B5.4.5.5 Basic Events

Table B5.4-9 contains a list of basic events used in the fault tree for "Malfunction of WPTT or Waste Package Transfer Carriage" during waste package export".

Table B5.4-9. Basic Event Probabilities for Malfunction of WPTT or Waste Package Transfer Carriage Malfunction during Waste Package Export

Name	Calc. Type[a]	Calc. Prob.	Fail. Prob.	Lambda (hr^{-1})[a]	Miss. Time (hr)[a]
51A-WPTT--CAM001-CAM-FOH	3	3.190E-006	—	3.190E-006	1
51A-WPTT--HC001--HC--SPO	3	5.230E-007	—	5.230E-007	1
51A-WPTT-HC002---HC--SPO	3	5.230E-007	—	5.230E-007	1
51A-WPTT-IEL001-IEL-FOD	1	2.750E-005	2.750E-005	—	—
51A-WPTT-IEL003--IEL-FOD	1	2.750E-005	2.750E-005	—	—
51A-WPTT-PLC001-PLC-SPO	3	3.650E-007	—	3.650E-007	1
51A-WPTT-PLC002--PLC-SPO	3	3.650E-007	—	3.650E-007	1
51A-OPTEVDRCLOSD-HFI-NOD	1	1.000E-003	1.000E-003	—	—
51A-OPWPTILTUP01-HFI-NOD	1	1.000E+000	1.000E+000	—	—

NOTE: [a] For Calc. Type 3 with an unspecified mission time or a mission time specified as 0, SAPHIRE performs the quantification using the system mission time, 1 hr. The mission time used by SAPHIRE is listed here regardless of whether it is specified explicitly in the SAPHIRE basic event or the system mission time is used as a default. See Table 6.3-1 for definitions of calculation types.

Calc. = calculation; Fail. = failure; Miss. = mission; Prob. = probability.

Source: Original

B5.4.5.5.1 Human Failure Events

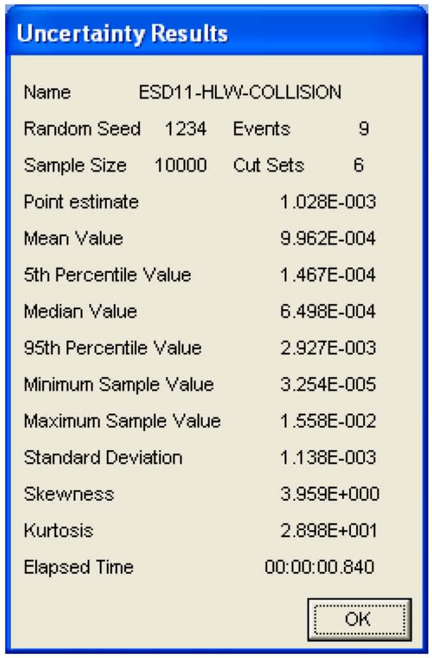
There are two operator errors; one involves initiation of tilt-up and the other extraction of the waste package with the TEV door closed.

B5.4.5.5.2 Common-Cause Failures

There are no CCFs identified for this fault tree.

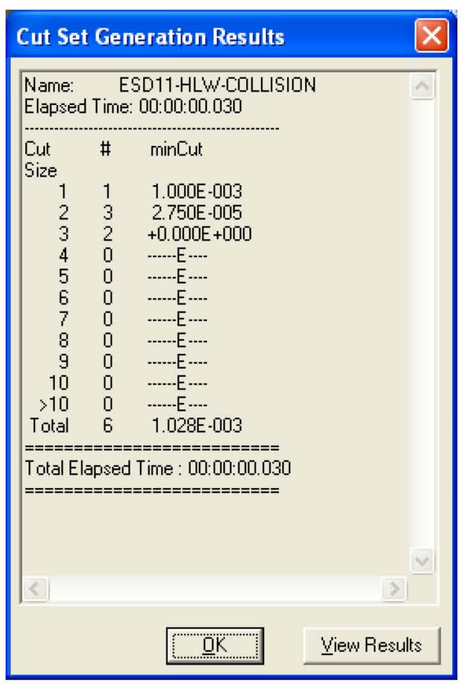
B5.4.5.6 Uncertainty and Cut Set Generation

Figure B5.4-17 contains the uncertainty results for "Malfunction of WPTT or Waste Package Transfer Carriage." Figure B5.4-18 provides the cut set generation results obtained from "Malfunction of WPTT or Waste Package Transfer Carriage" malfunction during extraction of the waste package from the shielded enclosure.



Source: Original

Figure B5.4-17. Uncertainty Results for Malfunction of WPTT or Waste Package Transfer Carriage



Source: Original

Figure B5.4-18. Cut Set Generation Results for Malfunction of WPTT or Waste Package Transfer Carriage

B5.4.5.7 Cut Sets

Table B5.4-10 contains the cut sets for "Malfunction of WPTT or Waste Package Transfer Carriage" during waste package export. The total probability per cask is 1.028E-003 with operator error causing the waste package to impact the closed TEV door the primary contributor.

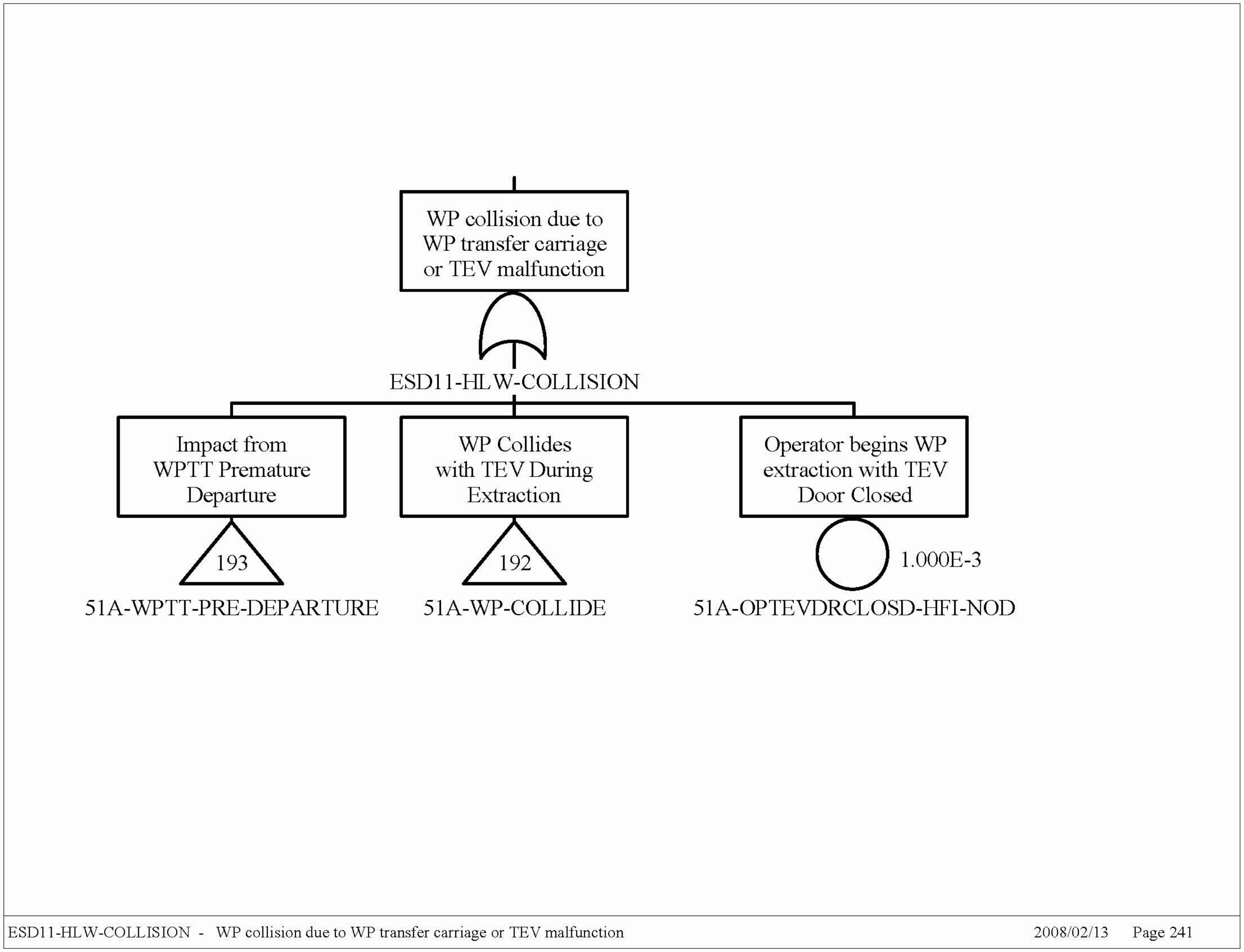
Table B5.4-10. Cut Sets for Malfunction of WPTT or Waste Package Transfer Carriage During Waste Package Export

Fault Tree	Cut Set %	Prob./Freq.	Basic Event	Description	Probability
ESD11-HLW-COLLISION	97.33	1.000E-003	51A-OPTEVDRCLOSD-HFI-NOD	Operator begins WP extraction with TEV Door Closed	1.0E-003
	2.68	2.750E-005	51A-OPWPTILTUP01-HFI-NOD	Operator Initiates Tilt Up	1.0E+000
			51A-WPTT-IEL001-IEL-FOD	Carriage Motor Interlock Fails	2.8E-005
	0.00	1.438E-011	51A-WPTT-HC002---HC--SPO	Remote Controller Sends Spurious Signal	5.2E-007
			51A-WPTT-IEL001-IEL-FOD	Carriage Motor Interlock Fails	2.8E-005
	0.00	1.004E-011	51A-WPTT-IEL001-IEL-FOD	Carriage Motor Interlock Fails	2.8E-005
			51A-WPTT-PLC002--PLC-SPO	On-Board PLC Initiates Spurious Signal	3.7E-007
		1.027E-003	= Total		

NOTE: PLC = programmable logic controller; TEV = transport and emplacement vehicle; WP = waste package; WPTT = waste package transfer trolley.

