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Attachments		Total Number of Pages
Attachment A.	Subsurface Layout and Diagrams	22
Attachment B.	Subsurface Operations Summary	9
Attachment C.	[Not Used]	1
Attachment D.	Subsurface Operations Master Logic Diagrams	13
Attachment E.	Subsurface Operations Hazard and Operability Evaluation	13
Attachment F.	Subsurface Operations Event Sequence Diagrams	6
Attachment G.	Subsurface Operations Event Trees	12

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DISCLAIMER

CONTENTS

Page

FIGURES

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

TABLES

Page

ACRONYMS AND ABBREVIATIONS

Acronyms

ALARA	as low as is reasonably achievable
BWR	boiling water reactor
BSC	Bechtel SAIC Company, LLC
CRCF 1, 2, 3	Canister Receipt and Closure Facility (1, 2, 3)
DHLW	defense high-level radioactive waste
DOE	U.S. Department of Energy
DSG	drip shield emplacement gantry
ESD	event sequence diagram
GROA	geologic repository operations area
HAZOP	hazard and operability (evaluation)
HEMF	Heavy Equipment Maintenance Facility
HEPA	high-efficiency particulate air (filter)
HLW	high level radioactive waste
HVAC	heating, ventilation, and air-conditioning
IHF	Initial Handling Facility
ITC	important to criticality
MCO	multi-canister overpack
MLD	master logic diagram
NRC	U.S. Nuclear Regulatory Commission
PCSA	preclosure safety analyses
PFD	process flow diagram
PLC	programmable logic controller
PRA	probabilistic risk assessment
PWR	pressurized water reactor
QA	quality assurance
SNF	spent nuclear fuel
SSCs	structures, systems, and components
TAD	transportation, aging and disposal
TBM	tunnel-boring machine
TEV	transport and emplacement vehicle
UNS	Unified Numbering System for Metals and Alloys

ACRONYMS AND ABBREVIATIONS (Continued)

WHF	Wet Handling Facility
WPTT	waste package transfer trolley

Abbreviations

ft	foot
ft^3	cubic foot
hr	hour
in	inch
km	kilometer, 10^3 m
kPa	kilopascal, 10^3 pascals
m	meter
m^3	cubic meter
min	minute
mm	millimeter, 10^{-3} m
mph	mile per hour
°C	degree Celsius (temperature)
°F	degree Fahrenheit (temperature)
psf	pound per square foot

1. PURPOSE

This document, along with its companion document entitled, *Subsurface Operations Reliability and Event Sequence Categorization Analysis* (Ref. 2.4.1), constitutes 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 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 beginning of operation to the end of the preclosure period.

The purpose of this analysis is to provide a systematic identification of potential accidental event sequences that could occur during Subsurface Operations and the development of potential event sequences that emanate from them. The categorization analysis in the companion report (Ref. 2.4.1) uses the event sequences developed in this analysis to perform a quantitative analysis of the event sequences for the purpose of categorization per the definition provided by 10 CFR 63.2 (Ref. 2.3.1).

"Subsurface Operations" as used in this calculation is broadly defined to include the series of waste package transport and handling operations which start with the lifting of a waste package into a transport and emplacement vehicle (TEV) within a surface handling facility, followed by transit to an emplacement drift in the subsurface, together with any other operation within an emplacement drift, such as drip shield emplacement, that could pose a nuclear safety hazard.

Background

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 10 CFR 63.112 (Ref. 2.3.1) and to be responsive to the acceptance criteria articulated in the *Yucca Mountain Review Plan, Final Report* (Ref. 2.2.72). 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 public or workers (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 filters when applicable. After completion of the event sequence development in the present analysis and its companion document, each Category 1 and Category 2 event sequence was conservatively matched with one of the categories of dose estimates.

"Event sequence" is defined in 10 CFR 63.2: (Ref. 2.3.1) as follows:

> Event sequence means 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.

An event sequence with a probability of occurrence before permanent closure that is less than one chance in 10,000 is categorized as *Beyond Category 2*. Consequence analyses are not required for these event sequences.

Paragraph (e) of 10 CFR 63.112 (Ref. 2.3.1) requires 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 an 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. 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 sub-criticality limit.

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, which 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 analysis determined the parameters that this event sequence analysis should include. Presence of moderation 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 sub-criticality limit. Other situations treated in the event sequence analysis for similar reason are multiple U.S. Department of Energy spent nuclear fuel (DOE SNF) canisters in the Canister Receipt and Closure Facility (CRCF) in the same general location and presence of sufficient soluble boron in the pool in the Wet Handling Facility (WHF).

The initiating events considered in the PCSA are limited to those that constitute a hazard to a waste form while it is present in the GROA per the definition of event sequence in 10 CFR 63.2. That is, an internal event due to a waste processing operation conducted in the GROA or an external event that imposes a potential hazard to a waste form, or waste processing systems, or personnel, (e.g., seismic or wind energy, flood waters) define initiating events that could occur within the site boundary. 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 (e.g., drops of casks, canisters, or fuel assemblies during loading at a reactor site, improper drying, closing, or inerting at the reactor site, rail accidents during transport, tornado missile strikes on a transportation cask) or during cask or canister manufacture (i.e., resulting in a reduction of containment strength) are not within the scope of the PCSA. Such potential precursors are subject to deterministic regulations (e.g., 10 CFR Part 50 (Ref. 2.3.2), 10 CFR Part 71 (Ref. 2.3.3) and 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, it is clear that very conservative design criteria and QA result in very unlikely exposures to radiation.

A risk informed approach to event sequence identification was followed. SSC and personnel activities that are associated with the direct handling of high-level radioactive waste (HLW) and low-level radioactive waste (LLW) are included in the event sequence analysis because they are much more safety significant than those uninvolved with waste handling. However, earthquake induced interactions of SSC not involved with waste handling, with those that are involved with waste handling, are quantitatively analyzed elsewhere in a separate seismic event sequence analysis, not included herein. Other such interactions are analyzed qualitatively also in an analysis, not included here.

Other boundary conditions used in the PCSA include:

- Plant operational state. 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 cease operations of the waste handling facility which further reduces the conditional probability of the occurrence of a second initiating event, given the first has occurred.

- Component failure modes. The failure mode of an 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, are not addressed in this analysis

Scope

The scope of the present Subsurface Operations analysis includes the identification of internal events spanning the operations of the lifting of a waste package within a waste handling facility by the TEV, the movement of a waste package along surface and subsurface rail lines by the TEV, eventually moving the waste package into an emplacement drift, together with any other operations or occurrences in the emplacement drift that can pose a hazard during the post-emplacement period, including drip shield emplacement, which occurs just prior to repository closure.

The results of this analysis includes: a process flow diagram (PFD), a master logic diagram (MLD), a hazard and operability (HAZOP) evaluation, event sequence diagrams (ESDs), and event trees. Initiating events considered in this analysis include internal events (i.e., events that are initiated during defined Subsurface Operations) as well as external events (i.e., events that are initiated outside Subsurface Operations, such as weather and seismicity). However, event sequences for external events (including seismic events) are not developed in this analysis. External events and associated event sequences are evaluated and documented separately. In addition, event sequences for construction-related subsurface activities are also evaluated and documented separately.

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2.2.69 MO0702PASTREAM.001. *Waste Stream Composition and Thermal Decay Histories for LA.* Submittal date: 02/15/2007. [DIRS 179925]

2.2.70 NASA (National Aeronautics and Space Administration) 2005. *Probabilistic Risk Assessment (PRA), Compliance Verification Guide.* Safety and Mission Assurance Requirements, NPR 8705.5. Washington, DC: National Aeronautics and Space Administration, Office of Safety and Mission Assurance. ACC: MOL.20071011.0006. [DIRS 183411]

2.2.71 NRC (U.S. Nuclear Regulatory Commission) 1983. *PRA Procedures Guide, A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants.* NUREG/CR-2300. Two volumes. Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 205084. [DIRS 106591]

2.2.72 NRC 2003. *Yucca Mountain Review Plan, Final Report.* NUREG-1804, Rev. 2. Washington, D.C.: U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards. TIC: 254568. [DIRS 163274]

2.3 DESIGN CONSTRAINTS

2.3.1 10 CFR Part 63. 2007. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. [DIRS 180319]

2.3.2 10 CFR Part 50. 2007. Energy: Domestic Licensing of Production and Utilization Facilities. [DIRS: 181964]

2.3.3 10 CFR Part 71. 2007. Energy: Packaging and Transportation of Radioactive Material. ACC: MOL.20070829.0114. [DIRS: 181967]

2.3.4 10 CFR Part 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. [DIRS: 181968]

2.4 DESIGN OUTPUTS

This analysis is used as an input to the following:

2.4.1 BSC 2008. *Subsurface Operations Reliability and Event Sequence Categorization Analysis*. 000-PSA-MGR0-00500-000-00A. Las Vegas, Nevada: Bechtel SAIC Company.

This analysis also supports preclosure safety evaluations of SSCs as important to safety (ITS), and nuclear safety calculations identifying operational and design requirements for the repository. The identification of potential safety hazards in this calculation is included in the license application.

In addition, a supplementary analysis which addresses construction hazards from Subsurface Operations (as well as other operations in waste handling facilities) is described in:

2.4.2 BSC 2008. *Construction Hazards Screening Analysis*. 000-PSA-MGR0-02000-000-00A. Las Vegas, Nevada: Bechtel SAIC Company.

3. ASSUMPTIONS

3.1 ASSUMPTIONS REQUIRING VERIFICATION

None used.

3.2 ASSUMPTIONS NOT REQUIRING VERIFICATION

None used.

4. METHODOLOGY

4.1 QUALITY ASSURANCE

This analysis is prepared in accordance with procedures EG-PRO-3DP-G04B-00037, *Calculations and Analyses* (Ref. 2.1.1), and LS-PRO-0201, *Preclosure Safety Analyses Process* (Ref. 2.1.4). Therefore, the approved version is designated as QA: QA. This analysis addresses the applicable criteria in Section 7 of the *Project Design Criteria Document* (Ref. 2.2.38). Specifically, it addresses Section 7.3.1 on the identification and systematic analysis of hazards and event sequences.

Documentation of suitability for intended use of QA: NA references: The operational description provided in Section 6 and in Attachment B is based (primarily) on reports, drawings, and calculations designated QA: QA such as (Ref. 2.2.34); and (Ref. 2.2.55). However, several of the operational descriptions and associated illustrations are based on information designated QA:NA.

QA:NA references have been used to provide input for the illustrations of the drip shield gantry, drift support, emplacement access door controls and a typical turnout, as well as secondary input for descriptions of retrieval and closure operations. The specific use of these documents in this analysis is shown in Table 1. These references are considered to be a reasonable basis for this use as they are consistent with QA: QA reports, drawings, and calculations, are provided by the relevant design groups on these topics, and alternative sources are not available at this time.

In addition, the engineering drawings listed in Table 1 were prepared using the QA:QA procedure EG-PRO-3DP-G04B-00046, *Engineering Drawings* (Ref. 2.1.2). The procedure requires that the drawings are checked by an independent checker and reviewed for constructability and coordination with other engineering disciplines before review and approval by the Engineering Group Supervisor and the Discipline Engineering Manager. The check, review, and approval process provides assurance that these drawings accurately document the design and operational philosophy of the facility.

One vendor supplied document is included in Table 1. In *Evaluation of WP Transporter Neutron Shielding Materials* (Ref. 2.2.66), Attachment II is vendor information on NS-4-FR provided by NAC International describing Genden Engineering Services and Construction Company of Japan shielding products. The vendor document provides descriptive information (i.e., a temperature limit) that is suitable for indirect input as used in this analysis.

4.2 USE OF SOFTWARE

Visio Professional 2003 and Word 2003, which are part of the Microsoft Office 2003 suite of programs, were used in this analysis for the generation of graphics and word-processing. This software, as used in this analysis, is classified as Level 2 software usage as defined in Ref. 2.1.3.

Table 1. Use of Non-Q References

Reference Number	Where Cited	Reason for Use
2.2.13	Figure A-3	Used as source for illustration of North Portal isometric view
2.2.17	Table A-2	Used to identify materials of conceptual TEV shielding
2.2.21	Attachments A and B	Used to develop operations description for DSG
2.2.23	Attachment B	Used to illustrate the method by which the waste package transfer trolley engages the loadout dock
2.2.25	Section 6.1.2.5, Attachment B	Used to support the development of the operations description for the drip shield gantry
2.2.26, 2.2.45	Figure A-11	Used in general description of emplacement access door, including nominal dimensions
2.2.27	Figure A-10, and Attachment A	Used as source for illustration of DSG and power rail
2.2.37	Figure A-2	Used as source for illustration of North Portal plan view
2.2.39	Figure A-12 and Attachment A	Used to describe and illustrate access main invert and rail
2.2.40	Figures A-12 and A-14, and Attachment A	Used to describe and illustrate emplacement drift invert configuration
2.2.41	Attachment A	Used to describe TEV paths in the subsurface and illustrate expected grades
2.2.42	Figure A-4	Used to develop illustration of typical turnout
2.2.43	Attachment B	Used to describe excavation methods
2.2.44	Figure A-11	Used for illustration of emplacement access door
2.2.46	Section 6.2.4.1	Used to describe that an emplacement drift is a high-radiation zone (a R5 radiation zone)
2.2.51, 2.2.52	Figure A-4	Used for illustration of typical turnout
2.2.53	Figures A-13, A-14, and Attachment A	Used to describe ground support for emplacement drifts and illustrate support system
2.2.60	Figure A-10	Used to provide the nominal dimensions of the drip shield gantry.
2.2.61	Figure A-5	Used to illustrate the travel path of the TEV on the surface and the proximity of the TEV rails to the other facilities
2.2.63	Sections 6.1.2.6, 6.1.2.7, Figure A-11 and Attachments A and B	Used to describe ventilation operations and the ventilation system in the subsurface and provide plan view of door components
2.2.66 (Vendor Attachment)	Section 6.2.5.2	Provides vendor data on NS-4-FR that indicates that the operating temperature limit may be challenged by TEV overheating

NOTE: DSG =drip shield emplacement gantry; TEV = transport and emplacement vehicle.

