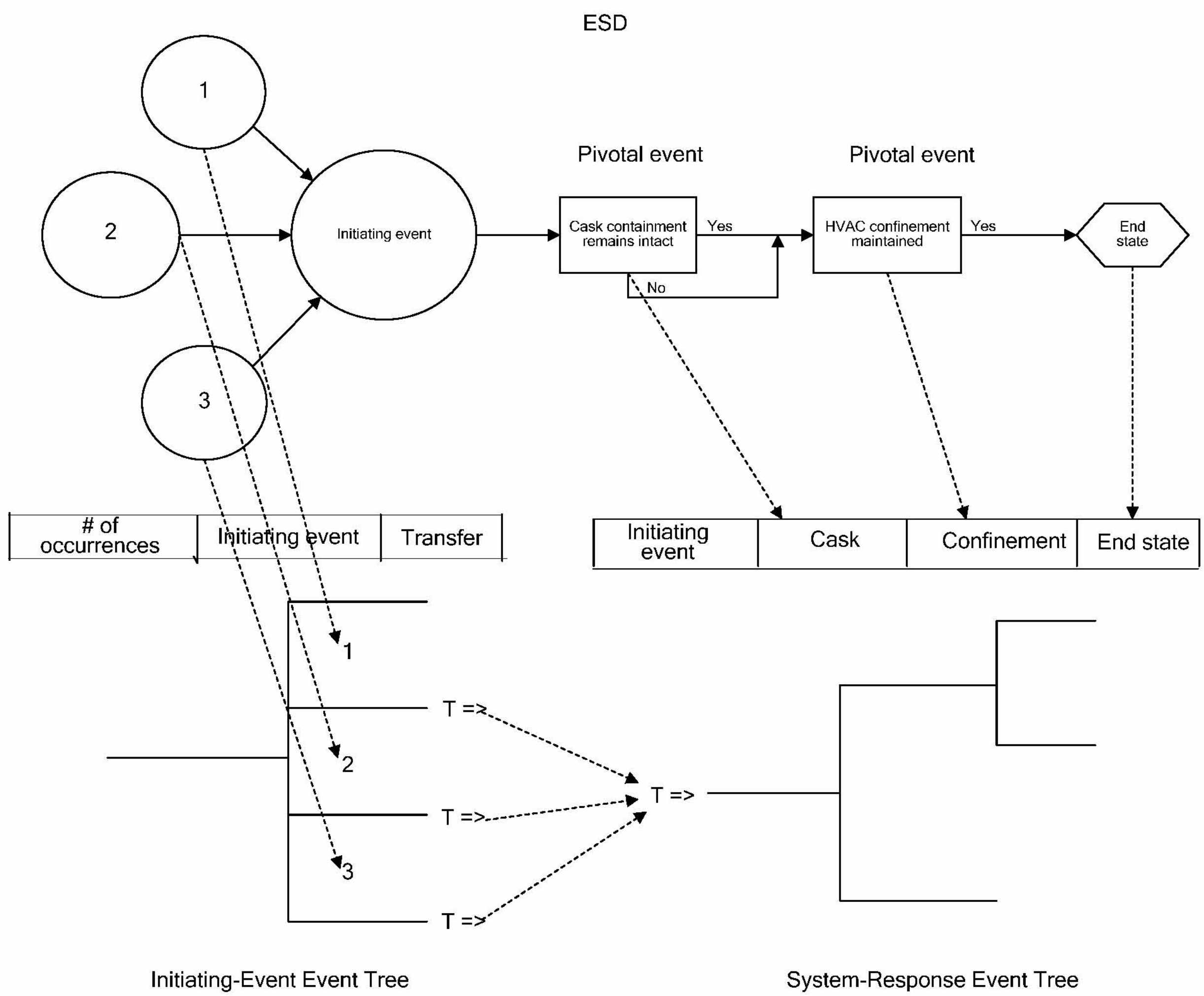


NOTE: This diagram illustrates a small portion of the overall handling operations for a typical waste handling facility.

Source: Original

Figure 4.3-3. Portion of a Simplified Process Flow Diagram for a Typical Waste-Handling Facility

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. The boxes (pivotal events) represent events that have binary outcomes: success (yes) or failure (no). 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 an 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–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, and 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 bubbles may be aggregated further into "big bubbles" 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 canister would include pivotal events that question the containment integrity of the canister and the availability of HVAC confinement. 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 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. 2.2.43), which ultimately stores event trees, fault trees, and reliability data, and quantifies the event sequences. 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. 2.2.66, 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 be associated with an end state. As illustrated in the event tree portion of Figure 4.3-4, each intersection of a horizontal and vertical line is referred to as a node (or branch point). Each node is associated with a conditional probability of following the vertical downward branch. By convention, the description of each branch is stated as a success, and the downward branch indicates a failure. The complement is the probability of taking the vertical upward branch, that is, the probability of success. 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. 2.2.66). Each facility has its own set of event trees. The first event tree 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 would start 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 IET and SRET is quantified for each waste container type (e.g., dual-purpose canisters (DPCs), transportation, aging, and disposal (TAD) canisters, DOE SNF that is handled in a facility). The event in the IET labeled "# of occurrences" represents the number of handlings (i.e., demands) for that initiating event. For example, each lift of a transportation cask provides an opportunity for a drop. 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, then only the SRET needs to be used with the initiating event in the place so denoted, in the second event tree. In this case, summation of event sequences is not necessary and 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. 2.2.14, Section 2.2.2.7).