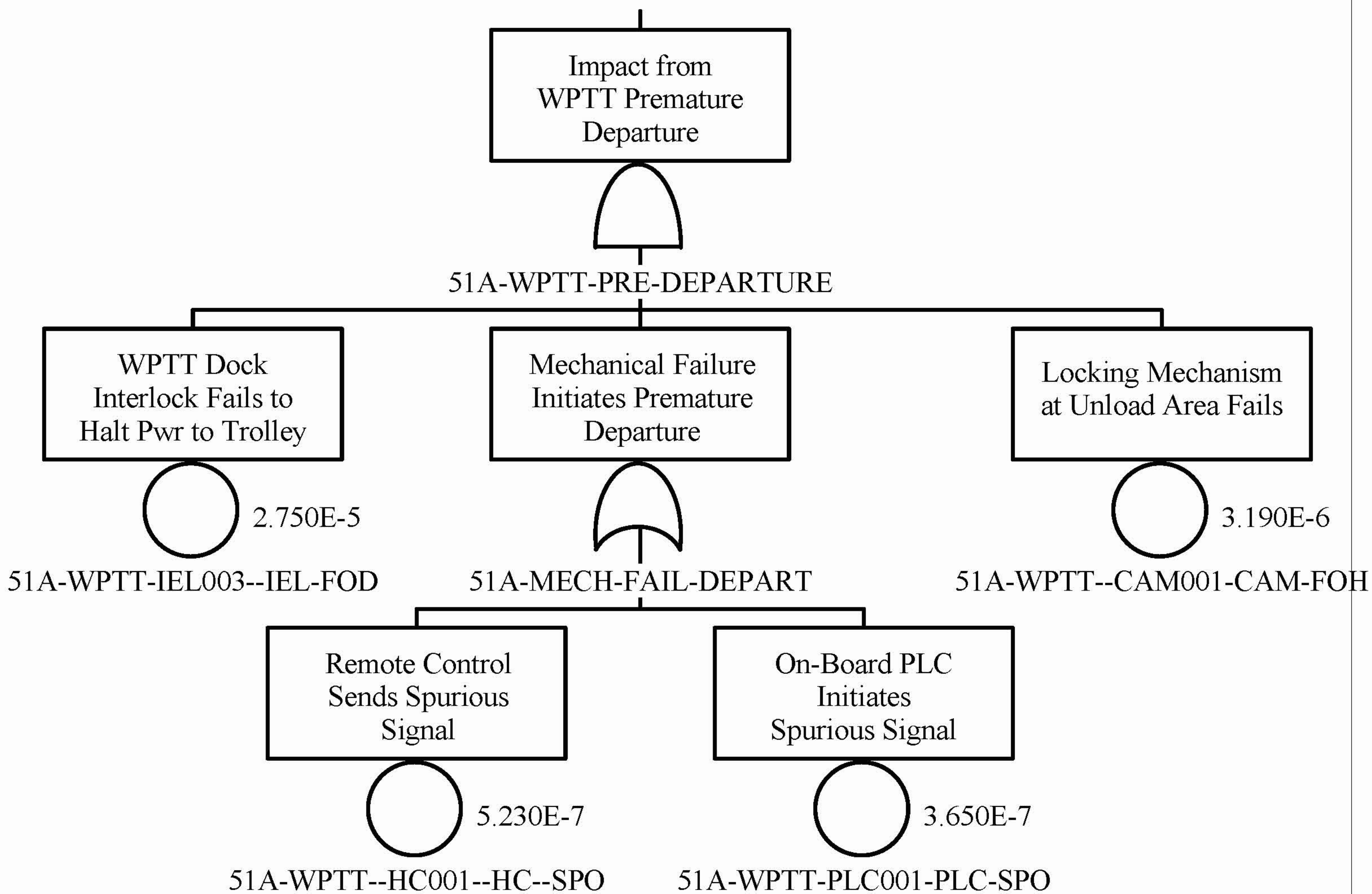
Source: Original

B5.4.5.8 Fault Trees



Source: Original

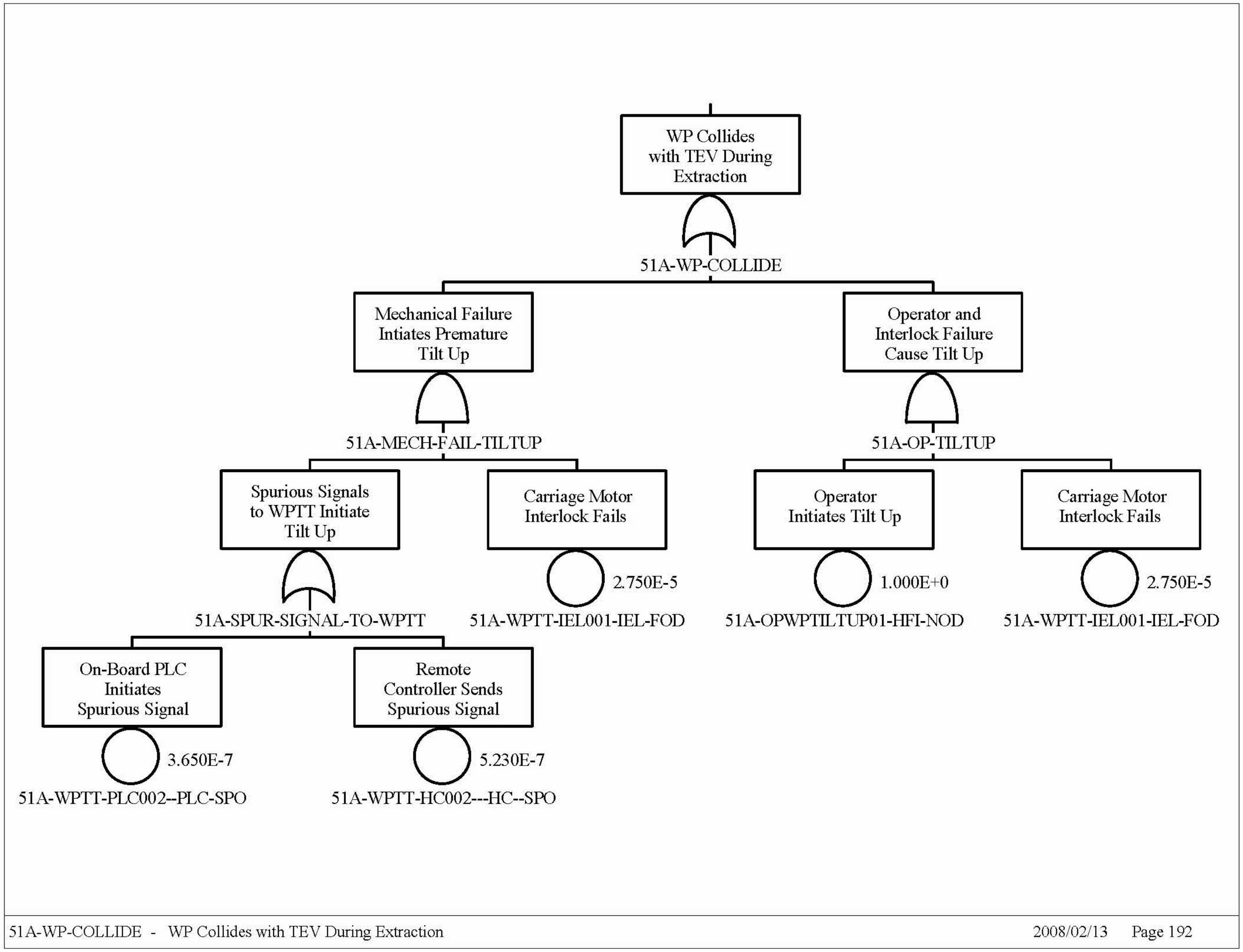
Figure B5.4-19. Fault Tree for Malfunction of WPTT or Waste Package Transfer Carriage



51A-WPTT-PRE-DEPARTURE - WPTT Prmature Departure from Unloading Dock 2008/02/27 Page 193

Source: Original

Figure B5.4-20. Fault Tree for Malfunction of WPTT or Waste Package Transfer Carriage (Continued)



Source: Original

Figure B5.4-21. Fault Tree for Malfunction of WPTT or Waste Package Transfer Carriage (Continued)

B6 PIVOTAL EVENT ANALYSIS

Miscellaneous linking fault trees that were not discussed in Attachment A are described in this section. Attachment A described fault trees that provided links between the event trees and basic events, fault trees containing split fractions, and initiating event fault trees described in Attachment B, Sections B1 to B5. This section describes the remaining types of initiating event fault trees that do not fit into these categories.

There are four types of fault trees discussed in this section: dropping an object onto a cask or waste package, impact to a cask by another vehicle or object, spurious movement of a crane causing an impact to or a tip over of a cask, loss of shielding leading to direct exposure, and introduction of liquid moderator.

B6.1 FAULT TREES INVOLVING DROPPING AN OBJECT

These "drop-on" fault trees describe dropping an object onto a cask or a waste package and are listed in Table B6.1-1. A typical fault tree for drop of an object onto a transportation cask is shown in Figure B6.1-1, and a fault tree for dropping an object onto a waste package is shown in Figure B6.1-2.

Table B6.1-1. Drop-On Fault Trees

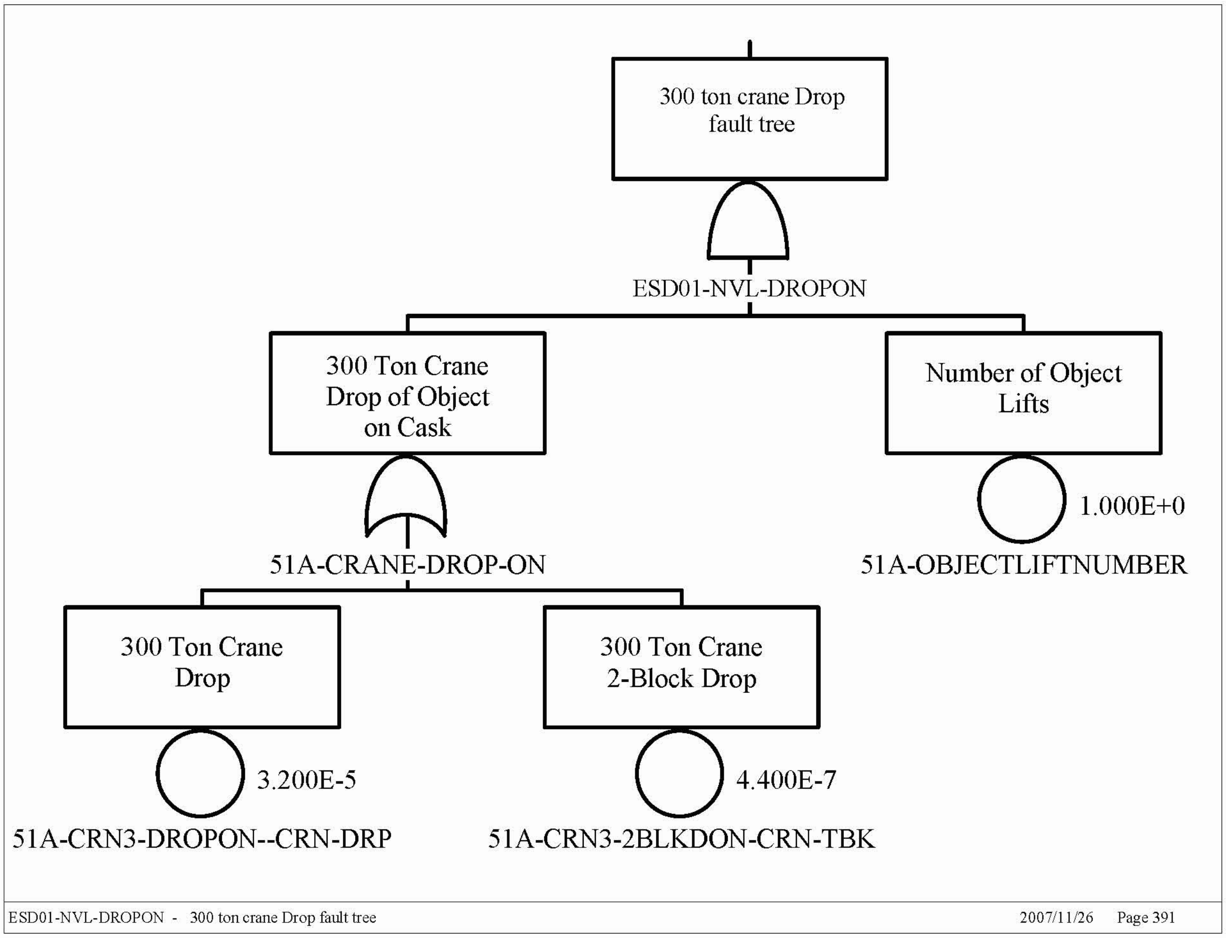
Fault Tree Name	Applies to ESD	Applies To	Number of Objects Lifted
ESD01-NVL-DROPON	ESD-01	Naval transportation cask	1
ESD02-HLW-DROPON	ESD-02	HLW transportation cask	1
ESD02-NVL-DROPON	ESD-02	Naval transportation cask	1
ESD03-HLW-DROPON	ESD-03	HLW transportation cask	1
ESD04-NVL-DROPON	ESD-04	Naval transportation cask	1
ESD07-HLW-DROPON	ESD-07	HLW canister	1
ESD07-NVL-DROPON	ESD-07	Naval canister	1
ESD09-HLW-DROPON	ESD-09	HLW waste package	2
ESD09-NVL-DROPON	ESD-09	Naval waste package	2
ESD11-HLW-DROPON	ESD-11	HLW waste package	1
ESD11-NVL-DROPON	ESD-11	Naval waste package	1

NOTE: HLW = high-level radioactive waste; NVL = naval.

Source: Original

In Figure B6.1-1 the 300-ton crane may drop a lifting fixture onto the transportation cask from a normal height or from a much higher than normal height due to a two-blocking event. The probabilities of crane drops are based on historical data discussed in Section 6.3 and Attachment C. The calculated probability of a crane dropping an object on a cask is 3.24E-005 for one object lifted.

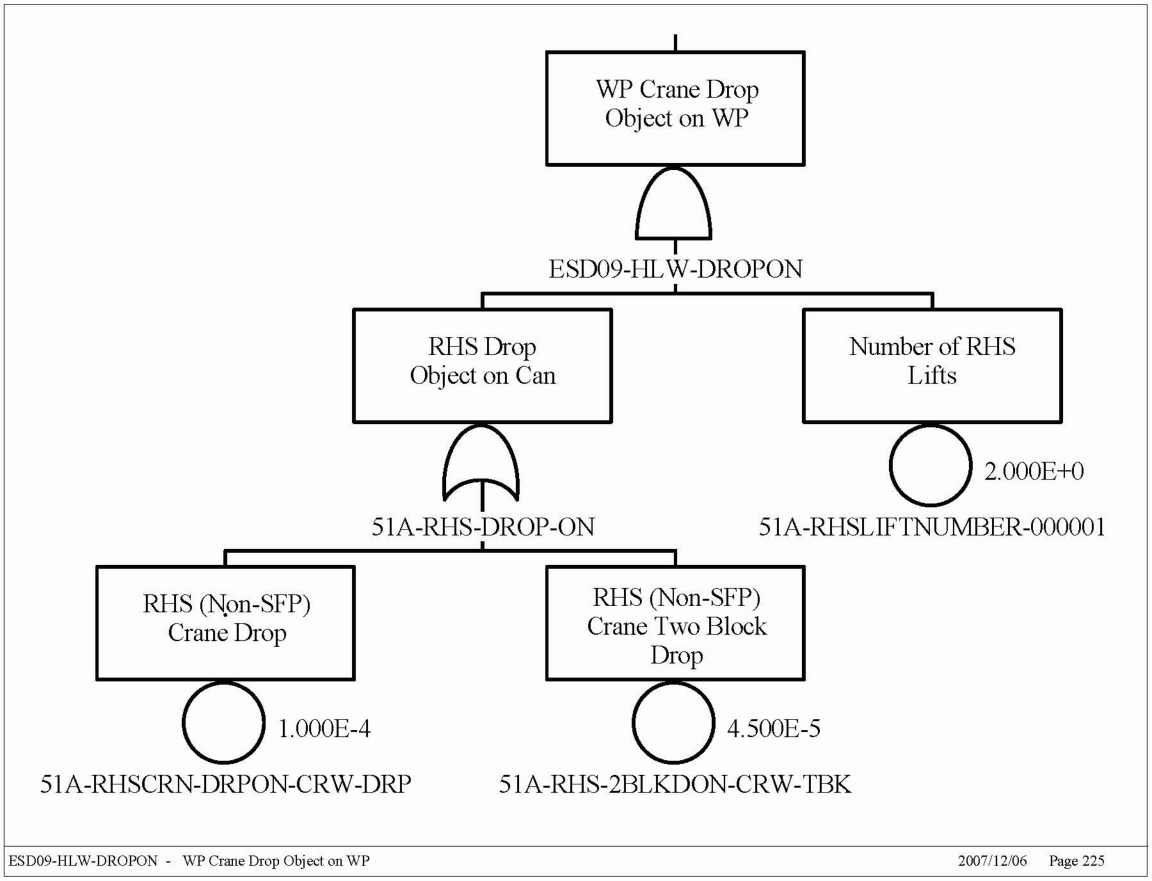
The data for the 300-ton crane is based on operational experience of cranes designed to be single failure proof (SFP).



Source: Original

Figure B6.1-1. Typical 300-Ton Crane "Drop-On" Fault Tree

In Figure B6.1-2 the remote handling system (RHS) crane may drop the inner or outer waste package lids onto the waste package from a normal height or from a much higher than normal height due to a two-blocking event. The probabilities of crane drops are based on historical data discussed in Section 6.3 and Attachment C. The calculated probability of a crane dropping an object on a cask is 3.0E-04 for the two objects lifted.



Source: Original

Figure B6.1-2. Typical RHS Crane "Drop-On" Fault Tree

B6.2 IMPACT TO A CASK BY ANOTHER VEHICLE OR OBJECT

These fault trees involve side impacts to the transportation cask by another vehicle or object. Table B6.2-1 lists the fault trees that describe these impacts.