Source: Original

The computer code, SAPHIRE, Version 7.26 (Software Tracking Number: 10325-7.26-01), was used in this analysis, but only to develop event trees, which are the graphical representations of event sequences. No other computations were performed with this software as reported herein. Therefore, as used in this analysis, this software is classified as Level 2 software usage as defined in Ref. 2.1.3.

All visual information displayed in this analysis is verified by visual inspection as a part of the preparation, checking, and review processes. All listed software was installed on personal computers and operated under Windows XP Professional operating system with SAPHIRE operated inside a VMware virtual machine with a VMware Player.

4.3 APPROACH AND ANALYSIS METHODS

In accordance with the *Calculations and Analysis* procedure (Ref 2.1.1), PCSA analyses to identify internal initiating events are performed in a manner that meets the requirements of 10 CFR 63.112(b), (c), and (d) (Ref. 2.3.1) and the intent of the applicable supporting requirements of American Society of Mechanical Engineers (ASME) Standard RA-S-2002 (Ref. 2.2.5) and ANSI/ANS-58.21-2007 (Ref. 2.2.3). The current analysis is the first part in identifying internal events and hazards for Subsurface Operations, and is focused within this scope at meeting the requirements of 10 CFR 63.112(b):

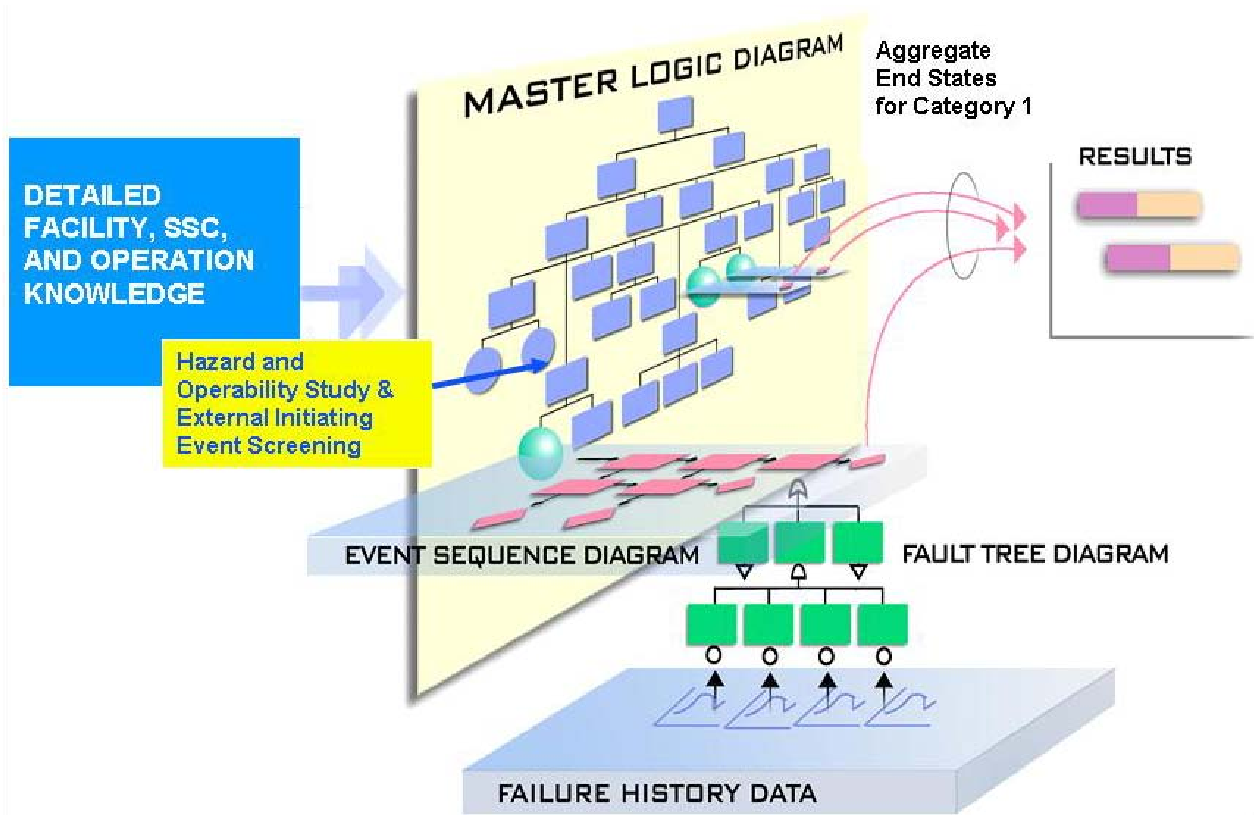
> "(b) An identification and systematic analysis of naturally occurring and human-induced hazards at the geologic repository operations area, including a comprehensive identification of potential event sequences."

The remaining parts of 10 CFR 63.112(c), and (d) (Ref 2.3.1), together with ANS/ANS-58.21-2007 (Ref. 2.2.3) are addressed in other PCSA analyses.

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 Subsurface Operations. Specific features of Subsurface Operations are discussed in Section 6, where the methods described here are applied. The PCSA uses the technology of probabilistic risk safety assessment (PRA) in references such as the ASME *Standard for Probabilistic Risk Assessment for Nuclear Power Plant Applications* (Ref. 2.2.5). 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. In a very real sense, the PCSA is a simulation of how a system acts when something goes wrong. The relationship of the methods of this PCSA is depicted in Figure 1. Phrases in ***bold italics*** in this section indicate methods and ideas depicted in Figure 1. Phrases in normal italics indicate key concepts.



Source: Modified from *Probabilistic Risk Assessment (PRA), Compliance Verification Guide* (Ref. 2.2.70).

Figure 1. Event Sequence Analysis Process

Identification of initiating events answers part of the question "What can go wrong?" The PCSA uses two methods for identifying initiating events: the MLD and the HAZOP evaluation, which are accepted methods of identifying and evaluating industrial hazards.

The basis of the PCSA is the development of event sequences. An event sequence may be thought of as a string of events that begins with an initiating event and eventually leads to potential consequences. 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 completes the answer to the question "What can go wrong?" and is defined by one or more initiating events, one or more pivotal events, and one end state. In the PCSA, event sequences end in *end states*. In this analysis, the end states of interest are: (1) Direct Exposure, Degraded or Loss of Shielding; (2) Radionuclide Release, Filtered; (3) Radionuclide Release, Unfiltered; (4) Radionuclide Release, Filtered, Important to Criticality; (5) Radionuclide Release, Unfiltered, Important to Criticality; (6) Important to Criticality; or (7) OK to indicate none of the above. The PCSA uses ***ESDs, event trees*** and ***fault trees*** to diagram event sequences.

The answer to the 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. 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 waste form and like factors in an event sequence such as availability of HEPA filtration, occurrence in water or air, and surrounding material such as transportation cask and 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 event sequences terminating 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, which 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 and the event sequence analysis which includes moderator intrusion, is sufficient to cover all repository configurations that are important to criticality.

The estimation of event sequence frequencies follows the development of event sequences, and answers the question "How likely is it?" The PCSA uses ***failure history*** records from references such as *Nonelectronic Parts Reliability Data 1995* (Ref. 2.2.67) and the *Nuclear Computerized Library for Assessing Reactor Reliability (NUCLARR)* (Ref. 2.2.68) together with 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, *Handbook of Parameter Estimation for Probabilistic Risk Assessment*, NUREG/CR-6823 (Ref. 2.2.6) are used to estimate frequencies of initiating events, event sequences, and the conditional probabilities of pivotal events.

Pivotal events 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/electronic equipment depends on the temperature at which it operates. 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 pivotal events. The level of detail of initiating events is such that they often are at a level of equipment assembly for which industry-wide reliability information does not exist. Fault trees are used to disaggregate or decompose the equipment (such as a crane) to SSCs for which reliability information is available. The PCSA, therefore, relies on ESDs and fault trees to represent the facility, equipment, and personnel responses to the initiating event.

The notion of the PCSA as a system simulation is important in that any simulation or model is an approximate representation of reality. Approximations lead to uncertainties regarding the frequencies of event sequences. The event sequence quantification process quantifies the uncertainties of the event sequences using Bayesian and Monte Carlo techniques. Figure 1 illustrates the results as horizontal bars in order to depict the uncertainties which give rise to potential ranges of results.

As required by the performance objectives for the geologic repository operations area through permanent closure (Ref. 2.3.1) each event sequence is categorized based on its frequency. Therefore, the focus of this analysis is to:

1. Identify potential internal initiating events, and external events relevant to this analysis as described in Section 4.3.1.

2. Construct ESDs and event trees to describe the event sequences associated with the initiating events.

The activities required to accomplish these two objectives are illustrated in Figure 2.

Event sequences are developed based upon a description of GROA operations as depicted in the process flow diagram of Section 6 and the equipment and operations descriptions of Attachments A and B. Accordingly, an event sequence, represented in an event sequence diagram, is particular to a given operational activity in a given operational area.

A MLD, supplemented by references describing operations, incidents and failures in other similar facilities, is the principal method for the identification of internal initiating events.

The initiating events identified in the MLD are grouped into ESDs according to whether they elicit a similar response of SSCs and operations personnel. Index numbers allow tracing of the initiating events to the ESDs in Attachment F. The ESDs show small bubbles surrounding a larger bubble. Each small bubble is a grouping of initiating events (from the MLD) that has not only the same SSCs and operations response but also the same pivotal event conditional probabilities. The larger bubble is termed an aggregated initiating event[1]. It is appropriate for purposes of categorization to add, within a given event sequence diagram and for a given waste form configuration, event sequences that elicit the same combination of failure and success of pivotal events and have the same end states. Categorization, therefore, is based on each event sequence that emanates from the larger circle, for each waste form.

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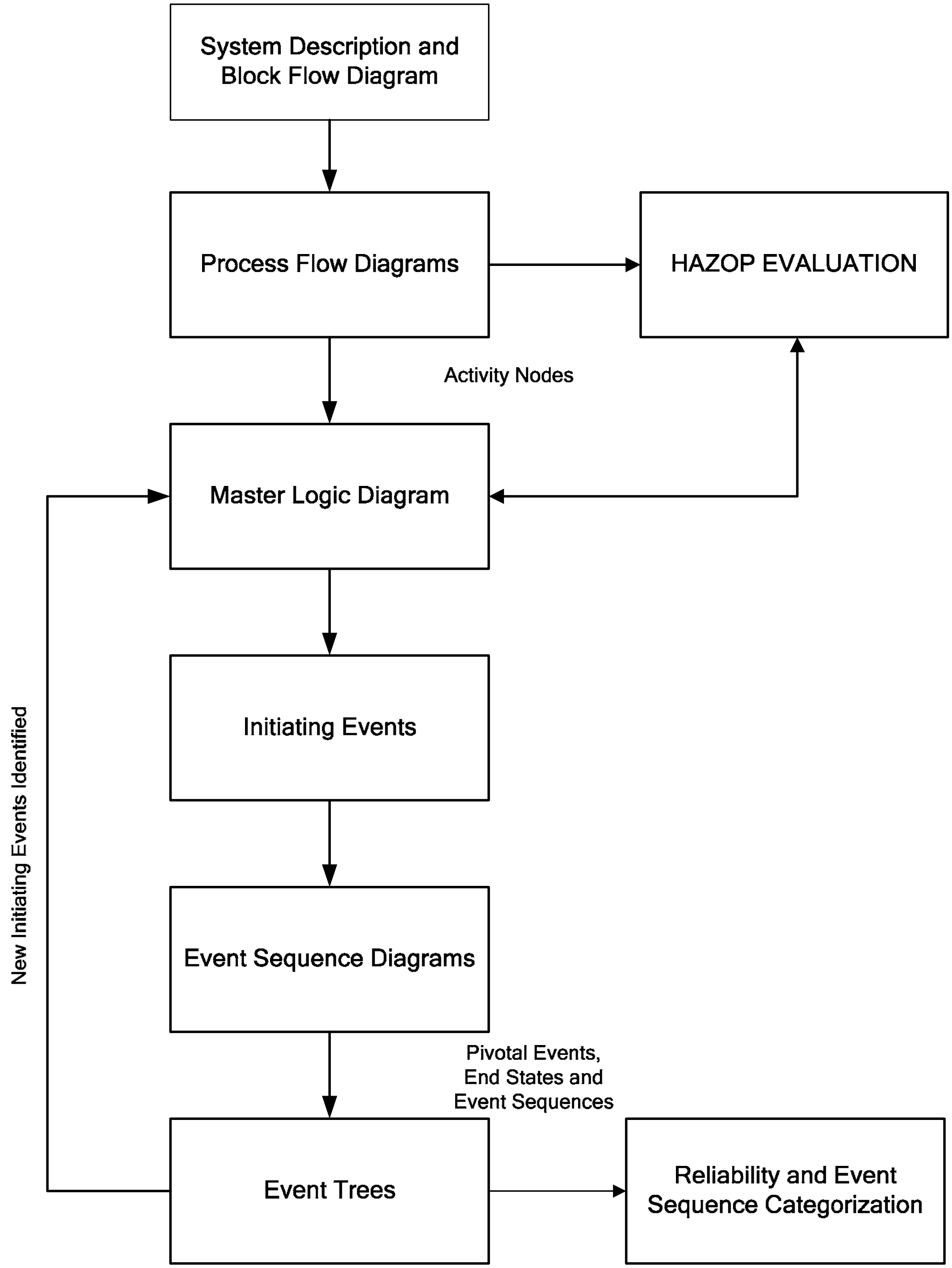
[1] This is not to be confused with the aggregation of doses for normal operations and Category 1 event sequences described in 10 CFR 63.111a (Ref 2.3.1).