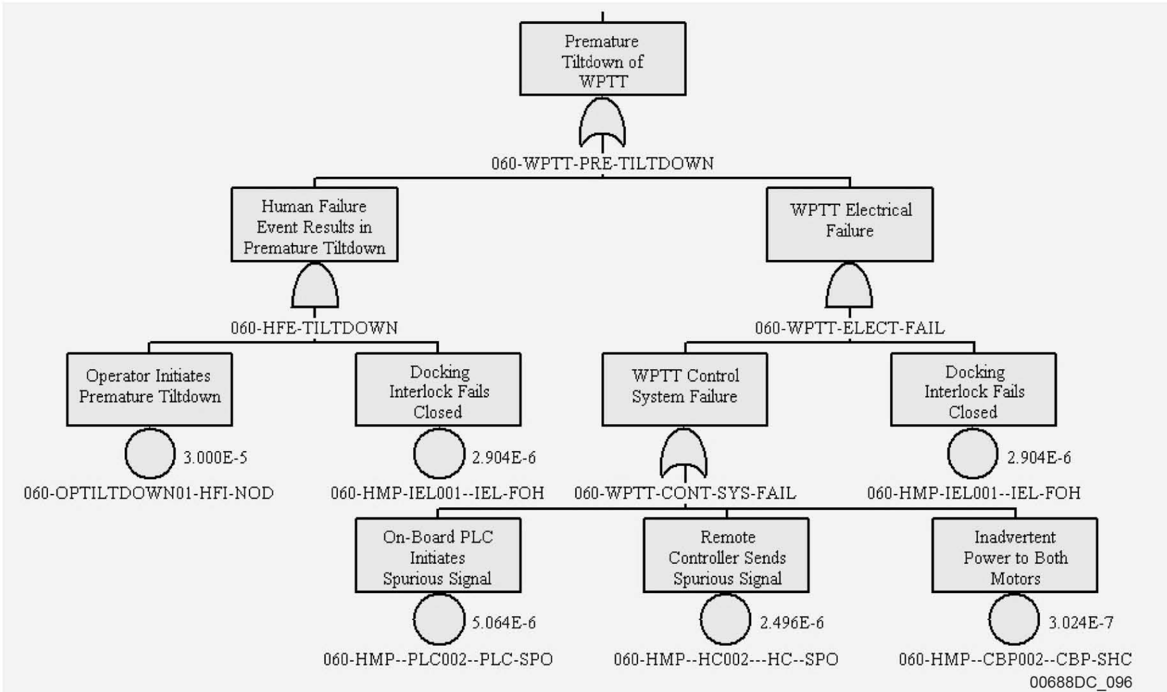
An initiating event for an event sequence may have the potential to affect several waste form types (for instance, a high-level radioactive waste (HLW) canister and a DOE standardized canister, or a TAD canister and a DPC). For example, the seismically-induced event sequence leading to a collapse of a surface facility could cause the breach of all the waste forms inside that facility. Similarly, a large fire affecting an entire facility also affects all the waste forms inside the facility. The number of occurrences over the preclosure period of an event sequence that affects more than one type of waste form 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 (reported in 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.

4.3.2 Initiating and Pivotal Event Analysis

The purpose of this analysis is to develop the frequency (i.e., number of occurrences over the 50-year operating lifetime of the facility) of each event sequence in order to categorize 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 easily be mapped 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 WPTT) may be unique to the YMP facility with little or no prior operating history. The components, however, of which it is composed, have usually been used before and there is an adequate set of reliability data for these components. The PCSA used 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. All initiating events use fault trees and the pivotal event associated with confinement is analyzed via a fault tree of the HVAC system. In effect, the use of fault trees creates a mapping 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 4.3-5 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 4.3-5. 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 usually failures or faults. Fault trees use logic or Boolean gates. Figure 4.3-5 shows 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 passes an output up the tree if all events immediately attached to it occur. An OR gate passes an output up the tree if one or more events immediately attached to it take place. An AND gate often implies components or system features that back up each other, so that if one fails, the other continues to adequately perform the function. 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. Fault tree analysis (FTA), as used in the PCSA, is well described in 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.