Table B6.2-1. Transportation Cask Impact Fault Trees

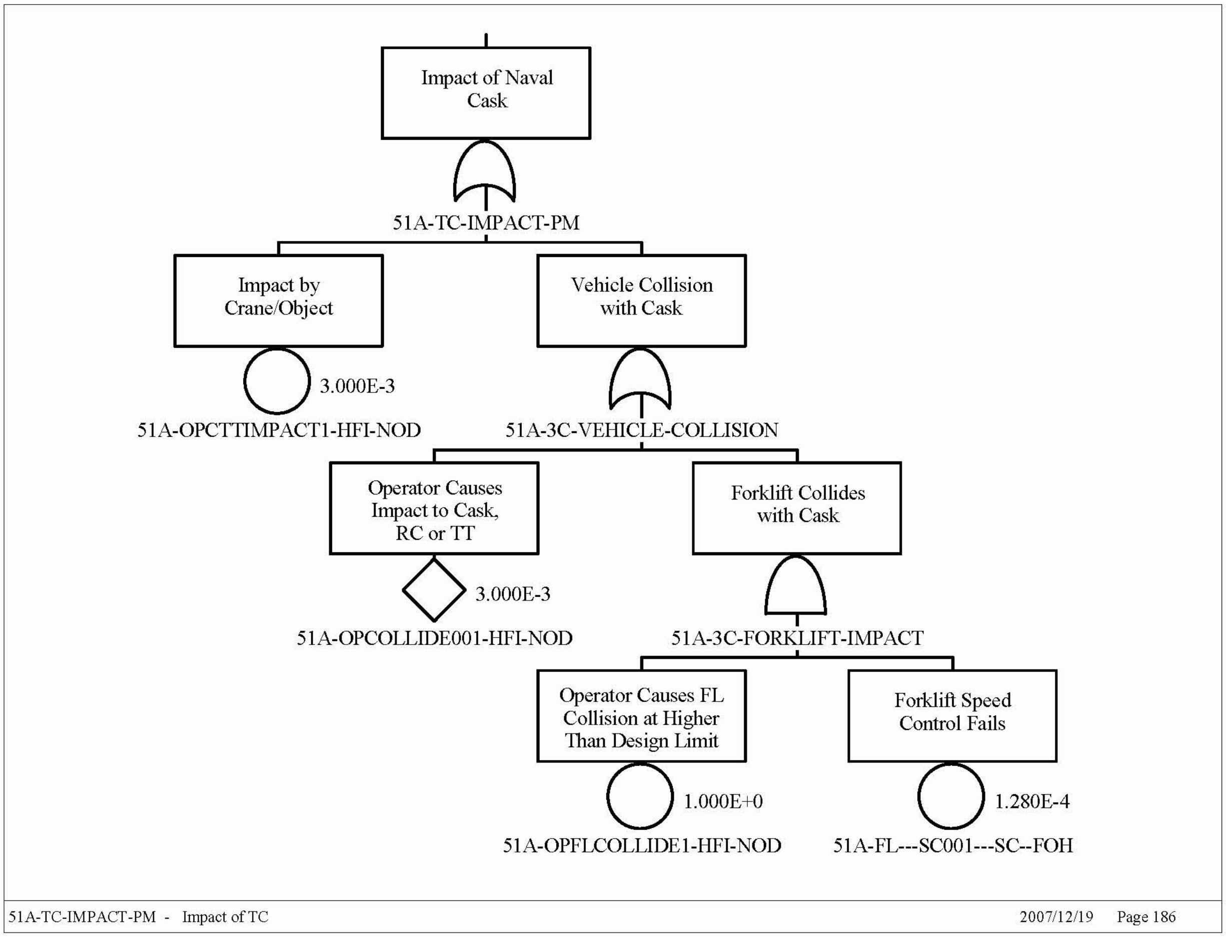
Fault Tree Name	Applies to ESD	Applies To
ESD01 NVL COL CSK (transfers to 51A-TC-IMPACT-PM)	ESD-01	Naval Transportation Cask
ESD02-HLW-SIDEIMP	ESD-02	HLW Transportation Cask
ESD02-NVL-SIDEIMP	ESD-02	Naval Transportation Cask
ESD03-HLW-SIDEIMP	ESD-03	HLW Transportation Cask
ESD03-NVL-SIDEIMP	ESD-03	Naval Transportation Cask

NOTE: ESD = event sequence diagram; HLW = high level waste; NVL = naval.

Source: Original

Figure B6.2-1 illustrates a side impact to a transportation cask that may occur due to the following operator errors:

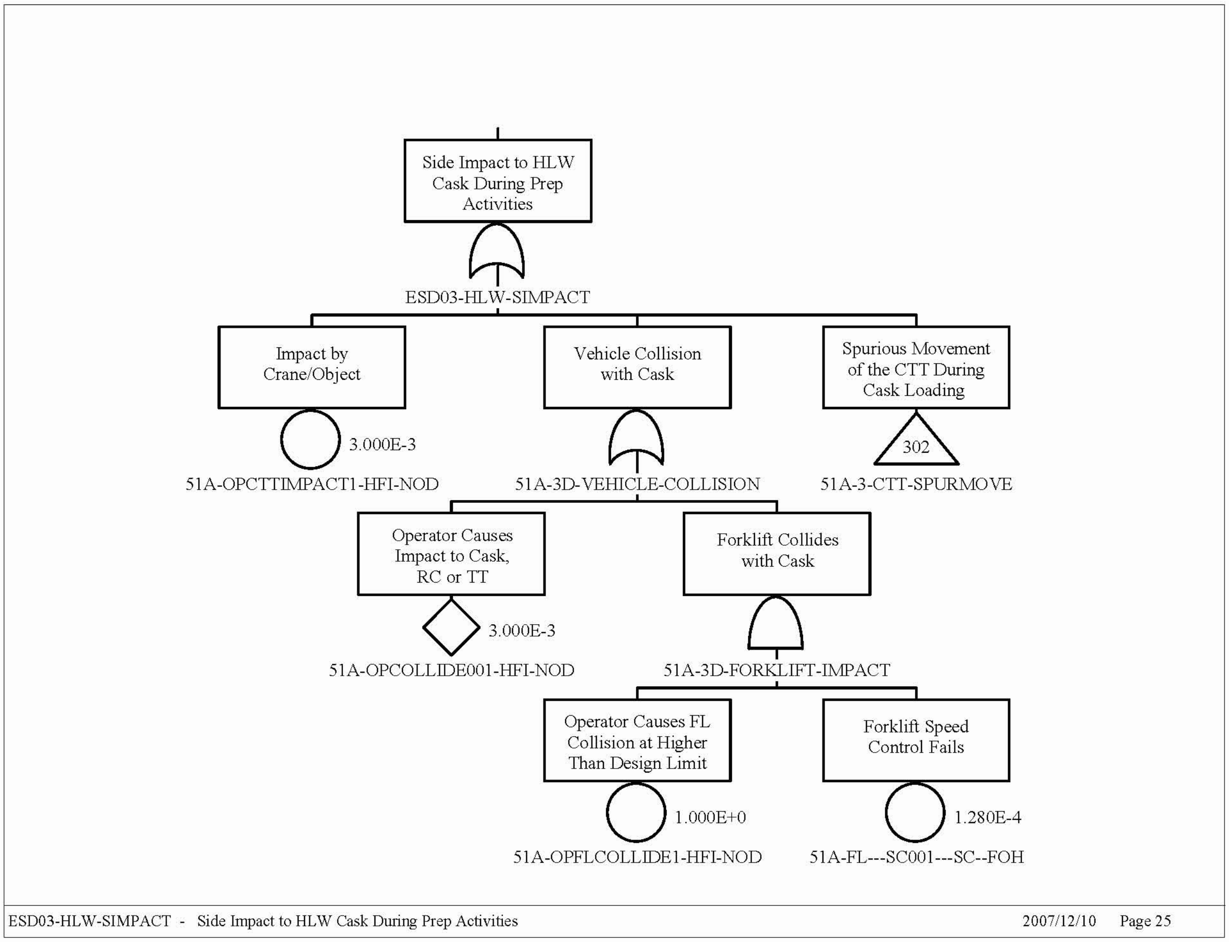
- Operator causing impact by the crane or object being carried by the crane
- Operator impacting a vehicle (such as a forklift) into the cask at the design speed
- Operator causing a forklift impact at higher than the design speed coupled with failure of the forklift speed control.



Source: Original

Figure B6.2-1. Typical Side Impact Fault Tree

Figure B6.2-2 is identical to Figure B6.2-1 except for the addition of another cause of a side impact, and the spurious movement of the CTT during cask loading which is described in Attachment B3.



Source: Original

Figure B6.2-2. Typical Side Impact with Spurious Movement of CTT Fault Tree

B6.3 IMPACT TO A CASK DUE TO SPURIOUS MOVEMENT

These trees involve impacts to or a tip over the transportation cask due to operator error or spurious movements of the crane or CTT. Table B6.3-1 lists the fault trees that describe these impacts.

Table B6.3-1. Transportation Cask Impact or Tipover Fault Trees

Fault Tree Name	Applies to ESD	Applies To
51A-CRANE-SPURMOVE	ESD-02	HLW Transportation Cask
	ESD-03	HLW Transportation Cask
	ESD-04	NVL Transportation Cask
51A-CTT-SPURMOVE	ESD-02	HLW Transportation Cask
*ESD01-NVL-TIPOVER	ESD-01	NVL Transportation Cask
*ESD02-HLW-TIP-CSK	ESD-02	HLW Transportation Cask

Table B6.3-1. Transportation Cask Impacts or Tipover Fault Trees (Continued)

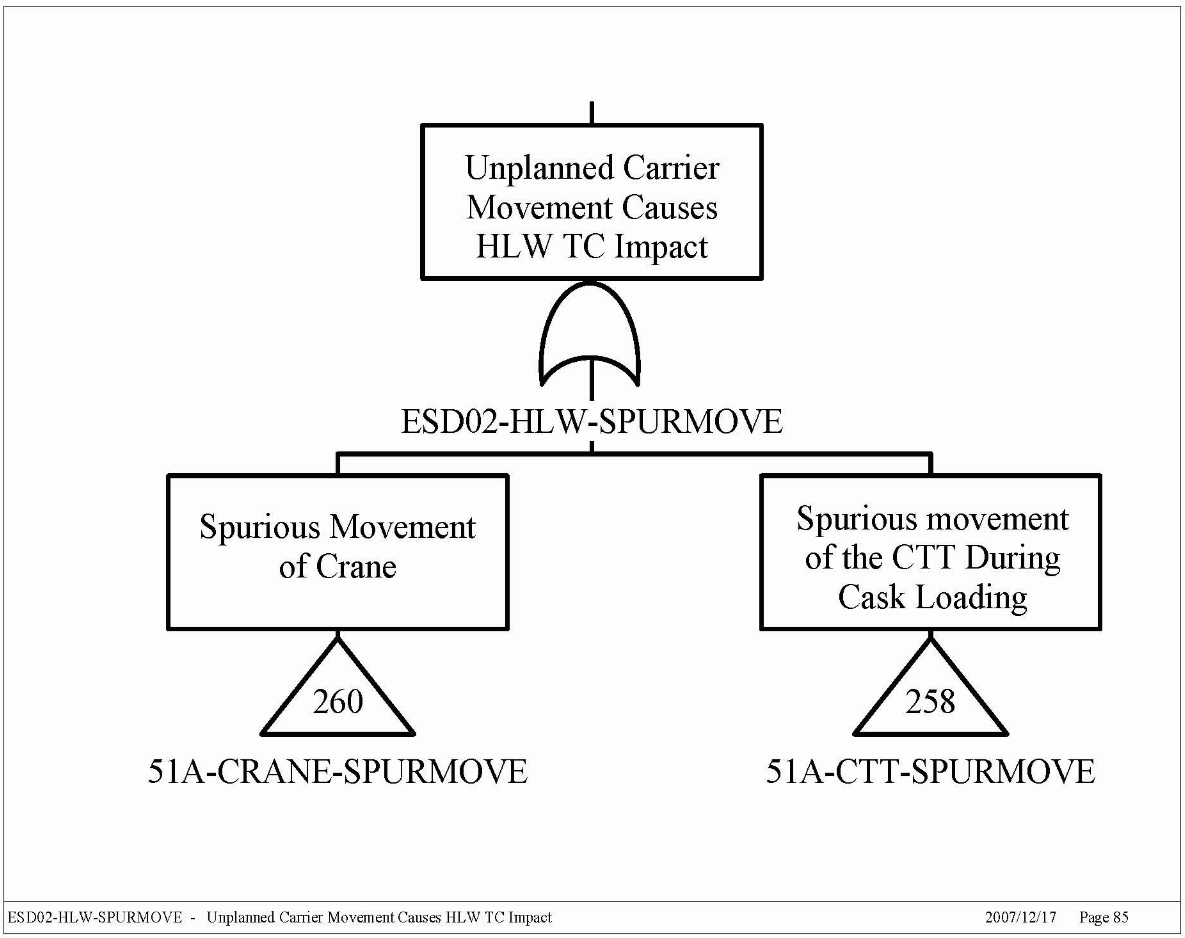
Fault Tree Name	Applies to ESD	Applies To
ESD03-HLW-CASKTIP	ESD-03	HLW Transportation Cask
ESD04-NVL-CASKTIP	ESD-04	NVL Transportation Cask
ESD05-HLW-CASKTIP	ESD-05	HLW Transportation Cask

NOTE: Entries marked with * are human failure events and are detailed in Section 6.4 and Attachment E.

CTT = cask transport trolley; HLW = high level waste; NVL = naval; SPURMOVE = spurious movement.

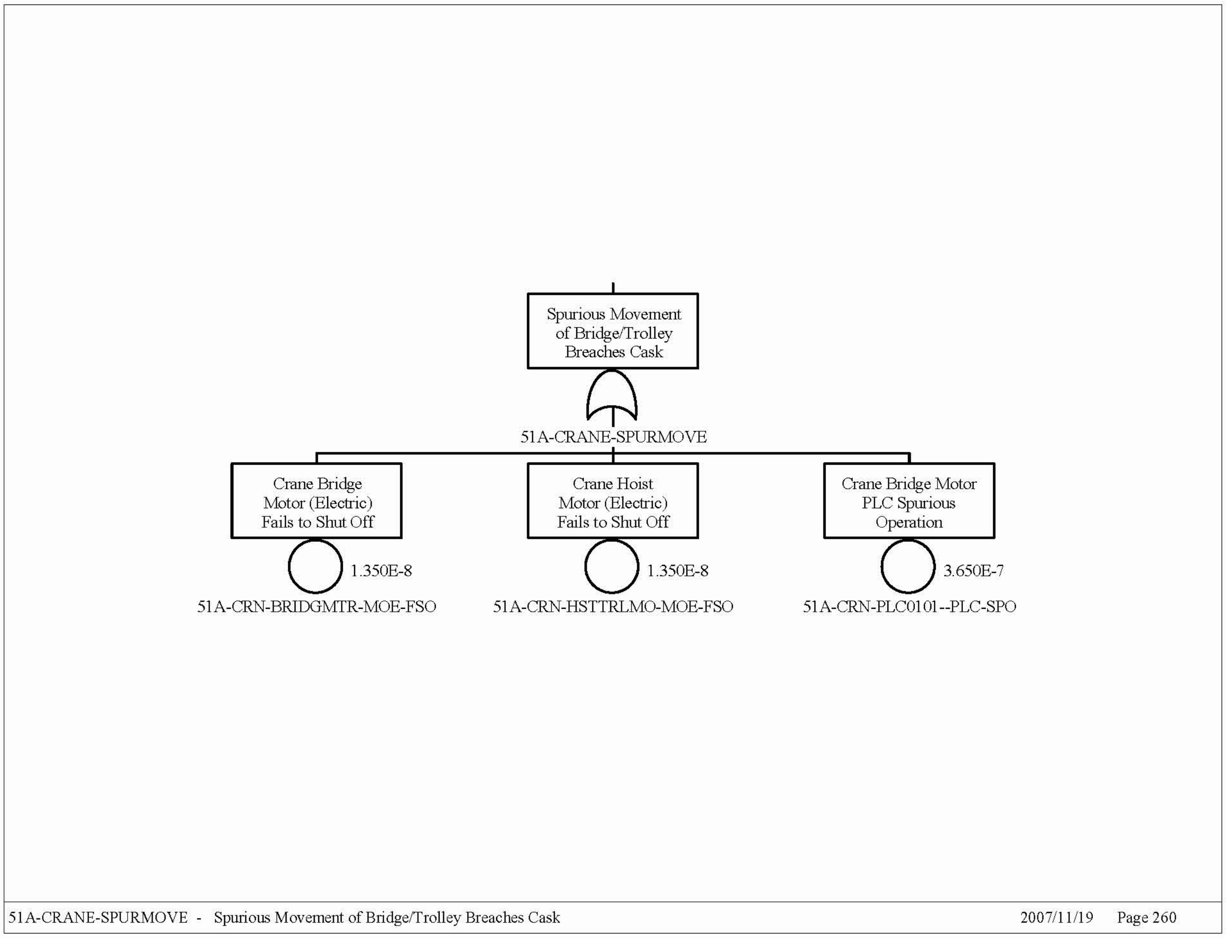
Source: Original

Figure B6.3-1 describes an impact to a cask due to spurious movement of the CTT during loading or spurious movement of the crane. The fault tree for spurious movement of the CTT is described in Attachment B. Spurious movement of the crane fault tree is shown in Figure B6.3-2. Spurious movement of the crane may occur due to failure of either the crane bridge or hoist motor to shut off, or spurious signals from the crane bridge motor PLC.