NOTE: HAZOP = hazard and operability evaluation.

Source: Original

Figure 2. Preclosure Safety Analysis Process

A HAZOP evaluation type of process is used to supplement the MLD with respect to identification of initiating events. A HAZOP evaluation is a common method in the chemical process industry that is typically used for a comprehensive identification of operational mishaps, failures, and sequences of events (hardware and human) that might lead to an undesired event. It is used in a more limited way in the PCSA because the PCSA uses event sequence diagrams and fault trees (consistent with PRA methodology) as described above to identify the sequences of events, operational mishaps and failures. In the PCSA, a HAZOP evaluation was performed solely as a supplementary method to identify initiating events. If the HAZOP evaluation study identified an initiating event that was not covered by the MLD, it was added to the MLD. Typically, the HAZOP evaluation addressed deviations in more detail than the MLD identified initiating events. The initiating events identified by the MLD are more appropriate for the PRA methodology used in the PCSA than are the deviations considered in the HAZOP evaluation. It was found that deviations identified in the HAZOP evaluation were often already identified on the MLD as initiating events. Therefore, initiating events on the MLD, as indicated by index numbers, were matched with each HAZOP deviation. When a match could not be made, an additional initiating event was added to the MLD to cover it. The MLD, then, constituted the means to diagram the comprehensive set of initiating events found from both the MLD and HAZOP evaluation. Table 7 gives an example of the coordination of the MLD and HAZOP evaluation. The HAZOP evaluation results are provided in Attachment E and the MLD results are provided in Attachment D.

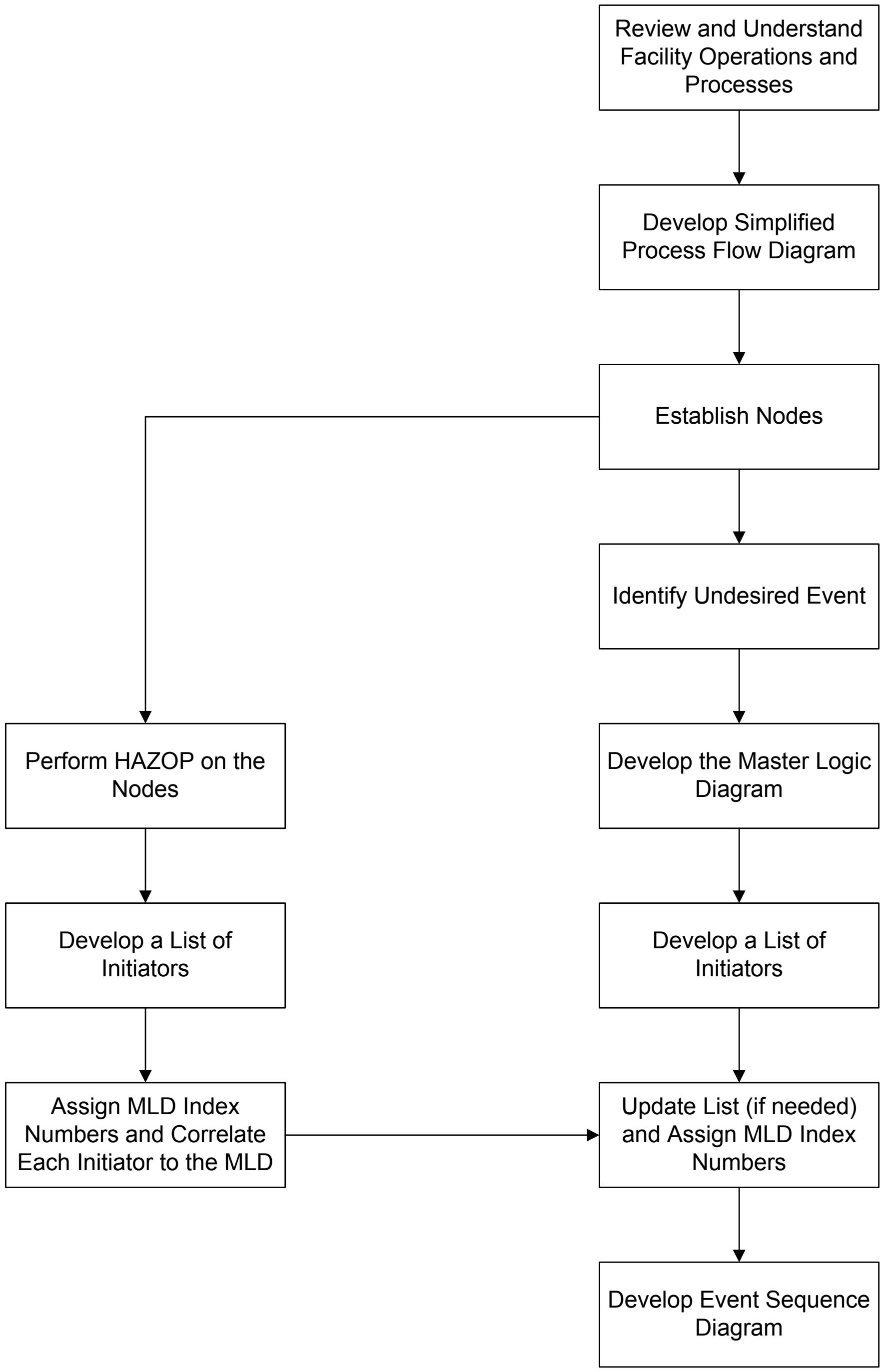
4.3.1 Initiating Event Development

The identification of initiating events is accomplished through a series of logically related activities that begins with understanding the facility (or operations area) and the operations and processes that occur within the facility or area (including the capabilities of the facilities and equipment to protect against external hazards and challenges). The process concludes with the identification of initiating events categorized at a level that is conducive to subsequent reliability analysis using fault trees in combination with historical records to estimate frequencies of occurrence. The process begins with a review of facility systems, processes, and operations. From this information a simplified PFD, as described in Section 4.3.1.1, is developed, which clearly delineates the process and sequence of operations to be considered within the analysis of the facility. The analyst then uses the PFD to guide development of an MLD. The MLD as a tool for initiating event development is described in *PRA Procedures Guide, A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants* (Ref. 2.2.71, Section 3.4.2.2).

Development of an MLD, as described in Section 4.3.1.2, is accomplished by deriving specific failures from a generalized statement of the undesired state. There are a number of ways that the preclosure safety analyst develops an understanding of how a system can fail. One way is to review engineering drawings and other design documents. These documents include mechanical handling block flow diagrams, mechanical engineering envelope diagrams, mechanical handling design reports, building layout drawings, process and instrumentation diagrams, ventilation and instrumentation diagrams, electrical diagrams, and fire hazard analyses. The analyst may review an engineering document simply as a user of the document. However, review in the context of the engineering design review process is another important way by which the analyst develops an understanding of how equipment could fail. The formal engineering design review process involves preclosure safety analysts as reviewers. As a design reviewer, the analyst considers how the equipment could fail and often suggests design changes to improve safety. As noted in the introduction to Attachment B, the description of operations in Section 6.1 and Attachment B emerged from a cooperative effort involving Preclosure Safety Analysis personnel (facility leads, human reliability analysts, and equipment reliability analysts), Nuclear Operations personnel, and other engineering personnel. Thus, the MLD is developed in a thoroughly integrated environment in which failure modes are identified by the preclosure safety analyst and discussed with equipment and facility designers and operations personnel. The MLD is cross-checked to the HAZOP evaluation, which is performed on the facility processes and operations and based on nodes that is, specifically defined portions of the handling operation, established in the PFD. Although the repository is in some ways to be the first of its kind, the operations are based on established technologies: transportation cask movement by truck and rail, crane transfers of casks and canisters, rail-based trolleys, air-based conveyances, robotic welding, pool operations, etc. The team assembled for the HAZOP evaluation (and available on call when questions came up) has experience with such technologies and is well equipped to perform a HAZOP evaluation. As has already been noted, the MLD is modified to include any initiators that are identified in the HAZOP evaluation but not already included in the MLD. The entire process is iterative in nature with insights from succeeding steps often feeding back to predecessors ensuring a comprehensive listing of initiating events. This listing is then screened and grouped for the development of the event sequences.

The top-down MLD and the bottom-up HAZOP evaluation provide a diversity of viewpoints that adds confidence that no important initiating events have been omitted. The HAZOP evaluation process focuses on identifying potential initiators that are depicted in the lower levels of the MLD. The following subsections further describe the way the PFD, MLD, and the HAZOP evaluation are used for defining initiating events, and the methodology for grouping of initiating events.

Two key elements of the PCSA methodology are establishing and maintaining traceability among the PFD, MLD, and HAZOP evaluation. A PFD is broken down into nodes that group operational activities within a facility such as receipt, preparation, transfer, etc. Individual blocks within the nodes are used to *identify* specific processes and operations that are evaluated with both a MLD and HAZOP evaluation to identify potential initiators. Following this *identification* step, initiating events are then assigned a specific MLD index number or identifier (e.g., EX-104) in the HAZOP evaluation table. This MLD index number correlates the initiator on the HAZOP evaluation to a corresponding initiator on the MLD. Any unique initiator index number can be traced back to the specific "node of origin" in its associated PFD in order to pinpoint the basis for a given event. This identifier is then carried forward in developing the ESD, providing the traceability that ties MLD and HAZOP initiators to the initiators on the ESD. Figure 3 illustrates the above methodology.



NOTE: HAZOP = hazard and operability evaluation; MLD = master logic diagram.

Source: Original

Figure 3. Initiating Event Identification

4.3.1.1 Process Flow Diagram

A PFD is a simplified representation of a facility's processes and operations. It graphically represents information derived from the facility mechanical handling system block flow diagram and indicates how the mechanical equipment is to be operated. It is simplified because only information relevant to event sequences (potentially leading to dose or criticality) is depicted. As the example in Section 4.3.4 shows, the general flow and relationships of the major operations and related systems that comprise a specific process are aggregated into nodes. These nodes represent groups of sequential steps in a process. The boundaries of each node are subjectively chosen to enable the analyst to easily keep in mind the operations within the node while considering what could go wrong within the node.