As illustrated in Figure 4.3-5, 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 led to design changes to either eliminate them or reduce the probability that they would cause the fault tree top event. For example, Figure 4.3-5 shows an HFE logically intersected with an electro-mechanical interlock such that both a crew error of commission and failure of the interlock must occur for premature WPTT tiltdown 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 and 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. 2.2.6) and *2004 ASME Boiler and Pressure Vessel Code* (Ref. 2.2.8) 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. 2.2.8) 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. 2.2.47). 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 1:

$$g(x_1, x_2, \ldots. x_i, \ldots x_n) = 0 \qquad \text{(Eq. 1)}$$

In Equation 1, 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 2:

$$P_f = \int \ldots \int f_x(x_1, x_2, \ldots x_i \ldots x_n) dx_1 dx_2 \ldots dx_n \qquad \text{(Eq. 2)}$$

Where f_x is the joint probability density function 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 4.3-6. Codes and standards such as *Minimum Design Loads for Buildings and Other Structures* (Ref. 2.2.6), guide the process of designing structures such that there is a margin, often called 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.

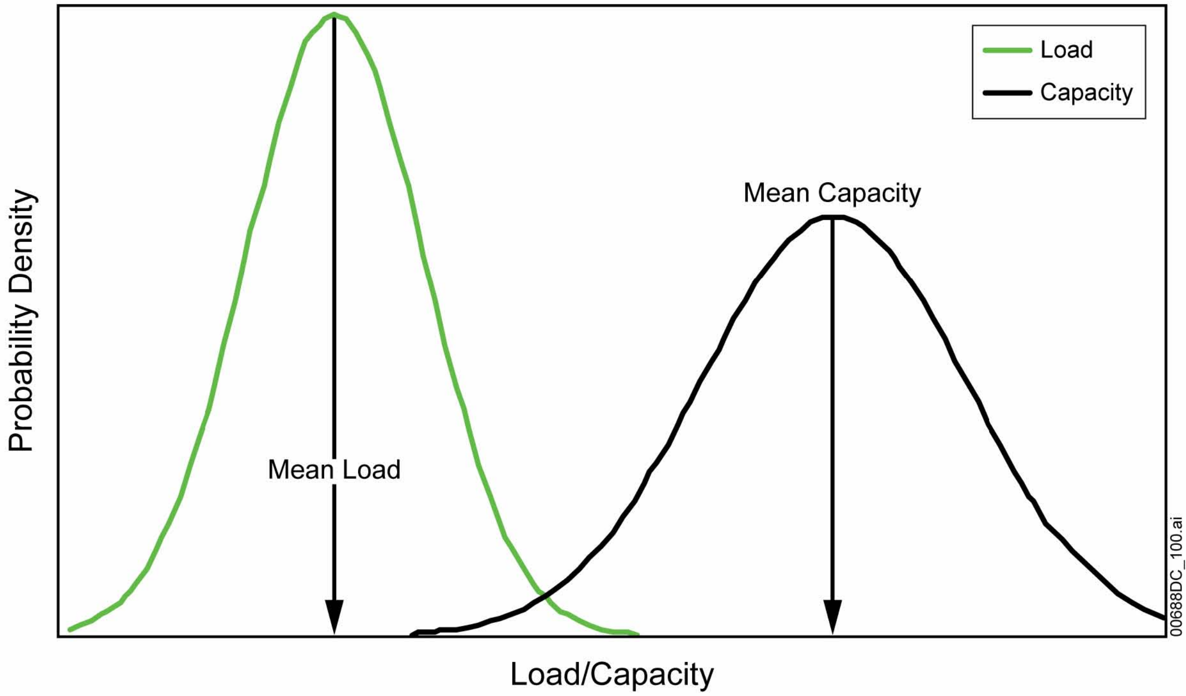


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Figure 4.3-6. Concept of Uncertainty in Load and Resistance

In the case in which Equations 1 and 2 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 3.

$$P_f = \int F(y)h(y)dy \quad \text{(Eq. 3)}$$

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 3, *F(y)* represents the cumulative density function of structural capacity and *h(y)* represents the probability density function 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 probability density function 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 separately in *Seismic Event Sequence Quantification and Categorization* (Ref. 2.4.4). Degradation of shielding owing to impact loads uses a strain to failure criterion within the simplified approach of Equation 4, 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. Analysis for heating up casks, canisters, and waste packages associated with loss of building forced convection cooling was similarly accomplished, but Equation 4 was used.

If load and capacity are known, then Equations 2 and 3 provide a single valued result, which is the mean probability of failure. Each function in Figure 4.3-6 is characterized by a mean value, $\overline{L}$ and $\overline{R}$, and a measure of the uncertainty, generally the standard deviation, usually denoted by σ_L and σ_R for *L* and *R*, 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 $V_R = \sigma_R/\overline{R}$ for load and resistance, 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. 2.2.36). 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.

Impact Events Associated with Containment Breach

A simplification of Equation 3, consistent with *Interim Staff Guidance HLWRS-ISG-02, Preclosure Safety Analysis – Level of Information and Reliability Estimation* (Ref. 2.2.73), and shown in Equation 4 is used in the PCSA. It is illustrated in Figure 4.3-7.

$$P_f = \int_0^h F(y)dy \qquad \text{(Eq. 4)}$$

In Equation 4, 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 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. The conditional probability of breach is an increasing function of drop height. Strain resulting from drops is calculated by dynamic finite element analysis using Livermore Software–Dynamic Finite Element Program for canisters and transportation cask drops (Ref. 2.2.36). 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.