Source: Original

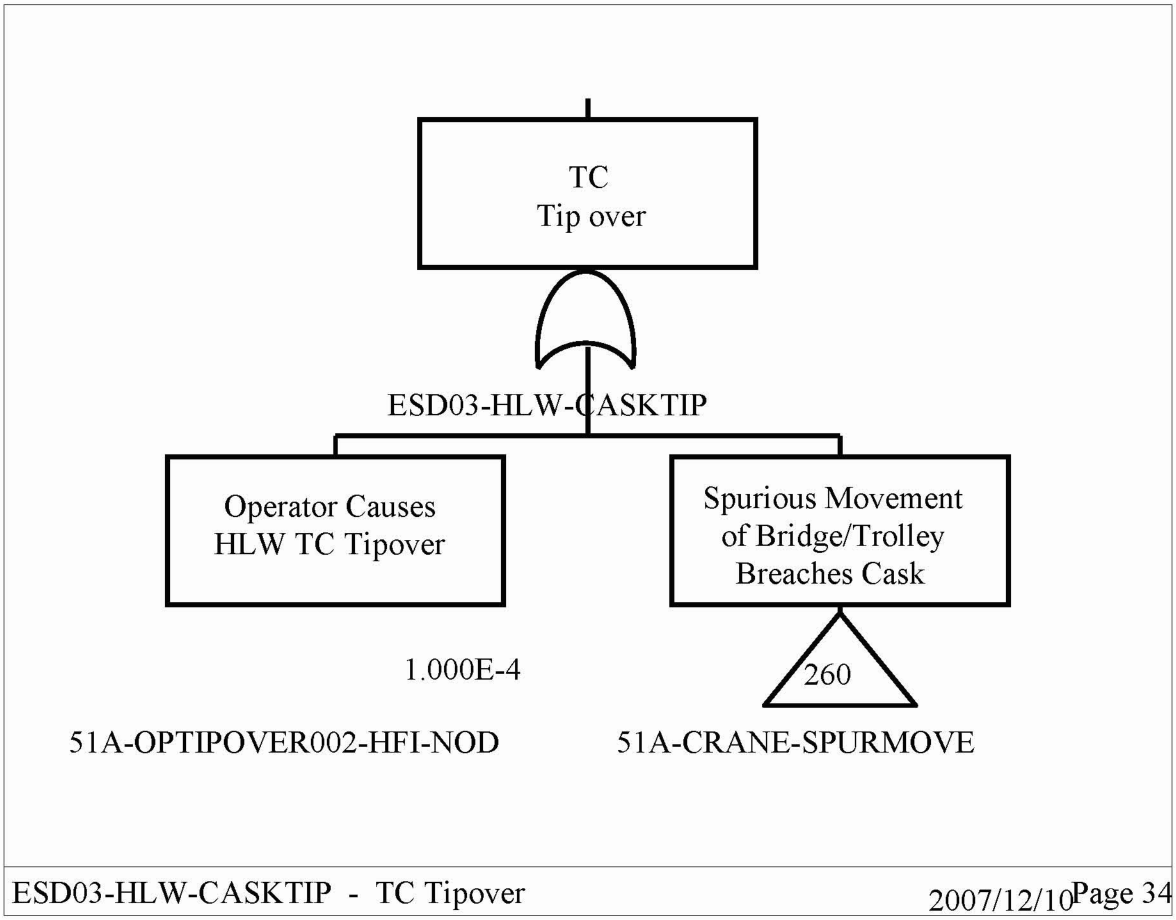
Figure B6.3-1. Spurious Movement of the Crane or CTT Fault Tree



Source: Original

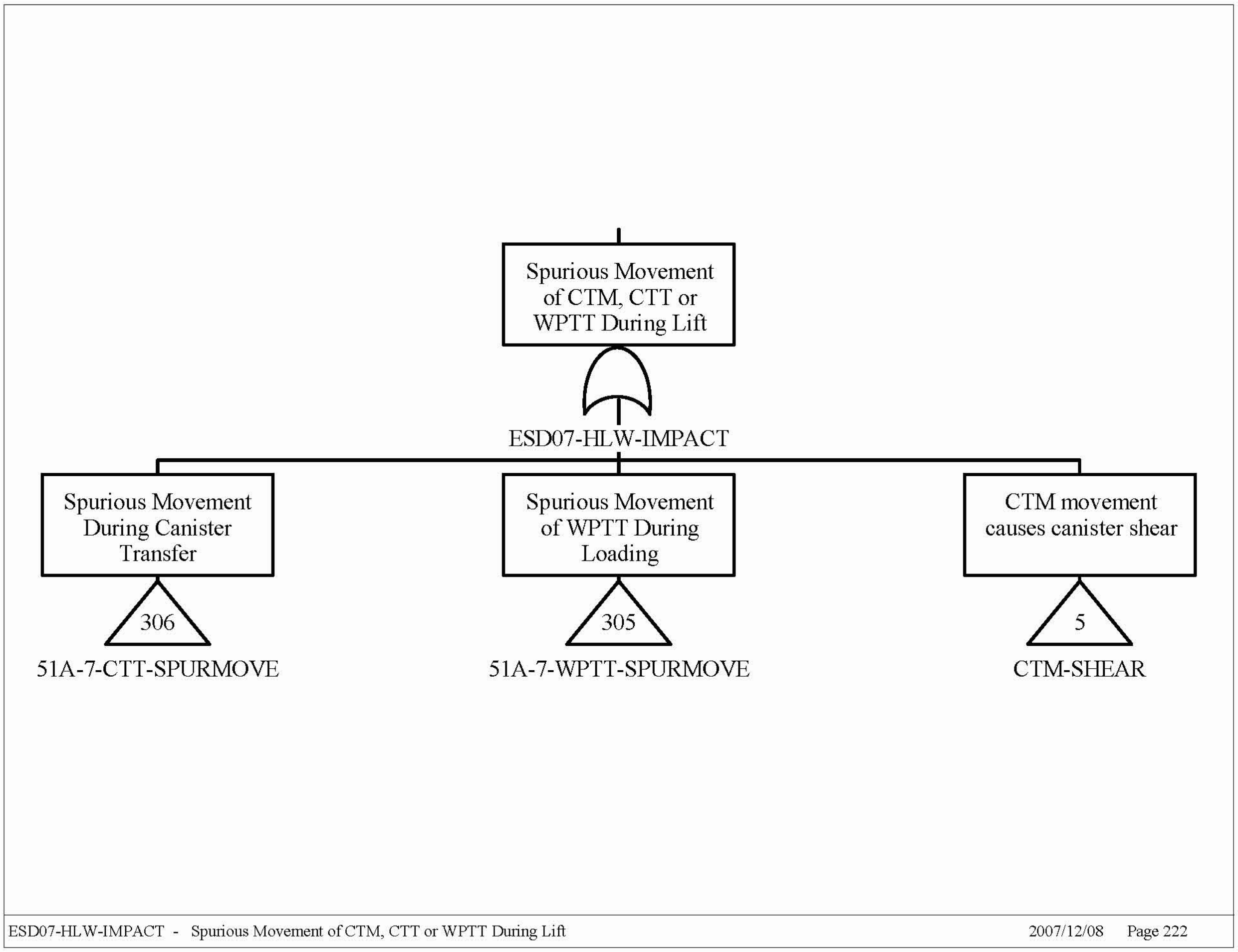
Figure B6.3-2. Spurious Movement of the Crane Fault Tree

Impacts due to a tip over may be caused by operator error or spurious movement of the crane as shown in Figure B6.3-3. The calculated probability of a tipover is 1.004E-04 due to the overriding influence of operator error causing the tipover.



Source: Original

Figure B6.3-3. Typical Tipover Fault Tree



Source: Original

Figure B6.3-4. Fault Tree for Spurious Movement CTM, CTT or WPTT during Lift

Figure B6.3-4 illustrates the fault tree for impact to a canister caused by spurious movement of the CTT during unloading of the transportation cask, the WPTT during loading of the WP, or the CTM during transfer of the canister. The calculated mean probability of an impact due to spurious movement of the carriers is 6.948E-09. Fault trees for the various spurious movements are addressed in their respective sections in Attachment B.

B6.4 LOSS OF SHIELDING LEADING TO DIRECT EXPOSURE

These fault trees describe direct exposure during canister transfer or while closing the waste package. Table B6.4-1 lists the fault trees that describe these direct exposures.

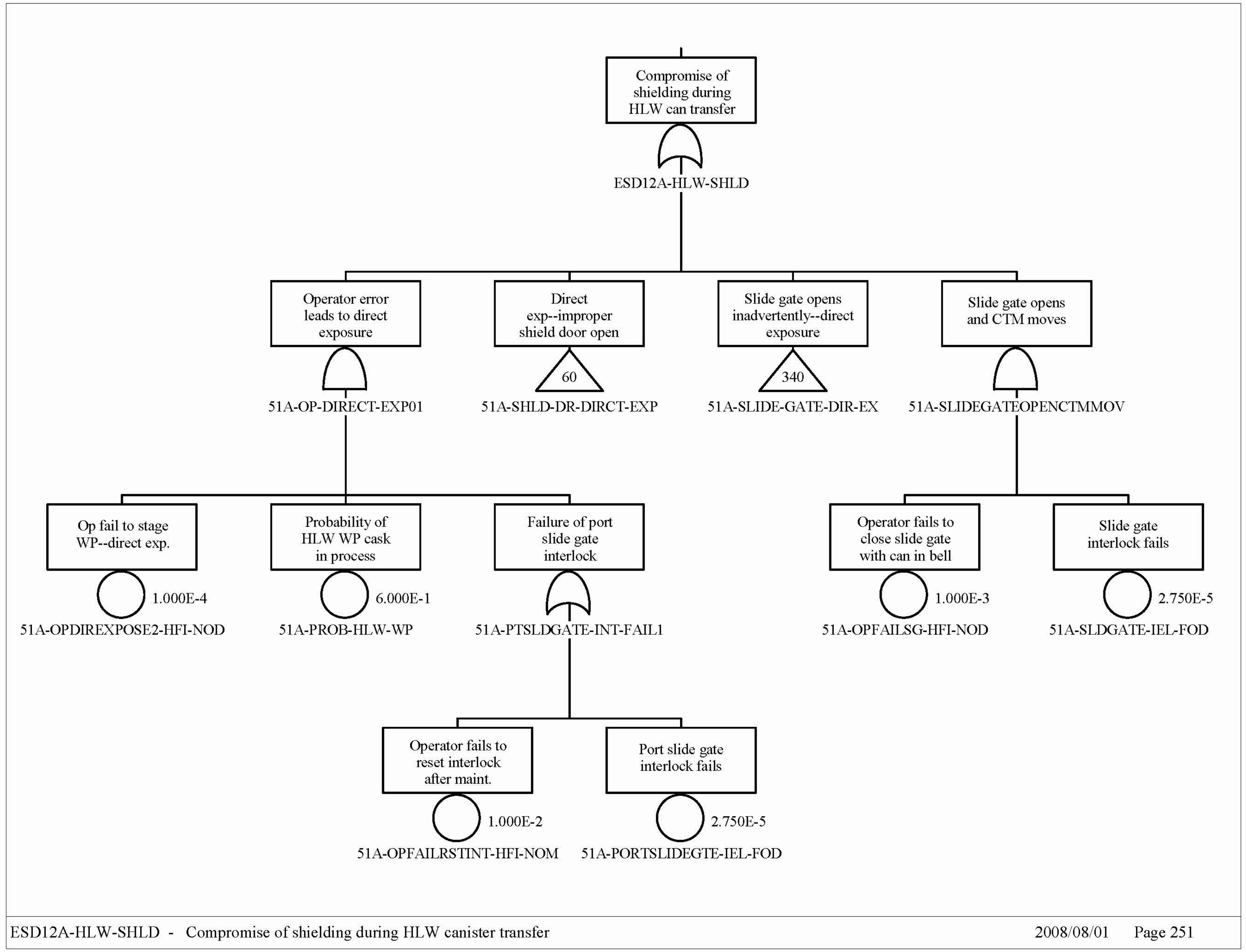
Table B6.4-1. Direct Exposure Fault Trees

Fault Tree Name	Applies To
ESD12A-HLW-SHLD	HLW canister
ESD12A-NVL-SHLD	Naval canister
ESD12B-HLW-SHLD	HLW canister in WP
ESD12B-NVL-SHLD	Naval canister in WP

NOTE: HLW = high-level radioactive waste; NVL = naval; SHLD = shielding; WP = waste package.

Source: Original

Figure B6.4-1 illustrates the potential causes of direct exposure during canister transfer. The potential causes include operator error coupled with interlock failures, and inadvertent opening of the shield door or slide gate. Fault trees for inadvertent opening of the shield door or slide gate are described in "Loading/Unloading Room Shield Door and Slide Gate Fault Tree Analysis" in Attachment B. The calculated probability of a direct exposure during this canister transfer is 1.954E-06.



Source: Original

Figure B6.4-1. Typical Direct Exposure Fault Tree due to Shield Door or Slide Gate Opening

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Figure B6.4-2 is a fault tree for direct exposure from a HLW waste package that has been improperly closed or shielded. The causes are improper installation of the waste package shield ring due to operator error (Figure B6.4-3), failure to properly install the shield ring or improper installation of the inner lid during closure (Figure B6.4-4). The calculated probability of a direct exposure from improper shield ring installation is 1.01E-04.