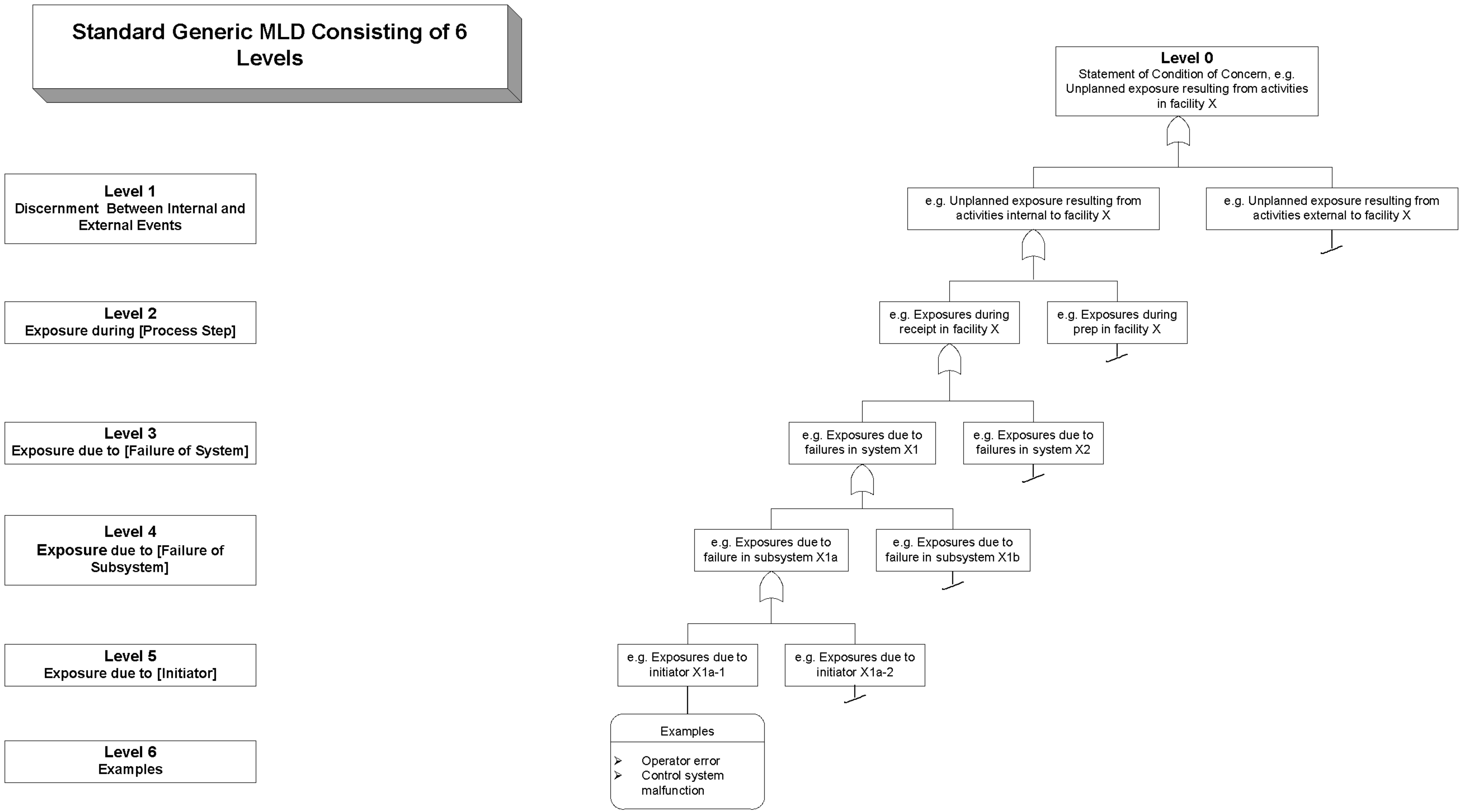
For this analysis, the analyst defines nodes in the PFD to identify those activities or processes that are evaluated for potential to initiate an event. The individual blocks within nodes are used to identify processes and operations that are further evaluated in the MLDs (Section 4.3.1.2). A detailed description of the nodes used for this analysis is provided in Section 6.1.

4.3.1.2 Master Logic Diagram

The MLD technique is a structured, systematic process to develop a set of initiating events for a system and is described in *PRA Procedures Guide, A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants* (Ref. 2.2.71), Section 3.4.2.2.. The method is adapted to the waste repository risk-informed PCSA. As a "top-down" deductive analysis, the MLD starts with a top event, which represents a generalized undesired state. For this analysis, 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 an MLD, the initiating events are shown at the next-to-lowest level. The lowest level provides examples to the initiating event.

For example, initiating events may be defined at either a categorical level (e.g., "crane drops load") that can be attributed to a specific crane (e.g., the 300-ton cask handling crane), down to a very specific level, such as a subsystem or component failure (e.g., "crane cable breaks") or a human failure event (e.g., "operator opens cask grapple").

A generalized logic structure for the PCSA MLD is presented in Figure 4. In the development of a specific MLD (demonstrated per the example MLD shown in Section 4.3.4), this structure is generally followed for each branch until initiators are identified. Once initiators are identified, the process is terminated in that branch.



Source: Original

Figure 4. Master Logic Diagram Framework

The levels of the MLD are defined as follows:

- Level 0: The entry point into the MLD is an expression of the undesired condition for a given facility. Level 0 is the top event of the MLD. In the MLD framework shown in Figure 4, the top event is expressed as "Unplanned exposure of individuals to radiation or radioactive materials due to operations in the facility." This top event includes direct exposure to radiation sources, or exposure as result of release of airborne radioactive material or conditions that could lead to a criticality. The basic question answered by the MLD through the decomposition is "How can the top event occur?"

- Level 1: This level differentiates between internal events and external events. The external event development at this level would be for initiating events that affect the entire facility (e.g., flooding). Common cause initiating events that affect less than the entire facility are incorporated at the appropriate level in the MLD.

- Level 2: This level identifies the operational area or process step where the initiating events can occur.

- Level 3: This level identifies the functional system or subsystem failure for the operational areas identified in Level 2.

- Level 4: This level also identifies the functional system or subsystem failure in somewhat more detail.

- Level 5: This level specifies the initiating event, usually in terms of equipment or component failure modes, that can result in the failure of system or subsystem in the specified operational activity (i.e., the actual deviations from successful operation that could lead to the exposure type). In the MLD used here to describe the example, each of the initiating event boxes is given an initiating-event identifier, e.g. EX-101, which carries over to a corresponding ESD. Level 5 is considered the appropriate grouping of initiating events for purposes of subsequent fault tree analysis.

- Level 6: This level provides an example to help elucidate the interpretation of the Level 5 initiating event group. Consistent with Figure 1, each Level 5 initiating event is modeled in detail by a combination of fault trees and/or direct use of empirical information. Level 6 entries, therefore, are found as failure modes in fault trees.

4.3.1.3 Hazard and Operability Evaluation

As previously discussed, the MLD and the HAZOP evaluation are strongly interrelated. Development of an MLD, as described in Section 4.3.1.2, is accomplished by deriving specific failures from a generalized statement of the undesired state. The MLD is then supplemented by performing a HAZOP evaluation of the facility processes and operations based on nodes established within the PFD that represent operations grouped by outcome. Any additional initiators noted by the HAZOP evaluation are added to the MLD as appropriate. The entire process is iterative in nature with insights from succeeding steps often feeding back to predecessors ensuring a comprehensive listing of initiating events. This listing is then screened and grouped for the development of event sequences.

The HAZOP evaluation process focuses on identifying potential initiators that are depicted in the lower levels of the MLD. Initiating events are assigned a specific MLD identifier (e.g., EX-202) in the HAZOP evaluation table. The MLD identifier correlates the initiator on the HAZOP evaluation with a corresponding initiator on the MLD. This numerical correlation is reflected in Section 4.3.4.2, Figures 8 and 9.

As discussed in Section 4.3.1, the HAZOP evaluation was conducted to supplement accuracy of the MLD results. The HAZOP evaluation is a "bottom-up" analysis used to supplement the "top-down" approach of the MLD (Ref. 2.2.1). It is a systematic study of the operations in each facility during the preclosure phase. The operations are divided into nodes, as shown in the PFD (Section 4.3.1.1).

The purpose of defining nodes is to break down the overall facility operations into small pieces that can be examined in detail. The analysis of each node is completed before moving on to another node. The intended function of each node is first defined. The "intention" is a statement of what the node is supposed to accomplish as part of the overall operation. For example, Node 4 of the PFD for the example facility in Section 4.3.4.2, (Table 5 and Figure 7) describes the emplacement of a waste package in drift. The intended function of this node is to move the waste package into a selected emplacement drift and place the waste package and pallet at the proper location.

A "deviation" is any out-of-tolerance variation from the normal values of parameters specified for the intention. Each potential variation may be identified in terms of one of the seven standard guidewords shown in Table 2.

Table 2. Standard Hazard and Operability Evaluation Guidewords and Meanings

Guidewords	Meaning	Comments
No	Negation of the Design Intention	No part of the design intention is achieved, or nothing else occurs
Less (Lower)	Quantitative Decrease	Refers to quantities less than required for success of the intention
More (Higher)	Quantitative Increase	Refers to quantities greater than required for success of the intention
Part Of	Qualitative Decrease	Only some of the intentions are achieved; some are not
As Well As	Qualitative Increase	All of the design and operating intentions are achieved together with some additional activity
Reverse	Logical Opposite of the Intention	Examples are reverse flow or chemical reaction or movement of container in wrong direction
Other Than	Complete Substitution	No part of the original intention is achieved. Something quite different happens

Source: Modified from Ref. 2.2.1, Table 6.14.

Each potential initiating event is first identified as a specific "deviation" from the well-defined, intended functions and behavior of each operational node. Deviations that have the potential for resulting in a radiological consequence are identified as a potential hazard, i.e., an initiating event that may result in an event sequence per the definition in 10 CFR 63.2 (Ref. 2.3.1).

The HAZOP evaluation process ensures that potential hazards are considered in the evaluation through a formalized application of "guidewords" that represent a set of potential deviations from normal (i.e., intended) operations. The HAZOP evaluation is performed by a multi-disciplinary team that is well-versed in the design, operations, safety and reliability issues, as well as human factors and human reliability. An experienced team leader leads, stimulates, and focuses the analysis to ensure that the HAZOP evaluation is conducted efficiently and productively.

The processes and definitions of terms for conducting a HAZOP evaluation have been widely applied in chemical and nuclear processing facilities for decades. The terminology commonly used in HAZOP evaluation is presented in Table 3. The application to the repository PCSA applies the HAZOP evaluation process with modifications to fit the nature of the facilities, operations, and level of information on design and operations. The modifications include the selection of parameters such as drop, transfer, transport, lift, speed and direction instead of pressure, flow, composition and phase change that are usually associated with chemical processes.

Table 3. Hazard and Operability Evaluation Terminology

Term	Definition
STUDY NODES (or Process Sections)	Sections of equipment with definite boundaries (e.g., a line between two vessels) within which process parameters are investigated for deviations. The locations (on piping and instrumentation drawings, diagrams, and procedures) at which the process parameters are investigated for deviations.
OPERATING STEPS	Discrete actions in a batch process or a procedure analyzed by a "HAZOP evaluation team." Steps may be manual, automatic, or software-implemented actions. The deviations applied to each process step are different than deviations that may be defined for a continuous process.
INTENTION	Defines how the plant or process node operates in the absence of deviations at the study nodes. This can take a number of forms and can either be descriptive or diagrammatic; e.g., flow sheets, line diagrams, and piping and instrumentation diagrams.
GUIDE WORDS	Simple words that are used to qualify or quantify the intention in order to guide and stimulate the brainstorming process to discover deviations. The guidewords shown in Table 2 are used the most often in a HAZOP evaluation. However, the list may be made more application-specific to guide the team more quickly to the areas where prior operations or experience have identified problems. Each guideword is applied to the process variables at the point in the operation (study node) which is being examined.
PROCESS PARAMETER	Physical or chemical property associated with the process. This includes general terms like mixing, concentration and specific items such as temperature, pressure, flow, and phase for processes, or general terms like lift, relocate, and specific terms like lift height and speed of movement for handling of containers.
DEVIATIONS	Departures from the intention that are discovered by systematically applying the guide words to process parameters (e.g., "more pressure", "too high lift height"). This provides a list of potential deviations for the team to consider for each node. Teams may supplement the list of deviations with ad hoc items.
CAUSES	Reasons why deviations might occur. Once a deviation has been shown to have a credible cause, it can be treated as a meaningful deviation. These causes can be hardware failures,

Table 3. Hazard and Operability Terminology (Continued)

Term	Definition
	human failure events, an unanticipated process state (e.g., change of composition, or introduction of an over-weight or over-sized container into a handling facility), or external disruptions (e.g., loss of power).
CONSEQUENCES	Results of the deviations should they occur (e.g., release of radioactive or toxic materials, exposure to radiation). Normally, the team assumes that active protection systems or safeguards fail to work. Consequences that are unrelated to the study objective are not considered. Minor consequences, relative to the study objective, are dropped.
SAFEGUARDS	Engineering or administrative controls that are used to prevent the causes or mitigate the consequences of deviations (e.g., alarms, interlocks, procedures). Safeguards are not credited when defining consequences of a deviation, but are addressed in evaluating the need for actions or recommendations.
ACTIONS (or Recommendations, Comments)	Suggestions for design or procedural changes (i.e., to provide new or additional safeguards) or areas for further study (e.g., analyses of reliability of active or passive systems credited as safeguards, human reliability analysis, or radiological consequence analyses).

Source: Modified from Ref. 2.2.1, Table 6.13.

This PCSA follows the HAZOP evaluation guidance provided in *Guidelines for Hazard Evaluation Procedures* (Ref. 2.2.1). The *Yucca Mountain Review Plan, Final Report*, (Ref. 2.2.72), Section 2.1.1.3.5), lists the American Institute of Chemical Engineers guidelines as a principal reference for performing a hazards evaluation. Consistent with the MLD, this HAZOP evaluation is focused on potential radiological hazards for the preclosure period that could lead to event sequences.