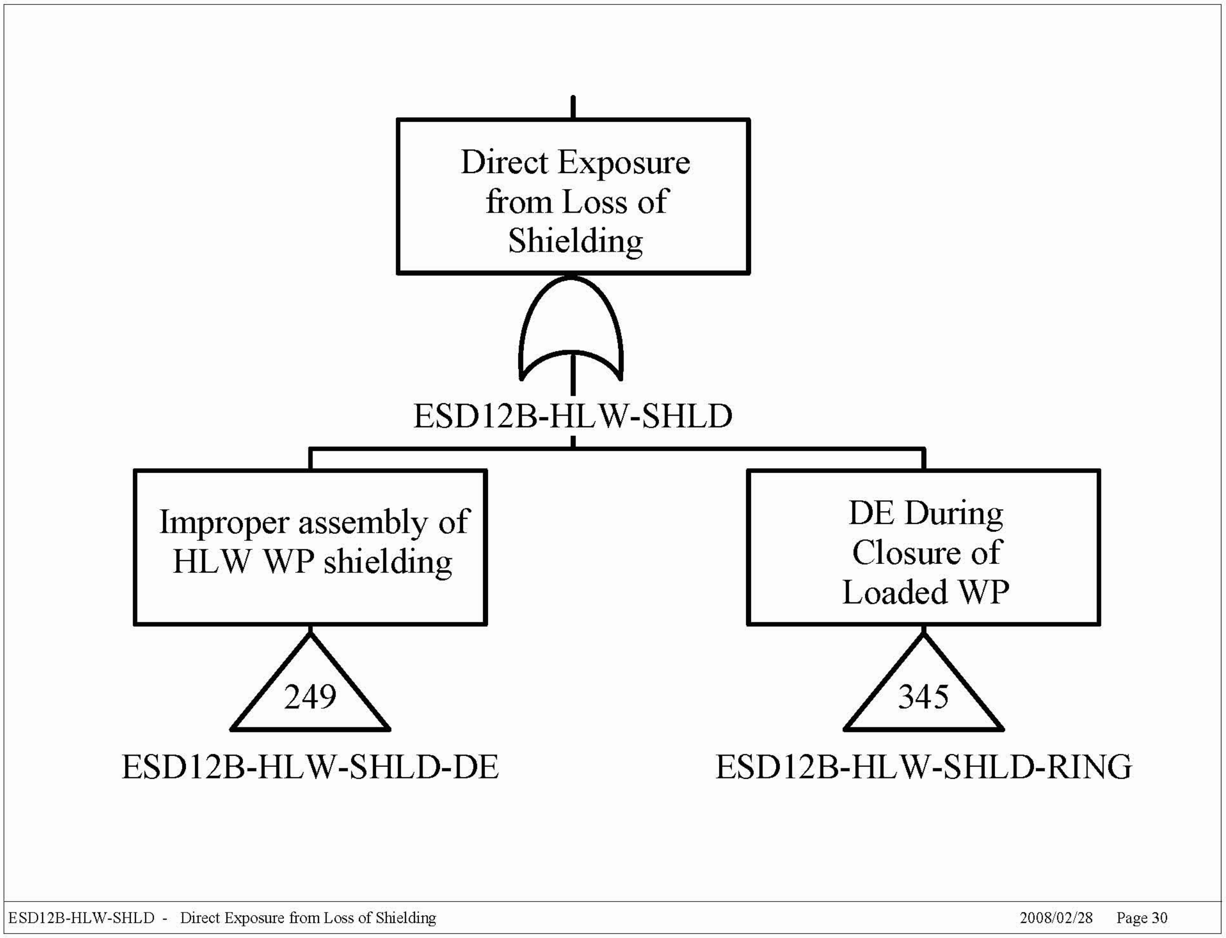


Figure B6.4-2. Direct Exposure from HLW due to Loss of Shielding

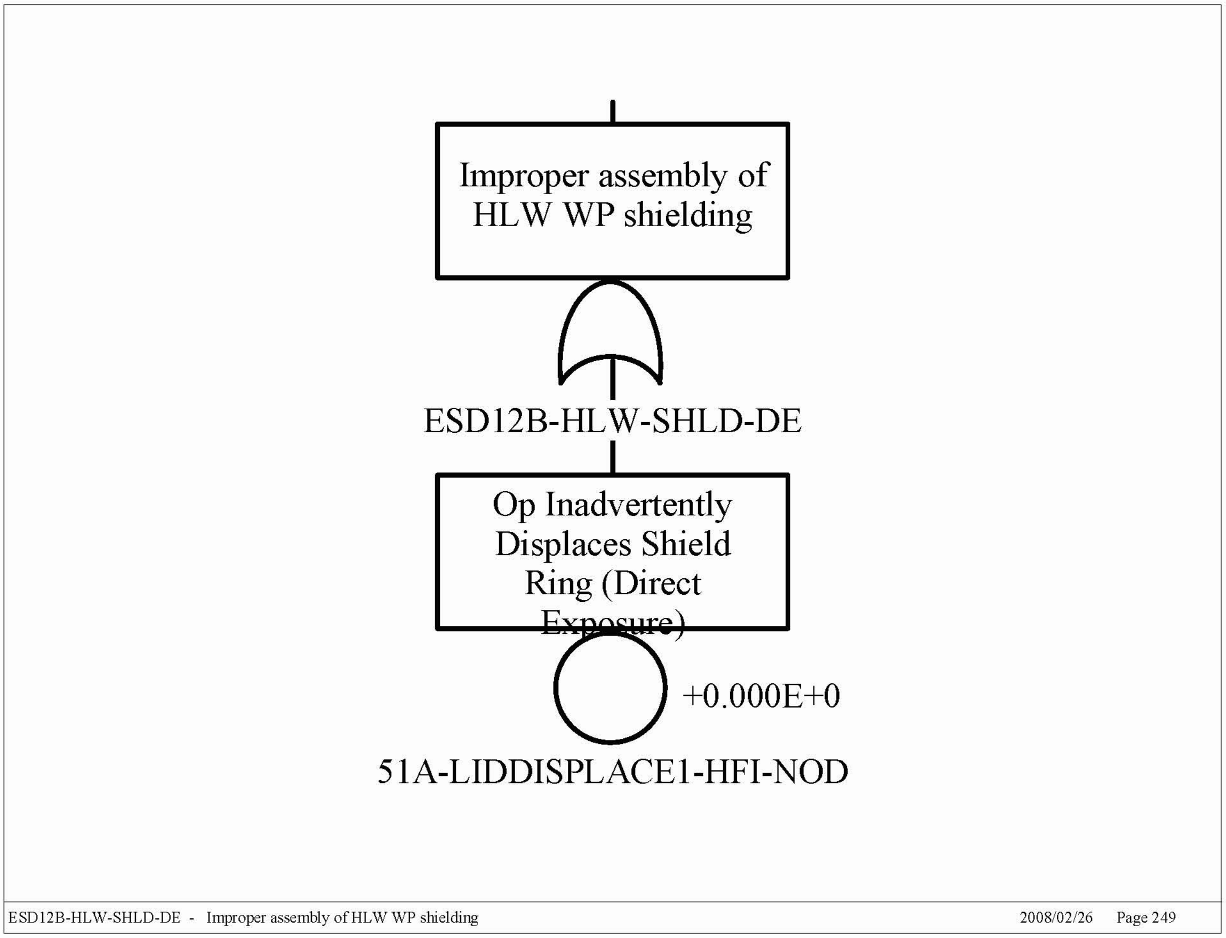


Figure B6.4-3. Direct Exposure from HLW due to Improper Assembly of Shield Ring

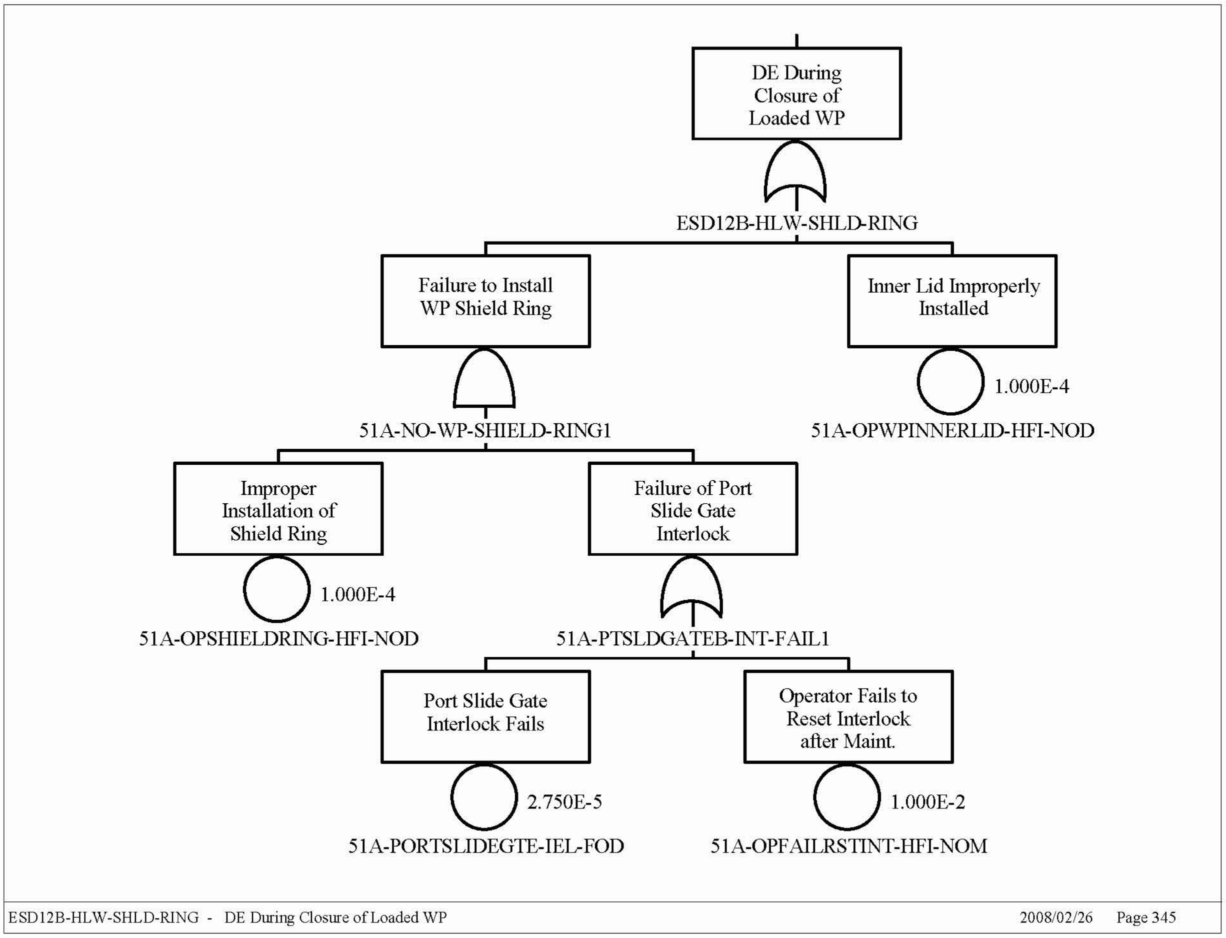


Figure B6.4-4. Direct Exposure from HLW during Closure of the WP

Figure B6.4-5 is a fault tree for direct exposure from a NVL waste package that has been improperly closed or shielded. Direct exposure results from improper assembly of the waste package shield ring or inadvertently displacement of the shield ring due to operator error (Figure B6.4-6). Direct exposure will also result from failure to properly install the shield ring or the improper installation of the inner lid during closure (Figure B6.4-4). The calculated probability of a direct exposure from improper shield ring installation is 4.01E-04.

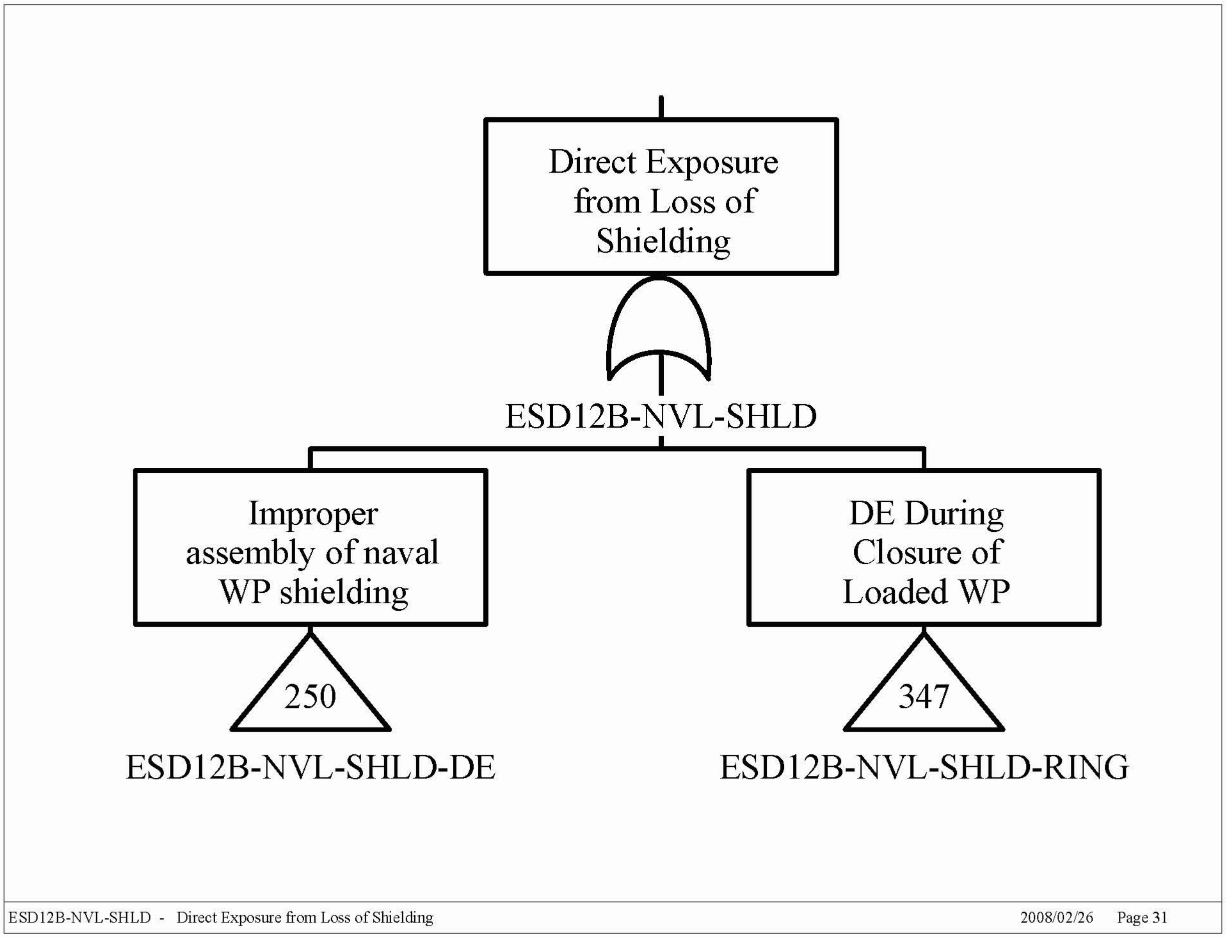


Figure B6.4-5. Direct Exposure from NVL Canister due to Loss of Shielding

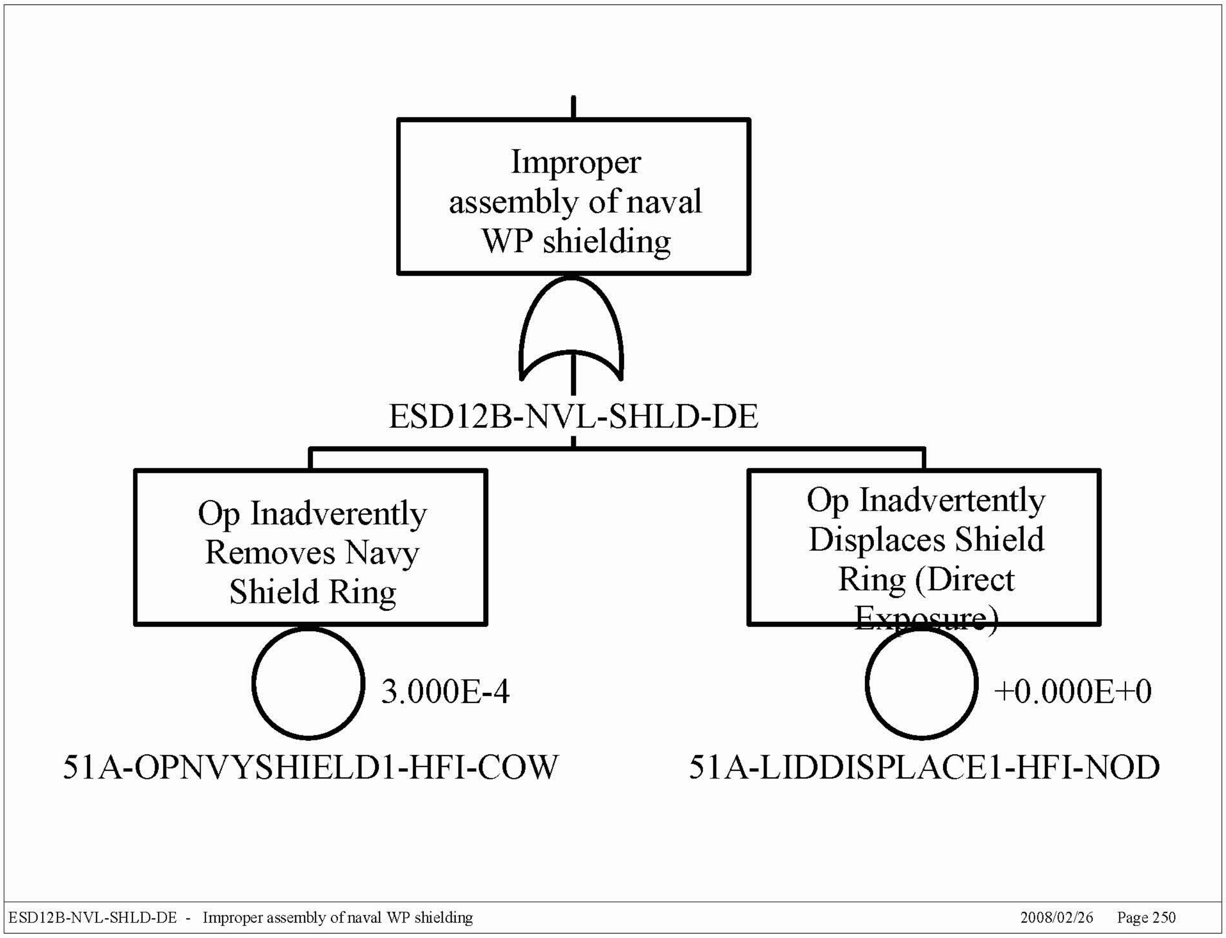


Figure B6.4-6. Direct Exposure from NVL Canister due to Improper Assembly of Shield Ring

B6.5 MODERATOR SOURCE

Internal floods are potential sources of moderator addition into a canister associated with pivotal events in the event sequences included in Section 6.1. Moderator intrusion into a canister can occur following a breach of the canister and a subsequent internal flooded. Table B6.5-1 lists the fault trees that describe the moderator events during IHF operations. It should be noted that HLW criticality is not affected by the presence of a moderator source; therefore, the moderator value for HLW sequences dealing with radiological releases important to criticality are set to "0.00E+00."

Table B6.5-1 Moderator Events during IHF Operations

Fault Tree Name	Applies To
MOD-NOFIRE	Transportation casks, canisters, and waste packages
MOD-FIRE	Transportation casks, canisters, and waste packages

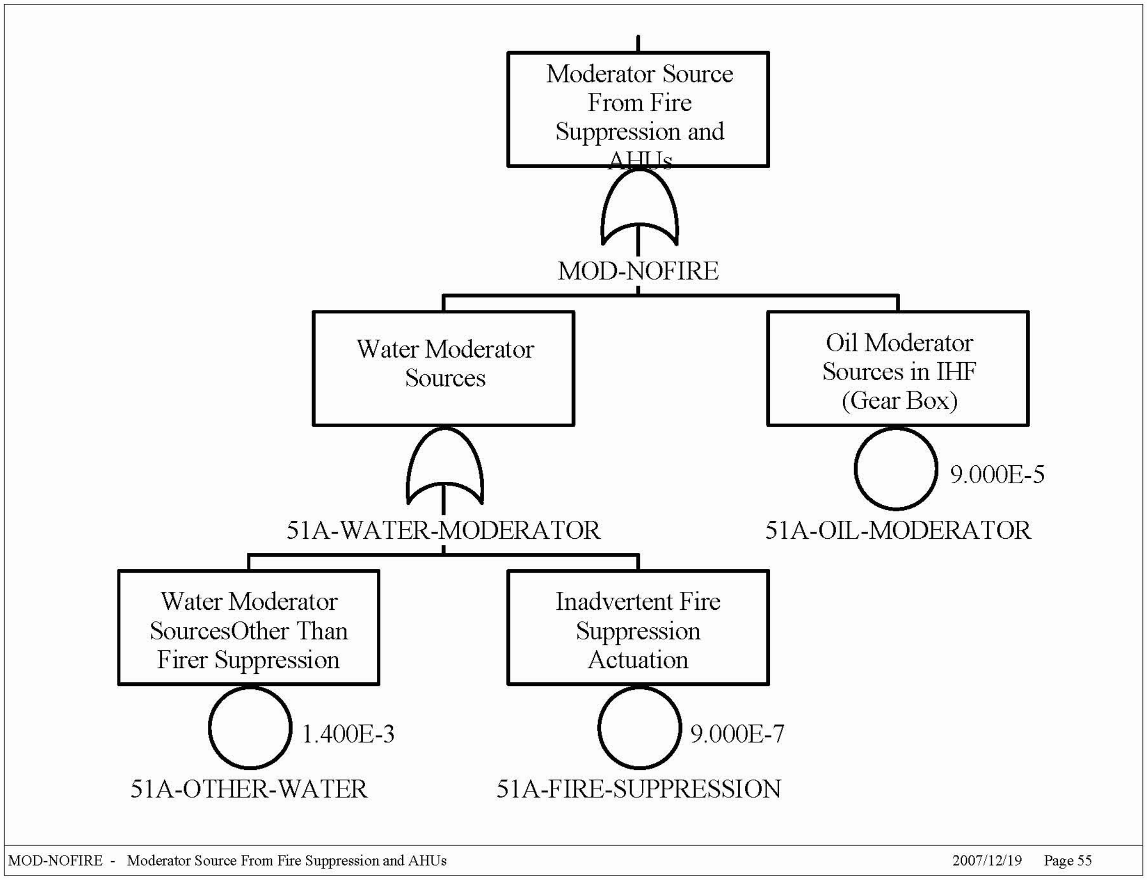
NOTE: MOD = moderator.

Source: Original

Figure B6.5-1 illustrates the possibility of a moderator source during normal operations in the IHF. Potential sources are:

- Oil from the 300-ton crane gear box
- Water from an inadvertent activation of the fire suppression system or air handling unit (AHU)
- Water from other sources in the facility (i.e., water pipe).

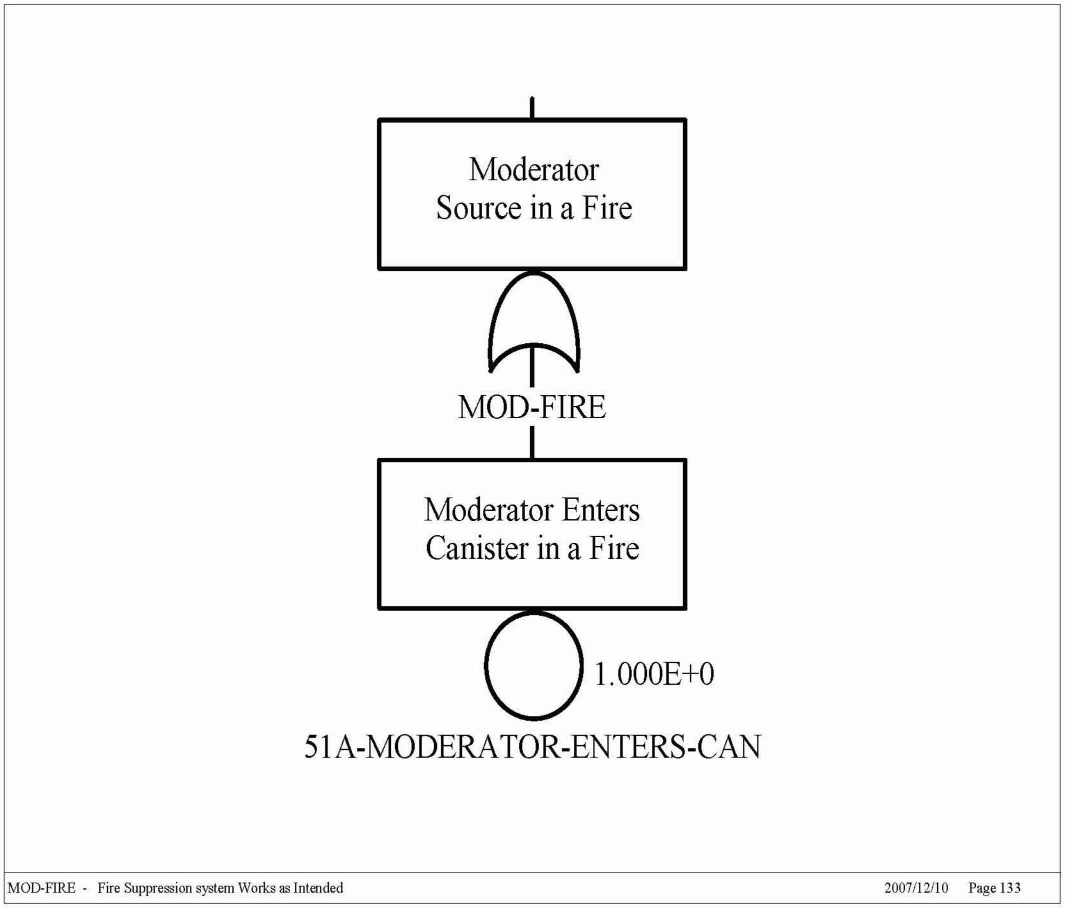
Details on moderator source failures are addressed in Section 6.2.2.6. The calculated probability of a moderator being present when there is no facility fire is 1.493E-03.



Source: Original

Figure B6.5-1. Moderator Source from Fire Suppression and AHUs

Figure B6.5-2 addresses the possibility of a moderator entering a breached transportation cask, canister, or waste package during a facility fire in the IHF. A conservative conditional probability, given a breach, of 1.00E+00 has been established for this event.



Source: Original

Figure B6.5-2. Moderator Source in a Fire

ATTACHMENT C
ACTIVE COMPONENT RELIABILITY DATA ANALYSIS

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ACRONYMS AND ABBREVIATIONS

Acronyms

CCCG	common-cause component group
CCF	common-cause failure
GROA	geologic repository operations area
HVAC	heating, ventilation, and air conditioning
NRC	U.S. Nuclear Regulatory Commission
PCSA	preclosure safety analysis
PRA	probabilistic risk assessment
SFTM	spent fuel transfer machine
TYP-FM	component type and failure mode code
YMP	Yucca Mountain Project

Abbreviations

hr	hour

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ATTACHMENT C
ACTIVE COMPONENT RELIABILITY DATA ANALYSIS

The purpose of component-level reliability data analysis is to provide reliability information for logic model quantification at the appropriate level agreed upon by the systems and data analysts. In this report, the term data is taken to mean reliability data analyzed as part of the preclosure safety analysis (PCSA) from published sources. The fault tree models described in Section 4.3.2 include random failures of active mechanical equipment as basic events. In order to numerically solve these models, estimates of the likelihood of failure of these equipment basic events are needed. This attachment provides a summary of the approach for developing these active component reliability estimates by gathering and reviewing industry-wide data, and applying Bayesian combinatorial methods to develop mean values and uncertainty bounds that best represented the range of the industry-wide information. The discussion also addresses the method used for estimating the probability of common-cause failures (CCF) among multiple components. Finally, a table is given showing the template data values input to the Yucca Mountain Project (YMP) PCSA SAPHIRE models (Section 4.2).

C1 INDUSTRY-WIDE COMPONENT RELIABILITY DATA

While data from the facility being studied is the preferred source of equipment failure rate information, it is common in a safety analysis for information from other facilities in the same industry to be used when facility-specific data is sparse or unavailable. Because the YMP activities are atypical of nuclear power plant activities and no operating history exists, it was necessary to develop the required data from the experience of other industries.

C1.1 COMPONENT DEFINITION

The purpose of component-level data analysis is to provide reliability information for logic model quantification at the appropriate level agreed upon by the systems and data analysts. To do this, it is necessary to clearly define component types, boundaries, and failure modes. The system analysis fault tree basic events identify the component and failure mode combinations requiring data, and the analysts' descriptions provide an understanding of the component operating environments. In response to these identified data needs, the data analysts compile data at the component failure mode level for input to the SAPHIRE models. However, this is best achieved via an iterative process between the system and data analysts to ensure that all basic events are properly quantified with appropriate failure data estimates.

1. Component Type. Corresponds to the category of equipment at the level for which data is required by the logic model and at which data will be developed by the data analyst. Examples of such component types are motor-driven pumps, cameras, diesel generators, and heat exchangers. For certain complex components, a larger component type such as the canister transfer machine is likely to be broken down by the system analyst in the logic model into constituent component types including motors and brakes, not only to facilitate the data analysis but to evaluate the contribution of various subcomponents to the overall component failure.

2. Component Boundaries. The boundary definition task is closely connected with the tasks of defining systems boundaries and fault tree construction. Therefore this task is performed jointly with the system analysts.

3. Failure Mode. Failure mode is defined as an undesirable component state (e.g., normally closed motor operated valve doesn't open on demand because of valve mechanical damage that occurred before the demand itself).