The HAZOP evaluation applies seven guidewords that, in principal, cover possible deviations that can occur in a given node of a given process. Table 2 lists the seven guidewords that are crafted to ensure that potential deviations are addressed in a systematic process. In practice, the application of the guidewords requires the knowledge and imagination of the HAZOP evaluation team to ensure that the set of deviations and hazards identified well represents the facility. In addition to the specific definition shown in Table 2, the guideword “other than” is applied as a kind of miscellaneous category to capture deviations not identified by the other six standard guidewords.

Each deviation is examined for potential consequences, as shown in Table 4. Each deviation that could result in an undesired effect is marked as a potential initiating event, even if safeguards are present in the design to prevent the deviation or to mitigate the consequences. Each deviation is examined to identify its potential causes. The HAZOP evaluation team may note and record the design or operational procedure that may be used to prevent or mitigate the consequences of an event. Subsequent analyses of the phenomenology of event sequence development and analyses of reliability of preventive and mitigative features will evaluate the hazard further.

Table 4. Examples of Deviations for a Chemical Process

Guide Words	Intention (Parameter)	Deviation
No	Flow	No Flow
More	Pressure	High Pressure
As Well As	One Phase	Two Phase
Other Than	Operation	Maintenance

Source: Modified from Ref. 2.2.1, p. 132.

For many process parameters, meaningful deviations are generated for each guideword. Moreover, it is not unusual to have more than one deviation from the application of one guideword.

After the HAZOP evaluation is finished, the results are compared with the MLD to verify the accuracy of the MLD. Deviations are matched one by one to the MLD. Initiating events were added to the MLD to encompass all deviations not previously included in the MLD.

4.3.2 Internal Event Sequence Development and Characterization

An event sequence is a series of actions and/or occurrences within the natural and engineered components of a GROA that could potentially lead to exposure of individuals to radiation. An event sequence begins with an initiating event and unfolds as a combination of failures and successes of intermediate events, called “pivotal events.” An event sequence terminates with an end state that identifies the type of radiation exposure or potential criticality, if any, resulting from the event sequence.

Event sequences are developed with the following objectives:

- Provide an accurate description of event sequences that could occur before permanent closure
- Identify the end state associated with each event sequence to enable the subsequent evaluation of radiological consequences
- Identify the SSCs; their safety function; and the procedural safety controls that are relied on to control the frequency of occurrence of event sequences or mitigate their consequences.

The first two objectives are addressed in this analysis. The third objective is addressed in the *Subsurface Operations Reliability and Event Sequence Categorization Analysis* (Ref. 2.4.1).

It is important to recognize that the ESDs are used to identify, before operation begins, potential future event sequences. An identified event sequence may or may not occur during the preclosure period. Therefore, a probabilistic framework is important. The uncertainty in occurrence is represented by probabilities or frequencies, which are developed and documented in the *Subsurface Operations Reliability and Event Sequence Categorization Analysis* (Ref. 2.4.1). These probabilities or frequencies, themselves, are uncertain and such uncertainty is typically represented by a probability distribution, also again developed and documented in the *Subsurface Operations Reliability and Event Sequence Categorization Analysis* (Ref. 2.4.1).

4.3.2.1 Event Sequence Diagrams

An ESD is a block flow diagram that displays the combinations of pivotal events that reflect the responses of SSCs and personnel after an initiating event or group of initiating events (Ref. 2.2.71, Section 3.4.3.2). To construct an ESD, the analyst begins with the initiating events that were identified by the MLD and the HAZOP evaluation and then, in effect, answer the question "What can happen next?" until an end state is reached. ESDs are designed to logically depict the progression of event sequences from their initiating event up to and including their end state. ESDs identify the key safety functions necessary to reach an end state after the initiating event as well as the associated SSC responses (although operator actions are not shown explicitly on the ESDs in this analysis, human failure events are implicit in some of the initiating events and pivotal events.) .An ESD is structured as a decision tree in which pivotal events are queried with two possible results: a yes/success (desired) outcome and a no/failure (undesired) outcome. The structure allows for a straightforward transposition of ESDs into event trees. In this PCSA, ESDs and the associated event trees consider human, mechanical, electrical, electronic, controller, structural, thermal and naturally occurring events. However, as noted in Section 1, event sequences for external events (including seismic events) are not developed in this analysis. External events and any associated event sequences are evaluated and documented separately.

Five possible end states are considered in the ESDs. The first end state addresses absence of radiation exposure; the other four end states classify the type of radiation exposure that could occur, as follows:

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

2. Direct Exposure—Indicates a potential exposure of individuals to direct or reflected radiation, excluding radionuclide release. This excludes radionuclide release from containment and the indication of a nuclear reactivity increase. In the PCSA, containment is provided by welded closed canisters, bolted and sealed transportation cask, and bolted and sealed shielded transfer casks.

3. Radionuclide Release—Indicates radiation exposure resulting from a release of radioactive material from containment.

4. Radionuclide Release, Also Important to Criticality—Refers to a situation in which criticality should be investigated as a breach of a waste form container has occurred (resulting in a radionuclide release), and (neutron) moderator[2] can potentially contact the waste form[3]. (Here and elsewhere in this analysis, the word "container" is used generically to denote a sealed barrier such as a canister, transportation cask, or waste package. In some event sequences, more than one barrier would have to be breached to allow a radionuclide release or contact of liquid moderator with the waste form.)

5. Important to Criticality—This end state refers to a situation in which a criticality investigation is indicated for Category 1 or 2 event sequences..

For the development of event trees, the above end states are further developed to differentiate the consequences of the various states of release and exposure. The eight mutually exclusive end states include:

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

2. Direct Exposure, Degraded Shielding–Applies to event sequences where an SSC providing shielding is not breached, but 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. Excludes radionuclide release from containment and an indication of reactivity increase.

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

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

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2 Introduction of a neutron moderator (simply termed "moderator" in the rest of the analysis) such as water into a canister containing nuclear fuel elements will typically increase the nuclear reactivity of commercial spent nuclear fuel waste forms.

3 A limited number of waste forms received by the repository have a very high fissile loading or are self-moderated, and therefore, in certain situations, they do not require the introduction of a moderator to achieve the conditions necessary to lead to a criticality event. These waste forms are DOE SNF containers with one of the following fuel types: (1) TRIGA (training, research, isotopes from General Atomics), (2) FFTF (Fast Flux Test Facility) or (3) Enrico Fermi. Criticality of these waste forms due to an impact is addressed elsewhere, and is not considered in this analysis.

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 nuclear reactivity increases.

6. Radionuclide Release, Filtered, Also Important to Criticality–This end state refers to a situation in which a breach of a canister has occurred (resulting in a radionuclide release) and a moderator, such as unborated water, has entered the canister. A filtered radionuclide release occurs and (unless the associated event Sequence is Beyond Category 2) 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) a criticality investigation is indicated.

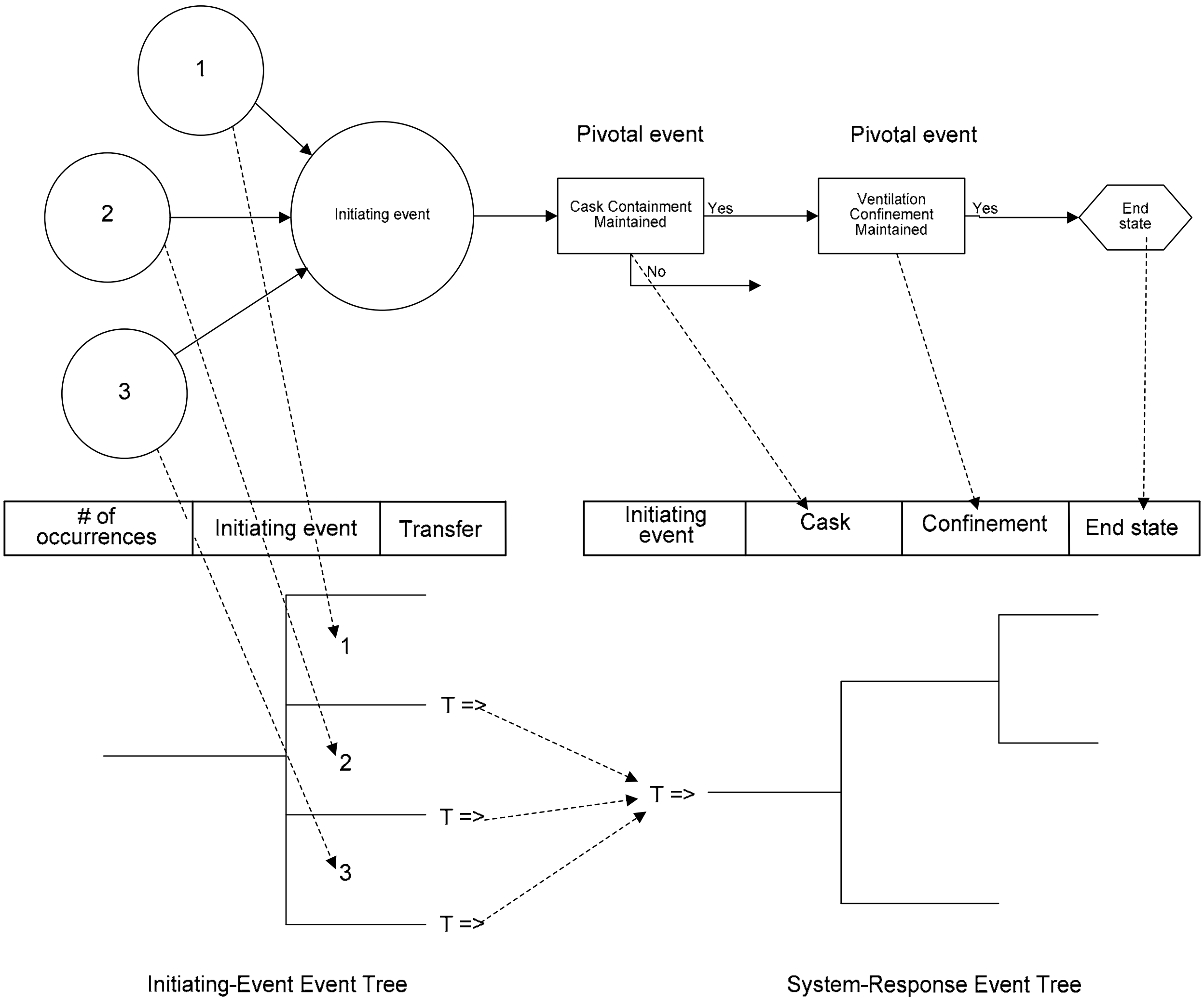
8. Important to Criticality–This end state refers to a situation in which criticality should be investigated without a radionuclide release.

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

As has already been noted, the criticality parameter of "moderation" is used as a basis for the development of event sequences important to criticality. The reason that the event sequence development includes only moderation was explained in Section 1. Under normal conditions, sealed canisters containing dry waste are received in sealed transportation casks. Normal conditions also include receipt of uncanistered dry SNF in sealed transportation casks. Category 1 and Category 2 event sequences involving moderator introduction into the canister (or cask, for uncanistered waste) result in an end state that needs to be evaluated in a separate analysis for criticality potential. Moderator could be introduced, for example, by actuation of the fire-suppression system or other water-distribution system, or by failure of lubricating oil reservoirs associated with cranes. Therefore, event sequences involving radiological release are identified with the end state also important to criticality if they result in contact between liquid moderator and the waste form.

4.3.2.2 Event Trees

Event tree construction is the next step in the development of event sequences according to *PRA Procedures Guide, A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants (*Ref. 2.2.71, Section 3.4.4.2). As shown in Figure 5, an event tree is a logic diagram that delineates the event sequences of an ESD.



Source: Original

Figure 5. Event Sequence Diagram, Event Tree Relationship

Event sequences are described and graphically depicted using one or two event trees depending on whether the ESD considered has one or more initiating events. When the ESD has only one initiating event, only a system response event tree is needed. The system response event tree structure has a one-to-one correspondence to that of the ESD. The system response event tree has a horizontal tree structure that starts with the initiating event, splits into upward and downward branches at nodes that represent pivotal events, and terminates into end states. Each path from the initiating event to an end state corresponds to an event sequence.

When the ESD has more than one initiating event, the system response event tree is preceded by an initiator event tree (indicated as an initiating event-event tree in Figure 5). The initiator event tree has one node from which as many branches are created as there are initiating events on the ESD. The initiator event tree assigns an initiating event to each branch, which terminates into a transfer to the same system response event tree. Since the conditional probability of one or more pivotal events may be specific to the initiating event assigned to each branch of the initiator event tree, the same system response event tree is quantified as many times as there are initiating events in the initiator event tree using different pivotal event probabilities as needed.

The description of the pivotal events, given the headings of the system response event tree, is by convention, expressed in terms of successful performance; an upward branch at a node represents success, and a downward branch represents failure. If a pivotal event does not appear in a particular event sequence (as indicated in the ESD), the event tree does not branch at that pivotal event.

Figure 5 illustrates the relationships between the ESD, initiator event trees, and the system response event trees. The ESD is shown at the top of the figure. The circles to the left, also known as small *bubbles* represent individual initiators. The larger circle (or big bubble) to the right of the small circles represents the aggregate initiator. The cask and confinement rectangles to the right of the large circle represent pivotal events leading to the end state. A horizontal line to the right of pivotal event box represents success of a system or component. A vertical line below the pivotal event box represents failure of a system or component. The link between the initiators in the ESD and the initiator event tree are shown as dashed lines from the small circles to individual branches on the initiator event tree. The link between pivotal events on the ESD and pivotal events on the system response event tree are also shown as dashed lines from the pivotal events on the ESD to the pivotal events on the system response event tree.

Initiators on the initiator event tree transfer to the initiating event in the system response event tree. This construction of the event trees is a feature of SAPHIRE that allows the analyst to specify basic rules to assign pivotal event probabilities in the system response event trees to be properly assigned to account for the conditions associated with each individual initiating event in the initiator event tree.

4.3.2.3 Internal Fire and Flooding Event Analysis

Fire and flooding initiating events identified in the MLDs are analyzed in the *Subsurface Operations Reliability and Event Sequence Categorization Analysis* (Ref. 2.4.1).

4.3.3 External Events

External initiating events are discussed further in the Monitored Geologic Repository External Events Hazards Screening Analysis (Ref. 2.2.15).

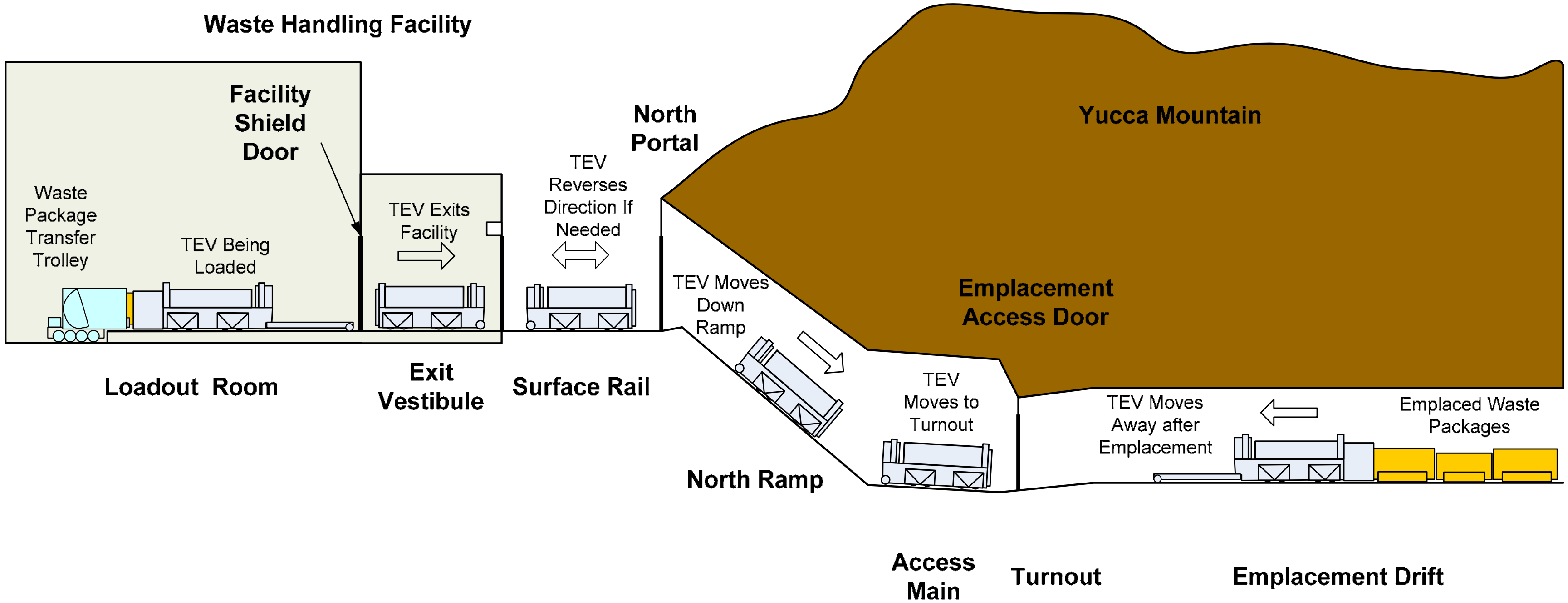
4.3.4 Example Facility Analysis

This section illustrates the various methodologies used to develop a PCSA analysis, along with the relationships of the PFD, MLD, HAZOP evaluation, ESDs and event trees in a simple example. This example portrays a generalized waste package transit and emplacement operation and differs from waste handling operations and features conducted in surface waste handling facilities. The selected example includes the transit and emplacement operation of the waste package into the subsurface, employing representative processes. This example also describes associated systems and equipment, shows a generic PFD and a generalized MLD, provides portion of a sample HAZOP evaluation, and describes development of an ESD and event tree for waste emplacement activities using a TEV. The analysis presented focuses on the specific operations within an emplacement drift. The objective of this example is to demonstrate how event sequences are developed employing the methodologies identified earlier. A generic description of Subsurface Operations emplacement operations is provided in the next section. The actual description of Subsurface Operations, the MLD, ESDs, and ETs begin in Section 6.

Typical Transit and Emplacement Operations Overview

A simplified schematic of the operations for the transit and emplacement process is shown in Figure 6. After personnel exit the Waste Package Loadout Area, the waste package together with a pallet is moved into this area on a waste package transfer trolley (WPTT). The waste package contains one of several types of canisterized waste types (or waste forms). The size of the waste package follows one of six possible sizes, depending on the contained waste form. The trolley rotates the waste package from vertical to horizontal, engaging a screw drive in the loadout station. The screw drive moves the waste package resting on the pallet on a sliding table from the trolley to a position under the TEV.

At this point, Subsurface Operations formerly start. With the waste package in the proper position, the TEV is remotely activated and the TEV's shield enclosure is raised. As the enclosure moves upward, it engages the bottom of the pallet and lifts the waste package to traveling height. The extended base-plate is then retracted back under the shield enclosure (providing shielding below the waste package) and the rear shield door is lowered. Subsequently, the TEV closes the front shield doors, and engages all safety interlocks, and the TEV is then ready for transit.



NOTE: TEV = transport and emplacement vehicle.

Source: Original

Figure 6. Simplified Schematic of Typical Waste Package Transit and Emplacement Operations

The interior facility shield door is opened and the TEV moves into the Loadout Vestibule (if present). The interior facility shield door is closed and the exterior door is opened. The TEV then exits the facility and starts travel on surface rail. All rail crossings of the TEV route along the surface rail are closed at this point.

The TEV travels along the dedicated surface rail line from the facility to the North Portal. As the TEV has no on-board crew, it moves from control point to control point as directed by on-board programmable logic controllers (PLCs) and under the observation of the central control. At each control point (which can be a crossing location or at a rail switch location), the TEV stops and awaits authorization to proceed from the central control. The TEV may also enter a section of track to reverse direction to properly align the front shield doors depending on the orientation of the emplacement drift.

Upon reaching the North Portal, the TEV is remotely surveyed and enters the North Portal access control to proceed down the North Ramp into the subsurface. Upon reaching the base of the North Ramp, the TEV proceeds along larger tunnels (access mains) to travel to the selected associated turnout drift and emplacement drift. Upon reaching the turnout drift for the selected emplacement drift, the TEV stops and calibrates its position.

Once clearance is received from the central control, the emplacement access door is opened and the TEV moves into the turnout, passing through the access door. After the TEV has completely cleared the threshold, the access door is closed. The TEV then moves along the turnout and into the emplacement drift proper and stops at a predetermined position. Central control then authorizes the TEV to prepare for emplacement by opening the front and rear shield door followed by extending the TEV base-plate. The TEV then moves forward slowly towards the emplacement position. Upon reaching a position which is sufficiently close to the prior emplaced waste package, the TEV stops again. The TEV shield enclosure is then lowered, placing the pallet on the invert of the emplacement drift.

At this point, the waste package is emplaced in the drift. After verification from central control, the TEV moves slowly away from the waste package to a point where there is sufficient clearance for further operations and stops. Again after receiving clearance from central control, the TEV raises the shield enclosure to travel height, retracts the base-plate and closes the front and rear shield doors. The TEV then moves slowly towards the access door. The door opens and the TEV exits the emplacement drift.

4.3.4.1 Process Flow Diagram Development

The initial effort in identifying initiating events and developing ESDs and event trees involves gathering and reviewing facility design and operating information and documentation, which is then used to develop a PFD that summarizes the processes occurring within the facility. Relationships between operations and systems that characterize a specific process with defined boundaries are combined into distinct nodes on the PFD. A PFD for transit and emplacement operation is shown in Figure 7. Explanations of the operations encompassed within each node are provided in Table 5. Descriptions of the special equipment used in the identified processes and listed in Table 5 are provided in Table 6. The emplacement operations for this example are emphasized in the PFD (Node 4, Figure 7).

As shown in the PFD (Figure 7) and as described earlier these four nodes represent operational boundaries in the example facility. These are analyzed further in the MLD. Figure 7 emphasizes those nodes relevant to operations and operations that can not lead directly to a potential release event are excluded from the nodes as shown.

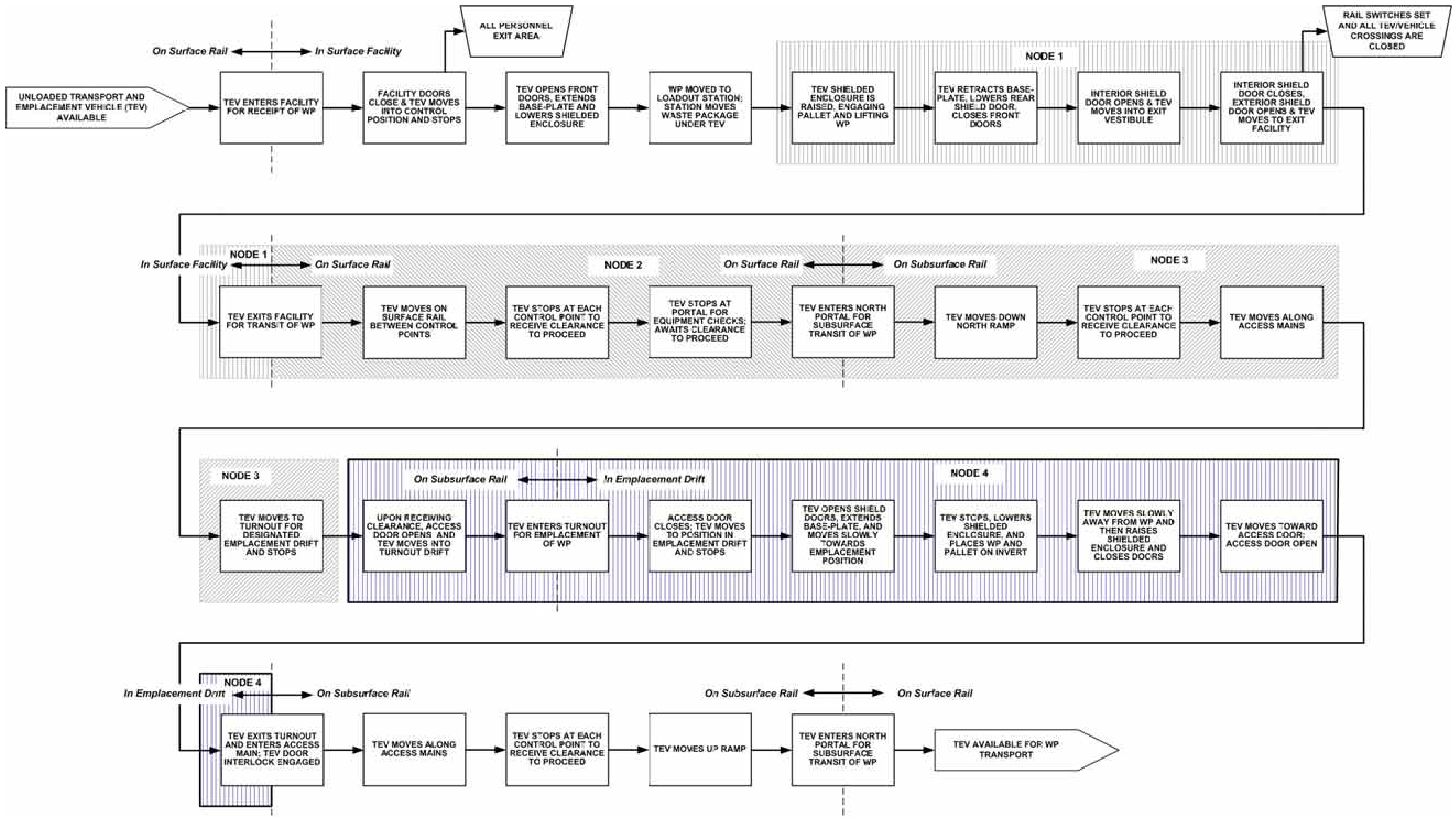
Node 4 is the focus of the illustrated example of the interrelationships between the MLD, HAZOP evaluation, ESD, and event tree described in the following sections.