4. Selection of Model and Parameters. Stochastic models of failures of different systems component are defined for component failure probability estimation depending on the system operational mode. A set of available models is given in SAPHIRE for Windows and includes the following:

   A. Components of stand-by systems. The main parameter of stand-by system is the unavailability upon demand. Such system unavailability can be modeled by fault tree, where basic events probabilities are equal to system components unavailabilities averaged by time. This model treats the time to failure as a random value with exponential distribution. Such component unavailability is the function of time. In case of periodic test, unavailability is a periodic function of time. For simplifying the calculation, time dependency is usually replaced by the average value over the considered interval. For periodically tested components, the interval average is the average value for the test interval.

      Three types of stand-by system components are identified:

      1) Periodically tested stand-by components. For such components it is necessary to estimate following parameters: failure rate, probability of failure per demand, average restoring time (for repair), and average outage time due to test and maintenance.

      2) Non-tested stand-by component. For such components, the exposure time is set to unit projected operation time for calculation of unavailability. But often the component is tested indirectly or replaced. For example, if the system gets a real actuation signal, the state of the non-tested component can be determined. In this case, the average time to failure for a component is set to the average interval between system actuations. In some instances, the component can be replaced along with the tested components. In this case, test interval for non-tested component is set to average time to failure of tested component.

      3) Monitored components. State of some stand-by components is tested continuously (monitoring). In this case component failure is revealed immediately.

B. Components of systems in operation. For systems in operation, the most important parameter is the probability of failure during the defined mission time. This probability may be estimated based on fault trees or another logic model, where basic event probabilities are set to unavailabilities of components over the interval mission time. Failures of operating components are modeled using an exponentially distribution with a failure rate different from the failure rate in stand-by mode.

   Operating systems contain two main types of components: restorable and non-restorable.

   1) Non-restorable components. Components that cannot be restored in case of failure. Exponential distribution of time between failures for such components is characterized by failure rate, λ.

   2) Restorable components. Components that may be restored in case of failure. In this case restoration means restoration without outage of operation.

C. Stand-by systems following demand. Stand-by systems must fulfill a specific function during the defined time after successful start. During this time such systems are described in the same way as operating systems.

D. Constant probability per demand. The model treats component failure probability as a fixed probability for every demand. For such components, tests are excluded from consideration.

For YMP, the operational mode of failure and standby failures predominate; therefore, constant failure rates and constant probabilities per demand were constructed.

Component types and failure modes were initially identified based upon a listing of the components considered to be likely to be encountered in the analysis. This list was compiled from expertise in database development and familiarity with general component requirements in a variety of facilities. As the fault tree modeling progressed, this list was augmented and tailored to the specific active components included in the PCSA models based on the YMP design.

Correspondingly, it was necessary to develop an active component and failure mode coding scheme that would be consistent with the fault tree model basic events, the needs of the SAPHIRE models, as well as with standard repository naming conventions for YMP equipment types.

The YMP PCSA basic event naming convention was therefore developed to incorporate the following information in the 24 character basic event name (consistent with the basic event field in SAPHIRE):

- Area code – physical design or construction area where a component would be installed

- System locator code – operational systems and processes

- Component function identifiers – component function
- Sequence code – numeric sequence and train assignment
- Component type code – three character identifier for general component type, such as battery, actuator, or pump
- Failure mode code – three character identifier for the way in which the component is considered in the fault tree models to have failed, (e.g., FTS for fails to start or FOD for fails on demand).

The area, system locator, and component function codes were obtained from engineering standards from the YMP repository as a whole to be consistent with overall site naming conventions. The sequence codes were taken from the component identification numbers on project drawings, if the design had progressed to that point at the time of the data development and modeling.

Active component type codes were developed to be consistent with the component function identifiers, but since the type codes were limited to three digits and the function identifiers were occasionally four-characters long, in some instances it was necessary to truncate the identifier to construct the type code.

Failure mode codes (FM) were developed using prior database conventions or abbreviations that would be as intuitively obvious as possible.

Both type (TYP) and failure mode were limited to three characters each in order to be consistent with the input constraints and conventions of the SAPHIRE template database feature, which allows the same component failure data to be applied to all items in the model.

A list of the component type and failure mode combinations is provided in Table C1.1-1.

Industry-wide data sources were then collected and reviewed to identify failure rates per hour or failure probabilities per demand that would be relevant to all of the TYP-FM combinations.

Table C1.1-1. YMP PCSA Component Types (TYP) and Failure Modes (FM)

TYP-FM	Component Name & Failure Mode
AHU-FTR	Air Handling Unit Failure to Run
ALM-SPO	Alarm/Annunciator Spurious Operation
AT-FOH	Actuator (Electrical) Failure
ATH-FOH	Actuator (Hydraulic) Failure
ATP-SPO	Actuator (Pneumatic Piston) Spurious Operation
AXL-FOH	Axle Failure
B38-FOH	Bearing Failure
BEA-BRK	Lifting Beam/Boom Breaks
BLD-RUP	Air Bag Ruptures
BLK-FOD	Block or Sheaves Failure on Demand

Table C1.1-1. YMP PCSA Component Types (TYP) and Failure Modes (FM) (Continued)

TYP-FM	Component Name & Failure Mode
BRH-FOD	Brake (Hydraulic) Failure on Demand
BRK-FOD	Brake Failure on Demand
BRK-FOH	Brake (Electric) Failure
BRP-FOD	Brake (Pneumatic) Failure on Demand
BRP-FOH	Brake (Pneumatic) Failure
BTR-FOD	Battery No Output Given Challenge
BTR-FOH	Battery Failure
BUA-FOH	AC Bus Failure
BUD-FOH	DC Bus Failure
BYC-FOH	Battery Charger Failure
C52-FOD	Circuit Breaker (AC) Fails on Demand
C52-SPO	Circuit Breaker (AC) Spurious Operation
C72-SPO	Circuit Breaker (DC) Spurious Operation
CAM-FOH	Cam Lock Fails
CBP-OPC	Cables (Electrical Power) Open Circuit
CBP-SHC	Cables (Electrical Power) Short Circuit
CKV-FOD	Check Valve Fails on Demand
CKV-FTX	Check Valve Fails to Check
CON-FOH	Electrical Connector (Site Transporter) Failure
CPL-FOH	Coupling (Automatic) Failure
CPO-FOH	Control system Onboard (TEV or Trolley) Failure
CRD-FOH	Badge/Card Reader Failure
CRN-DRP	200-Ton Crane Load Drop
CRN-TBK	200-Ton Crane Two-Blocking Load Drop
CRS-DRP	Crane using Slings Load Drop
CRW-DRP	Waste Package Crane Load Drop
CRW-TBK	Waste Package Crane Two-Blocking Load Drop
CSC-FOH	Cask Cradle Failure
CT-FOD	Controller Mechanical Jamming
CT-FOH	Controller Failure
CT-SPO	Controller Spurious Operation
CTL-FOD	Logic Controller Fails on Demand
DER-FOM	Derailment Failure per Mile
DG-FTR	Diesel Generator Fails to Run
DG-FTS	Diesel Generator Fails to Start
DGS-FTR	Diesel Generator - Seismic - Fails to Run for 29 Days
DM-FOD	Drum Failure on Demand
DM-MSP	Drum Misspooling (Hourly)
DMP-FOH	Damper (Manual) Fails to Operate
DMP-FRO	Damper (Manual) Fails to Remain Open (Transfers Closed)
DMS-FOH	Demister (Moisture Separator) Failure

Table C1.1-1. YMP PCSA Component Types (TYP) and Failure Modes (FM) (Continued)

TYP-FM	Component Name & Failure Mode
DRV-FOH	Drive (Adjustable Speed) Failure
DTC-RUP	Duct Ruptures
DTM-FOD	Damper (Tornado) Failure on Demand
DTM-FOH	Damper (Tornado) Failure
ECP-FOH	Position Encoder Failure
ESC-FOD	Emergency Stop Button Controller Failure to Stop (on Demand)
FAN-FTR	Fan (Motor-Driven) Fails to Run
FAN-FTS	Fan (Motor-Driven) Fails to Start on Demand
FRK-PUN	Forklift Puncture
G65-FOH	Governor Failure
GPL-FOD	Grapple Failure on Demand
GRB-FOH	Gear Box Failure
GRB-SHH	Gear Box Shaft/Coupling Shears
GRB-STH	Gear Box Stripped
HC-FOD	Hand Held Radio Remote Controller Fails to Stop (on Demand)
HC-SPO	Hand Held Radio Remote Controller Spurious Operation
HEP-LEK	Filter (HEPA) Leaks (Bypassed)
HEP-PLG	Filter (HEPA) Plugs
HOS-LEK	Hose Leaking
HOS-RUP	Hose Ruptures
IEL-FOD	Interlock Failure on Demand
IEL-FOH	Interlock Failure
LC-FOD	Level Controller Failure on Demand
LRG-FOH	Lifting Rig or Hook Failure
LVR-FOH	Lever (Two Position; Up-Down) Failure
MCC-FOH	Motor Control Centers (MCCs) Failure
MOE-FOD	Motor (Electric) Fails on Demand
MOE-FSO	Motor (Electric) Fails to Shut Off
MOE-FTR	Motor (Electric) Fails to Run
MOE-FTS	Motor (Electric) Fails to Start (Hourly)
MOE-SPO	Motor (Electric) Spurious Operation
MOH-FOH	Motor (Hydraulic) Failure
MSC-FOH	Motor Speed Control Module Failure
MST-FOH	Motor Starter Failure
NZL-FOH	Nozzle Failure
PIN-BRK	Pin (Locking or Stabilization) Breaks
PLC-FOD	Programmable Logic Controller Fails on Demand
PLC-FOH	Programmable Logic Controller Fails to Operate
PLC-SPO	Programmable Logic Controller Spurious Operation
PMD-FTR	Pump (Motor Driven) Fails to Run
PMD-FTS	Pump (Motor Driven) Fails to Start on Demand

Table C1.1-1. YMP PCSA Component Types (TYP) and Failure Modes (FM) (Continued)

TYP-FM	Component Name & Failure Mode
PPL-RUP	Piping (Lined) Catastrophic
PPM-PLG	Piping (Water) Plugs
PPM-RUP	Piping (Water) Ruptures
PR-FOH	Passive Restraint (Bumper) Failure
PRM-FOH	EPROM (HVAC Speed Control) Failure
PRV-FOD	Pressure Relief Valve Fails on Demand
PV-SPO	Pneumatic Valve Spurious Operation
QDV-FOH	Quick Disconnect Valve Failure
RCV-FOH	Air Receiver Fails to Supply Air
RLY-FTP	Relay (Power) Fails to Close/Open
SC-FOH	Speed Control Failure
SC-SPO	Speed Control Spurious Operation
SEL-FOH	Speed Selector Fails
SEQ-FOD	Sequencer Fails on Demand
SFT-COL	Spent Fuel Transfer Machine Collision/Impact
SFT-DRP	Spent Fuel Transfer Machine Fuel Drop
SFT-RTH	Spent Fuel Transfer Machine Fuel Raised Too High
SJK-FOH	Screw jack (TEV) Failure
SRF-FOH	Flow Sensor Failure
SRP-FOD	Pressure Sensor Fails on Demand
SRP-FOH	Pressure Sensor Fails
SRR-FOH	Radiation Sensor Fails
SRS-FOH	Over Speed Sensor Fails
SRT-FOD	Temperature Sensor/Transmitter Fails on Demand
SRT-FOH	Temperature Sensor/Transmitter Fails
SRT-SPO	Temperature Sensor Spurious Operation
SRU-FOH	Ultrasonic Sensor Fails
SRV-FOH	Vibration Sensor (Accelerometer) Fails
SRX-FOD	Optical Position Sensor Fails on Demand
SRX-FOH	Optical Position Sensor Fails
STR-FOH	Steering (Tractor or Trailer) Failure
STU-FOH	Structure (Truck or Railcar) Failure
SV-FOD	Solenoid Valve Fails on Demand
SV-FOH	Solenoid Valve Fails
SV-SPO	Solenoid Valve Spurious Operation
SWA-FOH	Switch, Auto-Stop Fails (CTT end of Hose Travel)
SWG-FOH	13.8kV Switchgear Fails
SWP-FTX	Electric Power Switch Fails to Transfer
SWP-SPO	Electric Power Switch Spurious Transfer
TD-FOH	Transducer Failure
TDA-FOH	Transducer (Air Flow) Failure

Table C1.1-1. YMP PCSA Component Types (TYP) and Failure Modes (FM) (Continued)

TYP-FM	Component Name & Failure Mode
TDP-FOH	Transducer (Pressure) Fails
TDT-FOH	Transducer (Temperature) Fails
THR-BRK	Third Rail Breaks
TKF-FOH	Fuel Tank Fails
TL-FOH	Torque Limiter Failure
TRD-FOH	Tread (Site Transporter)
UDM-FOH	Damper (Backdraft) Failure
UPS-FOH	Uninterruptible Power Supply (UPS) Failure
WNE-BRK	Wire Rope Breaks
XMR-FOH	Transformer Failure
XV-FOD	Manual Valve Failure on Demand
ZS-FOD	Limit Switch Failure on Demand
ZS-FOH	Limit Switch Fails
ZS-SPO	Limit Switch Spurious Operation

NOTE: AC = alternating current; CTT = cask transfer trolley; DC = direct current; EPROM = erasable programmable read-only memory; HEPA = high efficiency particulate air (filter); HVAC = heating, ventilation, and air conditioning; MCC = motor control center; TEV = transport and emplacement vehicle; TYP-FM = component type and failure mode; UPS = uninterruptible power supply.

Source: Original

C1.2 INDUSTRY-WIDE RELIABILITY DATA

Industry-wide data sources are documents containing industrial or military experience on component performance. Usually they are previous safety/risk analyses and reliability studies performed nationally or internationally, but they can also be standards or published handbooks. For the YMP PCSA, an industry-wide database was constructed using a library of industry-wide data sources of reliability data from nuclear power plants, equipment used by the military, chemical processing plants, and other facilities. The sources used are listed in Table C1.2-1.