4.3.4.2 Master Logic Diagram Development

With the PFD finished, development of the MLD begins. For the current analysis, the MLD top event end state used is: "Unplanned exposure of individuals to radiation or radioactive materials due to activities associated with Subsurface Operations" (Figures 8 and 9).

After the MLD top event is determined, the immediate and necessary causes for the occurrence of this top event are determined. These are not the basic causes of the event but the immediate causes or immediate mechanisms for the next level events. In turn, the causes of these events are listed in the next level of the MLD. The immediate and necessary causes of the top event are now treated as subsidiary events. In turn, the causes of these events are listed in the next level of the MLD. In this way the diagram is expanded, continually disaggregating the upper events until the resolution necessary to identify initiating events is reached.

The top event is decomposed into facility events that are external or internal, in accordance with the MLD methodology described in Section 4.3.1.2. The analyst identifies the external events (i.e., those events that generally affect the entire facility, such as natural hazards or internal flooding) and then analyzes these events separately. This is a reasonable approach because these initiators are generally outside the control of facility personnel or are not a result of facility operations. In addition, these initiators are common to all or most facilities on a site, and much of the analysis could be applicable for all. Note that the external events appear on the left branch in Figure 8, and the next logical split is illustrated but not decomposed further for this example. The right branch, "Exposures resulting from Subsurface Operations," begins the evaluation of the internal initiators that are not related to fire or flooding, and includes the facility operating activities identified in the PFD.



NOTE: Only activities involving handling of the waste package are designated as nodes.
CRCF = Canister Handling and Closure Facility; IHF = Initial Handling Facility; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Figure 7. Simplified Process Flow Diagram for Example with Node 4 Emphasized for Further Discussion

Table 5. Process Node Descriptions for Example

Node No.	Description
1	Node 1 of the PFD represents the loading of the waste package into the TEV and the subsequent movement of the loaded TEV out of the associated waste handling facility (IHF, CRCF 1, CRCF 2 or CRCF 3). The loading operation by the TEV is designated as the start of Subsurface Operations. Prior to start of TEV operation, the sealed waste package is moved under the TEV which is positioned at the loadout station. When the waste package is in the proper position, the TEV is remotely activated and the shield enclosure is raised, engaging the pallet, and lifting the WP and pallet to travel height. The TEV then retracts its base-plate, and closes the front and rear shield doors, which completely encases the waste package in shielding. If the TEV is in a CRCF facility (CRCF 1, 2 or 3), the Loadout Vestibule inner access (shield) door is then opened remotely from central control, and the loaded TEV moves backward (the end into which the waste package is loaded into the TEV is designated as the "front.") carrying the waste package out of the WP Loadout Room and into the Loadout Vestibule. After the TEV enters the vestibule, the Loadout Vestibule inner access (shield) door is closed. Then, the facility exterior overhead (non-shield) door is remotely opened and the loaded TEV moves backward again and exits the facility along the dedicated rail system. In the IHF, there is no Loadout Vestibule and the shield door is the facility exterior door. Similar to the CRCF, after the TEV is loaded, the shield door is then remotely opened and the loaded TEV moves backward and exits the facility along the dedicated rail system. The rail here is a branch line connecting the facility to the main line which in turn allows movement to the North Portal. Equipment involved in node operations: • TEV • WP • WP pallet • TEV rail system (including running rails, third rail power and anchorages) • Facility exterior shield door (in IHF only) • Facility Interior Loadout Vestibule shield door (in CRCF only) • Facility exterior overhead door (non-shielding) (in CRCF only). Additional equipment present during node operations: • Waste package transfer trolley • Loadout station (Two stations in CRCF) [a] • WP handling crane (100/20 short ton capacity) (Two cranes in CRCF) • Loadout platform (Three in CRCF) • Air handling unit (in CRCF's WP Loadout Room only) • Fan coil unit (in CRCF's Loadout Vestibule only).

Table 5. Process Node Descriptions for Example (Continued)

Node No.	Description
2	Node 2 includes the transit of the TEV containing a waste package along the dedicated surface rail from a waste handling facility to the North Portal (the only operations entrance into the subsurface). TEV operations are directed by on-board programmable logic controllers to move to from control point to control point. At each control point the TEV stops to await an affirmative signal from central control to continue to the next point. The TEV is also always under observation by workers in central control and these operators can stop the TEV if any off-normal condition is detected. Along the route, the TEV moves from the branch line from the facility through a switch onto the main (trunk) line. The main rail line passes to the northwest of operations area, alongside the waste handling and supporting facilities. Access along the route is not restricted but operational controls restrict workers from remaining in close proximity to the TEV for any length of time. The route from CRCF 1 to CRCF 3 to the North Portal has several roadway crossings. The route of the TEV crosses the route of the site transporter to the aging pads, if traveling from CRCF 2 or CRCF 3. Vehicular traffic may be encountered at any of these crossings. In addition, the TEV passes through a rail switch from branch line onto the main line, and encounter other rail switches as other branch lines join the main line. Further, while the TEV can travel either forwards or backwards, the TEV in many cases also traverses a side switch to reverse the direction of the TEV to enter the North Portal in the correct orientation for entering a selected emplacement drift. To enter the subsurface, the TEV enters the North Portal area which is excavated through the surface soils into the underlying rock, and is supported by rock bolts, wire mesh and fibercrete. The area above the portal is also fenced and the portal contains a security barrier to limit worker entrance into the subsurface. At the security gate of the North Portal the TEV stops and is surveyed for operational status. Equipment involved in node operations: • TEV • WP • WP pallet • TEV rail system (including running rails, third rail power, rail base, rail crossings, rail switches, and embankments). Additional equipment present during node operations: • North portal ground support system • Service vehicles possible at crossings, including Site Transporter • North Portal gates and security system (including fences) • Control and warning signs • North Portal lightning arrestors.

Table 5. Process Node Descriptions for Example (Continued)

Node No.	Description
3	Node 3 on the PFD represents the transit of the TEV (containing a waste package) along the subsurface rail system from the North Portal to a selected emplacement drift turnout, where the TEV stops. As on the surface, TEV operations are directed by on-board programmable logic controllers to move the TEV from control point to control point and then stopping to await an affirmative signal from central control to continue to the next point. Using cameras and on-board instruments, the TEV is also always under observation by workers in central control and these operators can stop the TEV if any off-normal condition is detected. Along the route, the TEV moves first down the decline of the North Ramp (with the steepest grade in the operating facility) and then along large tunnels (access mains) to the emplacement drift. While entrance into the operations area of the subsurface is restricted, workers may be present at various points in the subsurface for maintenance, security or for in situ monitoring and testing associated with performance confirmation. As on the surface, access along the access main is not restricted but operational controls restrict workers from remaining in close proximity to the TEV for any length of time. The subsurface route also encounters rail switches as the access main divides into various segments. Equipment involved in node operations: • TEV • WP • WP pallet • TEV rail system (including running rails, third rail power, rail base, and rail switches). Additional equipment present during node operations: • Access main and ramp ground support system • Electrical and communications utilities cable systems.
4	Node 4 on the PFD represents the movement of the waste package within the TEV from the start of the emplacement turnout drift into the emplacement drift and the subsequent operations of the TEV to emplace (position) the waste package within the emplacement drift with other waste packages. After the TEV (which is stopped) completes a position calibration, central control authorizes the access door to open. Upon receiving clearance from central control, the TEV proceeds through the turnout drift switch and into the access door threshold, entering the emplacement drift turnout. After the TEV clears the doorway, the access door is closed by central control. The TEV moves to a specific location in the drift and stops. After receiving clearance, the TEV opens the front and rear shield doors and extends its base-plate. Then, the TEV moves slowly forward to the emplacement position. At this point, the TEV again stops, and lowers the shield enclosure to the lowest position. This action effectively places the pallet and waste package on the emplacement drift's invert (base). The TEV then proceeds to exit the emplacement drift. Again after receiving clearance, the TEV slowly moves away from the waste package to a predetermined distance from the waste package. At this point the TEV raises the shield enclosure and closes both shield doors. Thereafter, TEV proceeds to move to the access door. As the TEV approaches the door, the emplacement access door is opened, and the TEV proceeds into the access door threshold and back into the emplacement drift turnout. The emplacement access door is closed, completing the node operations. Equipment involved in node operations: • TEV • WP • WP pallet • TEV rail system (including running rails, third rail power, rail base, and rail switches, including the switch at the turnout drift) • Emplacement access door. Additional equipment present during node operations: • Emplacement Drift ground support system • Invert support system.

NOTE: [a] CRCF has two process lines and only the CRCF has a Loadout Vestibule.

CRCF = Canister Receipt and Closure Facility; IHF = Initial Handling Facility; PFD = process flow diagram; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Table 6. Equipment Descriptions for Example

Equipment Type	Description
TEV	The TEV is a remotely-controlled, rail-based vehicle, which is powered by a third rail. It operates without an on-board crew, and is controlled by an on-board programmable logic controller system. The TEV's progress is monitored from a central control (i.e., the Central Control Center Facility). For transport, the TEV has eight wheels, each driven by an electric motor. Disc brakes are integral to the motors on each wheel. In addition, the TEV has a separate braking system, independent of the wheel brakes, which is used to stop the TEV in the event of a failure of the wheel brakes. To lower and raise the TEV shield enclosure, six screw jacks are mounted on the TEV exterior with the front and rear jacks used in normal operations. The two central jacks act as backup units. The maximum speed of the electric motors conforms to ASME NOG-1-2004. 2005, *Rules for Construction of Overhead and Gantry Cranes (Top Running Bridge, Multiple Girder)* (Ref. 2.2.4). The TEV has approximately 0.25 m (10 in) of shielding, formed by metal (stainless steel and depleted uranium) and polymer composite (as a neutron shielding).
Waste Package	Waste packages are emplaced in the subsurface, each containing canisterized nuclear waste. A nuclear waste canister (or several canisters) is sealed into a cylindrical waste package within surface handling facilities prior to the transport into the subsurface. The general waste package design consists of two concentric cylinders in which the canisters are placed. The inner vessel is stainless steel and the outer corrosion barrier is Alloy 22, a corrosion-resistant, nickel-based alloy. The waste package itself consists of a single design with six configurations: 1. TAD waste package (holding a TAD canister containing either 21-PWR fuel assemblies or 44-BWR fuel assemblies 2. 5-DHLW/DOE Short 3. 5-DHLW/DOE Long 4. 2-MCO/2-DHLW 5. Naval Short 6. Naval Long.
Rail System	The TEV uses a dedicated rail line for movement on the surface and in the subsurface. The running rail of this system is 171 lb (weight per linear yard) (85 kg/m) crane rail with a gauge of 11 ft (3.35 m). Power for operation is provided by a third rail, mounted outside the running rail. On the surface, the running rail is directly anchored (i.e., without ties) to a concrete pad extending along the alignment. In the subsurface, along the access mains, the rail is directly anchored to a reinforced concrete slab poured on top of the construction invert. Within emplacement drifts, the running rail is supported by a steel structure or frame anchored to the base of the opening (i.e., the invert). Spacing between these steel members is filled with ballast.
Facility Shield Door	A shield door provides equipment and personnel access to the WP Loadout Room. The loadout shield door is a dual-panel slide-open type door, made up of two side-by-side 16-inch-thick steel plates with each weighing approximately 55 tons (110 tons for the door set). Each door is operated by an electric motor turning a screw drive, which interacts with a door mounted bracket. The door overlaps the aperture on the top, bottom, and both sides to provide shielding. A staggered door edge provides shielding between the mating seams. The weight of the door is supported by heavy-duty rollers under the bottom of the door, which run in a floor-recessed channel. The shield doors are controlled from the central control operations room. A local emergency open button is provided local to the doors, inside of the Waste Package Loadout Area. The doors are also provided with obstruction sensors, such that they cannot close if the TEV, or other equipment, is in the way of the doors closing.