Table C1.2-1. Industry-wide Data Sources Used in YMP PCSA Active Component Reliability Database

Industry-wide Data Sources Used in YMP PCSA Active Component Reliability Database
Guidelines for Process Equipment Reliability Data with Data Tables. [CCPS] (Ref. C5.1)
Savannah River Site, Generic Data Base Development (U) [SRS Reactors] (Ref. C5.5)
The In-Plant Reliability Data Base for Nuclear Plant Components: Interim Report-The Valve Component. NUREG/CR-3154 (Ref. C5.6)
Waste Form Throughputs for Preclosure Safety Analysis.[BSC 2007](Ref. C5.7)
Probabilistic Risk Assessment (PRA) of Bolted Storage Casks, Updated Quantification and Analysis Report. [EPRI PRA] (Ref. C5.8)

Table C1.2-1. Industry-wide Data Sources Used in YMP PCSA Active Component Reliability Database (Continued)

Industry-wide Data Sources Used in YMP PCSA Active Component Reliability Database
Component Failure and Repair Data for Coal-Fired Power Units. EPRI AP-2071 [EPRI Pipe Failure Study] (Ref. C5.10)
Mechanical Reliability: Theory, Models and Applications. [AIAA] (Ref. C5.11)
Military Handbook, Reliability Prediction of Electronic Equipment. MIL-HDBK-217F [MIL-HDBK-217F] (Ref. C5.12)
The In-Plant Reliability Data Base for Nuclear Power Plant Components - Pump Component. NUREG/CR-2886. (Ref. C5.13)
Some Published and Estimated Failure Rates for Use in Fault Tree Analysis [du Pont] (Ref. C5.14)
Analysis of Station Blackout Risk. Volume 2 of Reevaluation of Station Blackout Risk at Nuclear Power Plants. NUREG/CR-6890 (Ref. C5.15)
Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants. NUREG/CR-6928. (Ref. C5.16)
"Train Accidents by Cause from Form FRA F 6180.54." [Federal Railroad Administration] (Ref. C5.17)
Summary, Commercial Nuclear Fuel Assembly Damage/Misload Study – 1985-1999. [McKenna] (Ref. C5.20)
Ruggedized Card Reader/Ruggedized Keypad Card Reader. [HID] (Ref. C5.21)
IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems. [IEEE-493] (Ref. C5.22)
IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear-Power Generating Stations. [IEEE-500] (Ref. C5.23)
The In-Plant Reliability Data Base for Nuclear Plant Components: Interim Report- Diesel Generators, Batteries, Chargers and Inverters. NUREG/CR-3831 (Ref. C5.24)
Instruments and Software Solutions (for Emergency Response and Health Physics [LAURUS] (Ref. C5.25)
A Survey of Crane Operating Experience at U.S. Nuclear Power Plants from 1968 through 2002. NUREG-1774. (Ref. C5.26)
Data Summaries of Licensee Event Reports of Valves at U.S. Commercial Nuclear Power Plants from January 1, 1976 to December 31, 1980. NUREG/CR-1363 (Ref. C5.28)
The Reliability Data Handbook. [Moss] (Ref. C5.32)
Control of Heavy Loads at Nuclear Power Plants. NUREG-0612. (Ref. C5.35)
Handbook of Reliability Prediction Procedures for Mechanical Equipment [NSWC-98-LE1] (Ref. C5.37)
"Using the EDA to Gain Insight into Failure Rates" [Rand] (Ref. C5.38)
Nuclear Computerized Library for Assessing Reactor Reliability (NUCLARR), Volume 5: Data Manual, Part 3: Hardware Component Failure Data. NUREG/CR-4639, (Ref. C5.39)

Table C1.2-1. Industry-wide Data Sources Used in YMP PCSA Active Component Reliability Database (Continued)

Industry-wide Data Sources Used in YMP PCSA Active Component Reliability Database
Nonelectronic Parts Reliability Data 1995. NPRD-95. [NPRD -95] (Ref. C5.40)
Umatilla Chemical Agent Disposal Facility Quantitative Risk Assessment. [SAIC Umatilla] (Ref. C5.41)
Offshore Reliability Data Handbook. 2nd Edition [OREDA-92] (Ref. C5.42)
Offshore Reliability Data Handbook. 4th Edition. [OREDA-2002] (Ref. C5.43)
Data Summaries of Licensee Event Reports of Pumps at U.S. Commercial Nuclear Power Plants: January 1, 1972-April 30, 1980. NUREG/CR-1205. (Ref. C5.45)
N-Reactor Level 1 Probabilistic Risk Assessment: Final Report. [N-Reactor] (Ref. C5.46)

NOTE: The code in brackets [XXXX] is used to aid the reader in identifying references in Table C4-1.

Source: Original

It was necessary to analyze the industry-wide data to compare the relevancy of the component data selected from the industry-wide data sources with the equipment in the YMP PCSA models.

The data source scope had to be sufficiently broad to cover a reasonable number of the equipment types modeled, yet with enough depth to ensure that the subject matter is appropriately addressed. For example, a separate source might have been used for electronics data versus mechanical data, so long as its use was justified by the detail and the applicability of the information provided. Lastly, the quality of the data source was considered to be a measure of the source's credibility. Higher quality data sources are based on equipment failures documented by a facility's maintenance records. Lower quality sources use either abbreviated accounts of the failure event and resulting repair activity, or do not allow the user to trace back to actual failure events. Every effort was made to use the highest quality data source available for each active component type and failure mode.

Data were selected from the industry-wide data sources using the following criteria:

- The component type (TYP) and failure mode (FM) identified in the data source had to match those in the basic events specified in the fault tree. For every component modeled, a comparison was made between the modeled component and the component found in the data source to ensure its suitability for the PCSA. Also, every attempt was made to match the failure modes. Often, the source described the failure mode as "all modes," whereas the fault tree required "fails to operate." In cases such as this, sources with more general failure modes were not used unless they were the only available sources.

- The data source had to be widely available, not proprietary. This ensured traceability and accessibility.

- Mid-level or low-level quality data sources were used only when high-level sources were not available.

- The operating environment is an important factor in the selection of data sources. The environment of a component refers not only to its physical state, but also its operational state. The operating conditions of a component include the plant's maintenance policy and testing policy. If either of these states differed from the modeled facility's state, then the data were reconsidered and usually rejected (unless no alternative existed).

A potential disadvantage of using industry-wide data is that a source may provide failure rates that are not realistic because the source environment, either physical or operational, may not correlate to the facility modeled. Part of the PCSA active component reliability analysis effort, therefore, was to evaluate the similarity between the YMP operating environment and that represented in each generic data source to ensure data appropriateness.

An example of how data were retrieved from the various data sources is described in the following example for check valves. The failure modes modeled in the PCSA for the check valve are fails per hour (FOH), fails to check (FTX), leaks (LEK), and spurious operation (SPO).

Table C1.2-2 shows a comparison between the failure rates for the check valve and its failure modes from three different industry-wide data sources.

Table C1.2-2. Data Source Comparison for Check Valve

Data Source	Equipment Description	Failure Modes	Data Values Provided	Equipment Boundary Given?	Taxonomy Given?
Ref. C5.1	Valve-non-operated, Check	• Fails to Check • Significant Back Leakage	Lower, Mean, Upper	Yes	Yes
Ref. C5.23	Driven Equipment Valves, Check	"All Modes"	Low, Recommended, High	No	Yes
Ref. C5.5	Check	• Fails to Open • Fails to Close • Plugs • Internal Leakage • Internal Rupture • External Leakage • External Rupture	Mean	No	No

NOTE: IEEE = Institute of Electrical and Electronics Engineers.

Source: Original

Table C1.2-3 shows actual numbers extracted from industry-wide data sources for five failure modes for check valves.

Table C1.2-3. Failure Rates Extracted from Various Data Sources for Check Valve

Failure Mode Description	Failure Mode Code	Data Source	Lower	Median	Upper	EF
Fails to Close (Hourly)	FOH	(Ref. C5.5)	1.27 × 10-7	7.74 × 10-7	4.70 × 10-6	6.1
Leaks	LEK	(Ref. C5.5)	6.98 × 10-7	3.49 × 10-6	1.75 × 10-5	5.0
Fails to Open (Hourly)	FOH	(Ref. C5.5)	1.27 × 10-7	7.74 × 10-7	4.70 × 10-6	6.1
Transfers Closed	SPO	(Ref. C5.23)	8.00 × 10-8	7.81 × 10-7	3.27 × 10-4	5.0
Transfers Open	SPO	(Ref. C5.23)	8.00 × 10-8	7.81 × 10-7	3.27 × 10-4	5.0

NOTE: EF = error factor; FOH = fails per hour; LEK = leaks; SPO = spurious operation.

Source: Original

At this stage of the analysis, it remains to decide which data is appropriate to keep and include in the data pool and which are discarded. The criteria for this process are discussed below.

The guidelines shown in Table C1.2-4 are based on observations of the analysts of their preferences and rationales during the data selection process among the data available at the time.

Table C1.2-4. Guidelines for Industry-wide Data Selection

Data Selection Guidelines	
1.	Preference for greater than zero failures (but not always able to exclude on this basis)
2.	Population of at least 5
3.	Denominator greater than 1,000 hours or 100 demands
4.	If mean or median values, some expression of uncertainty surrounding these values (either upper or lower bounds or lognormal error factor)
5.	Data analyst's confidence in the applicability of the data to the YMP based on: • Component design • Driver/operator • Size • Component application • Active versus passive service • Materials/fluids moved (e.g., water versus caustic versus viscous) • Component boundary • What's included and excluded in component definition (e.g., motor, electrical connections) • Failure modes • Operating environment • Physical (e.g., heat, humidity, corrosive) • Functional (e.g., operation, maintenance, and testing frequency)

NOTE: YMP = Yucca Mountain Project.

Source: Original

Given the fact that the YMP will be a relatively unique facility (although portions will be similar to the spent fuel handling and aging areas of commercial nuclear plants), the data development perspective was to collect as much relevant industry-wide failure estimate information as possible to cover the spectrum of equipment operational experience. It is assumed that the YMP equipment would fall within this spectrum (Assumption 3.2.1). The scope of the sources selected for this data set was deliberately broad to increase the probability that YMP operational experience would fall within the bounds. A combined estimate that reflected the uncertainty ranges defined by the data source values was developed. This process is addressed further in the Bayesian estimation Section C2.

Every attempt was made to find more than one data source for each TYP-FM, although the unique nature of many equipment types made this difficult. Data was extracted from several sources in many cases, then combined using Bayesian estimation (as described further below), and compared by plotting the individual and combined distributions. However, the comparison process often resulted in one source being selected as most representative of the TYP-FM. Ultimately, 53% of the TYP-FMs were quantified with one data source, 7% with two data sources, 8% with three data sources, and 32% with four or more data sources.

C1.3 CRANE AND SPENT FUEL TRANSFER MACHINE DROP ESTIMATES

Industry-wide data was used to quantify the likelihood of experiencing a drop from the 200-ton crane while handling waste forms and their associated containers and for estimating drop probability for cranes used to maneuver waste packages. In addition, drop likelihoods for the spent fuel transfer machine (SFTM) were estimated using industry-wide data.

The rationale for using industry-wide data for these estimates was that a significant amount of crane experience exists within the commercial nuclear power industry and other applications and that this experience could be used to bound the anticipated crane performance at YMP. Further, the repository is expected to have training for crane operators and maintenance programs similar to those of nuclear power plants.

Handling incidents that resulted in a drop were included in the drop probability regardless of cause; they may have been caused by equipment failures (including failures in the yokes and grapples), human error, or some combination of the two.

The industry-wide data for cranes was taken from NUREG-0612 (Ref. C5.35), *A Survey of Crane Operating Experience at U.S. Nuclear Power Plants from 1968 through 2002*. NUREG-1774 (Ref. C5.26), and the *Probabilistic Risk Assessment (PRA) of Bolted Storage Casks, Updated Quantification and Analysis Report* (Ref. C5.8). NUREG-0612 (Ref. C5.35) has several appendices that contain crane data from the Occupational Safety and Health Act Administration, the U.S. Navy, Waste Isolation Pilot Plant, Licensee Event Reports, and from the results of a fault tree analysis. The *Probabilistic Risk Assessment (PRA) of Bolted Storage Casks, Updated Quantification and Analysis Report* (Ref. C5.8) provides estimates from Savannah River Site crane experience in addition to fault tree analysis. Crane failure information was also obtained from quantitative risk study performed for the U.S. Army chemical weapons destruction program (Ref. C5.41).

The information from each of these sources was evaluated in terms of quality, applicability to YMP, and to ensure that the events cited included both equipment failures and human failures. For the industry-wide data provided in terms of the number of events, another major factor was the ability to reasonably and justifiably estimate a meaningful denominator of number of lifts (demands) conducted by the crane population considered in the data source. If this could not be done, the source information could not be used.

A key consideration in evaluating the industry-wide crane data for the 200-ton cranes was the NOG-1 (Ref. C5.3) design requirements that will be placed upon the YMP cranes versus the crane design features reflected in the input data sources. NUREG-1774 (Ref. C5.26, Table 12, pp. 61 – 63) provides a list of the nuclear power plants that had upgraded their cranes to single-failure-proof status consistent with licensee response to U.S. Nuclear Regulatory Commission (NRC) *NRC Bulletin 96-02* (Ref. C5.9) which requested specific information relating to their heavy loads programs and plans consistent with the recommendations of NUREG-0554 (Ref. C5.34). This information was used to constrain the denominator of the number of very heavy load lifts from NUREG-1774 (54,000) by using a percentage of percent of nuclear power plants reporting single failure proof cranes out of total plants (43/109). When this information is evaluated the crane drop frequency calculates to 3.16E-05 which is rounded to 3.2E-05 for these analyses. Conversely, a separate category of non-single-failure-proof cranes for the waste package manipulating cranes was developed using the remaining percentage (66/109) to adjust the number of lifts. The number of crane drop incidents used as the numerator of the 200-ton crane drop estimate from NUREG-1774 (Ref. C5.26) was also restricted to those involving very heavy loads (defined in NUREG-1774 as >30 tons) of single-failure-proof cranes. Drops occurring during sling lifts were parsed into a separate category and used to estimate the sling lift-related drop likelihood.

Load drop likelihood due to two-blocking was also estimated using industry-wide data. NUREG-0612 (Ref. C5.35) describes a two-blocking event as: "The act of continued hoisting to the extent that the upper head block and the load block are brought into contact, and unless additional measures are taken to prevent further movement of the load block, excessive loads will be created in the rope reeving system, with the potential for rope failure and dropping of the load." Two-blocking events in the various data sources were evaluated based upon the type of crane involved, as was done for the drop likelihood estimates.

As a result, several categories of crane drop estimates were developed, were coded with TYP-FM designators, and were included in the template database for input to SAPHIRE:

CRN-DRP	200-Ton Crane Load Drop	3.2E-05/demand
CRN-TBK	200-Ton Crane Two Block Causing Load Drop	4.4E-07/demand
CRS-DRP	200-Ton Crane using Slings Load Drop	1.2E-04/demand
CRW-DRP	Waste Package Crane (Not Single Failure Proof) Load Drop	1.1E-04/demand
CRW-TBK	Waste Package Crane (Not Single Failure Proof) Two Block Causing Load Drop	4.6E-05/demand

In each of these cases, as with the other active component reliability estimates, an effort was made to include a variety of operating experience and combine it together using a parametric empirical Bayes approach. However, for the CRS and CRW estimates, since only NUREG-1774 (Ref. C5.26), data was considered to be applicable, a Jeffreys' non-informative prior approach for the beta distribution was used, since the estimates were per lift (demand).

These crane incident estimates were combined in the SAPHIRE models with the number of estimated YMP crane lifts.