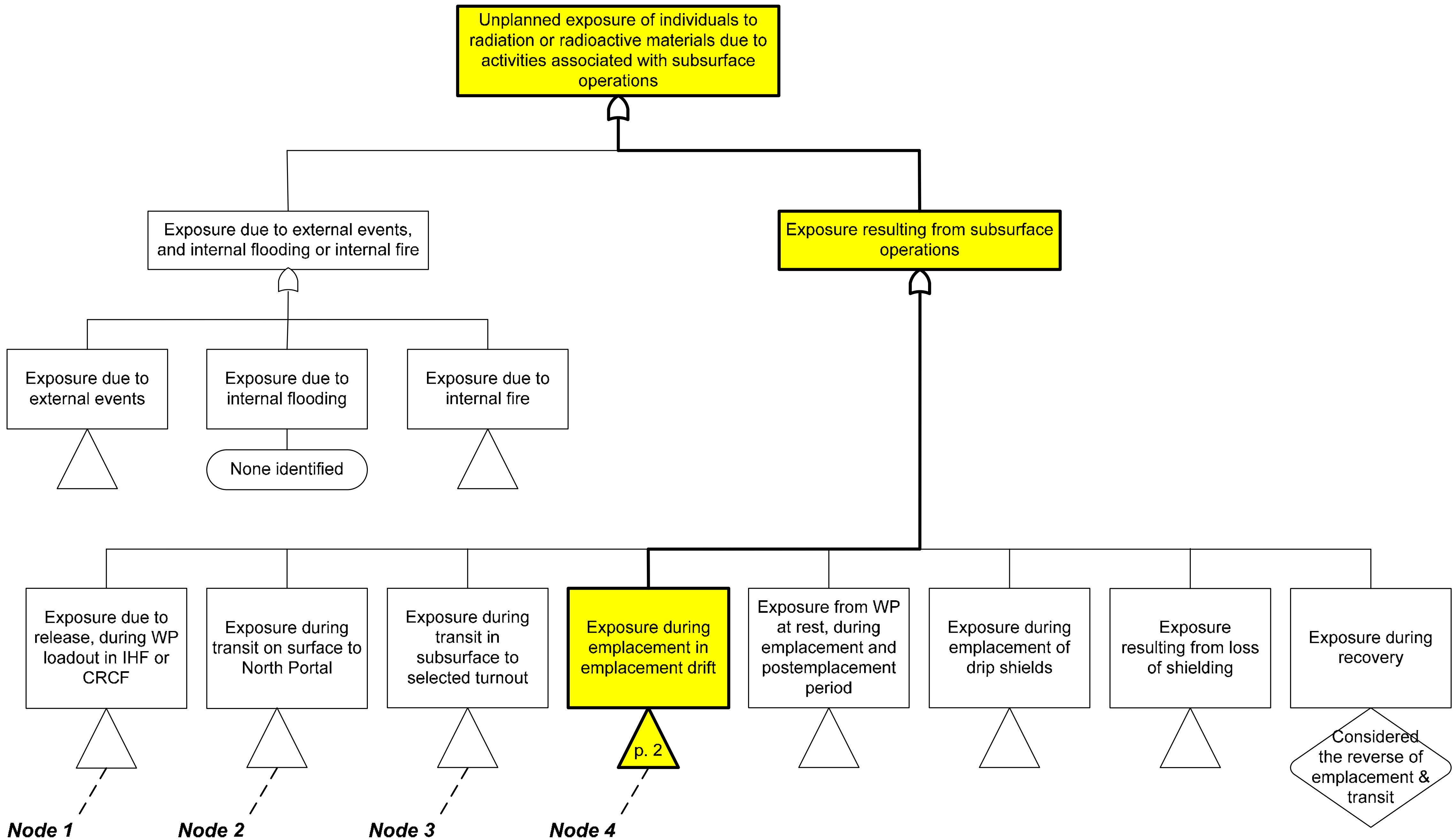
Table 6. Equipment Descriptions for Example (Continued)

Equipment Type	Description
Pallet	During waste package handling operations, the waste package rests on a waste package pallet (a metal frame or cradle). The pallet consists of two V-shaped supports of Alloy 22 metal, which are tied together by stainless steel tubes. To prevent damage to the waste package, the waste package is handled solely using this pallet. This ensures that the handling equipment does not make direct contact with the waste package during normal Subsurface Operations.
Emplacement Access Door	The emplacement access door is a counter-opening, two-panel design in which one panel opens inward and the other panel opens outward. The overall doorway is has a clear opening of 5.0 x 3.8 m (16.5 x 12.4 ft) in width/height, and the door is 5.9 x 4.3 m (19.3 x 14.1 ft) in overall dimension to accommodate door framing. The access doors (both door panels) weigh approximately 2.7 metric tons (3.0 short tons). For operation, the two door panels are linked together by an equalizer bar/tune-up bar that provides the linkage required for counter-opening the assembly. The linkage also contains an adjustment mechanism to provide fine-tuning of the door sealing. This design uses a single actuator and linkage bar to open and close both doors, thereby reducing the maintenance cost when compared to dual actuators. The actuator provides the driving force necessary to open the emplacement access door.
Overhead Door (CRCF)	The exterior door on the CRCF Loadout Vestibule is a vertically-opening, overhead telescoping (roll-up) door which does not function as a shield door. To permit the exit of the TEV, the door has a minimum opening width/height of 4.8 x 3.5 m (15.9 x 11.4 ft), allowing 76 mm (3 in) of clearance around the TEV mechanical operating envelope. Using an approximate measure of 50 kg/m^2 (10 lbs/ft^2), the door weighs on the order 1.0 metric ton (1.1 short tons), including a 25% allowance for framing elements. The overhead door is operated by electric power with an auxiliary hand chain. The door is surface-mounted with guides set back a sufficient distance to provide a clear opening when door is in the open position. The overhead door, hardware, and anchors are designed to withstand a wind pressure of 0.96 kPa (20 psf) without damage. The vestibule roll-up doors are not opened unless the outside wind speed and the radiation within the Loadout Vestibule are below the set threshold values.

NOTE: BWR = boiling water reactor; CRCF = Canister Receipt and Closure Facility; DHLW = defense high-level radioactive waste; DOE = U.S. Department of Energy; IHF = Initial Handling Facility; MCO = multicanister overpack; PFD = process flow diagram; PWR = pressurized water reactor; TAD = transportation, aging, and disposal; TEV = transport and emplacement vehicle; WP = waste package.

Source: Descriptions are based on information in Attachment A.

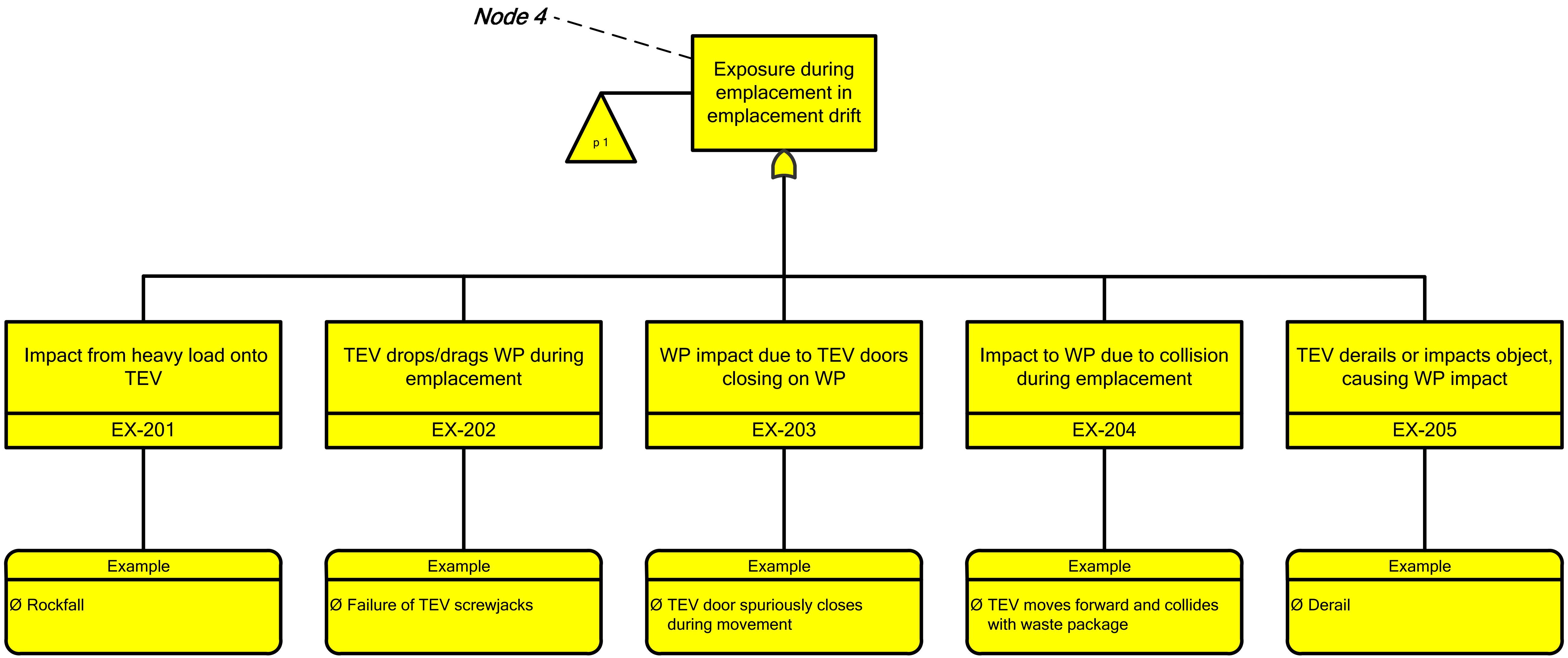
For the Subsurface Operations, the analyst defines the next level in terms of the PFD operational boundaries. In accordance with the generalized logic structure for the PCSA MLD, the boundaries should be functions, operational areas, or major systems where the events occur. The operational areas are not necessarily divided by physical boundaries, such as facility rooms, but rather by activities that are related or that share a goal. For the example analysis, the nodes identified in the PFD are reviewed for the facility's operational goals.



NOTE: Unplanned exposure of individuals to radiation or radioactive materials is referred to as "exposure" in this figure.
CRCF = Canister Handling and Closure Facility; IHF = Initial Handling Facility; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Figure 8. Unplanned Exposure Of Individuals To Radiation Or Radioactive Materials Due To Activities Associated With Subsurface Operations (Page 1)



NOTE: Unplanned exposure of individuals to radiation or radioactive materials is referred to as simply "exposure" in this figure.
TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Figure 9. Unplanned Exposure Of Individuals To Radiation Or Radioactive Materials Due To Activities Associated With Subsurface Operations (Page 2)

Although the facility processes are segregated into four operational nodes for this example, additional systems or operations can be identified where exposure can occur, as shown on the MLD (Figure 8).

These activities which can lead to an exposure are summarized as follows:

- **During WP Loadout in IHF or CRCF**: Includes all activities that can potentially occur from the time the TEV raises and engages the waste package pallet at the loadout station until the outer or shield access door is closed behind the TEV as it exits a waste handling facility.

  - Example equipment failure: During lifting of pallet, all screw jacks fail, dropping waste package.

  - Example human failure: Worker closes shield door before TEV passes through doorway.

- **During transit on surface to North Portal**: Includes all activities that can potentially occur during the TEV transit on the surface from the time the TEV exits a waste handling facility to the time it enters the North Portal.

  - Example equipment failure: TEV derails and impacts object.

- **During transit in the subsurface to the selected turnout**: Includes all activities that can potentially occur during the TEV transit in the subsurface from the time the TEV enters the North Portal to the time the TEV stops at the switch leading to the selected emplacement drift turnout.

  - Example equipment failure: TEV rail fails, derailing TEV which in turn strikes a rock wall.

  - Example human failure: Worker closes switch along TEV path, causing TEV to derail.

- **During emplacement in an emplacement drift**: Includes all activities for waste package emplacement that can potentially occur from the time the TEV enters the emplacement drift turnout until the TEV exits the turnout and the access door is closed behind the TEV.

  - Example equipment failure: TEV fails to stop during emplacing a waste package.

  - Example human failure: Worker closes access door while TEV is passing through doorway.

- **From a waste package at rest during the post-emplacement period**: Includes all events that can potentially occur from the time the waste package emplacement to the start of closure activities such as drip shield emplacement.
  - Example equipment failure: Rockfall onto waste package during post-emplacement.
- **During emplacement of drip shields**: Includes all events that can potentially occur during the activities for emplacing drip shields over the waste packages in an emplacement drift at the start of closure.
  - Example equipment failure: Running rail fails, derailing gantry.
  - Example human failure: A worker lowers the drip shield rapidly.
- **Loss of shielding**: Includes activities where a potential exposure occurs due to shielding failure alone, and can occur during the transit of the TEV on surface or when the waste packages are at rest in the emplacement drift.
  - Example equipment failure: TEV front shield doors open inadvertently during travel through a rail crossing, exposing workers in waiting vehicles.
  - Example human failure: Worker inadvertently enters an emplacement drift, exposing himself/herself.
- **During recovery (waste package movement)**: Recovery is defined in this analysis to apply to the movement of a limited number of waste packages from and to locations in the subsurface or to return a waste package to a waste handling facility. Recovery as defined does not include activities to respond to an off-normal event, such as a waste package drop in an emplacement drift. The term is also distinct from *retrieval*, which involves the permanent removal of all emplaced waste packages, as defined in 10 CFR 63.2 (Ref. 2.3.1). Retrieval is not included in preclosure safety analyses. Recovery includes all events that can potentially occur during the activities to remove, as part of normal operations, a waste package from an emplacement drift and move the package to another drift or return the package to a surface facility. Essentially, recovery operations are the reverse of emplacement and transit operations and therefore examples of equipment or human error are the same as for emplacement and transit operations. Therefore, event sequences specifically for recovery are not developed because they are bounded by event sequences for emplacement.

The process of identifying more specific types of failures (i.e., developing subsequent MLD levels) is continued until an event that initiates each failure is identifiable. Following the branch for exposure during emplacement activities (Figure 9, p. 2), the analyst identified five groups of initiating events, and assigned index numbers EX-201 to EX-205. As these events are part of an example, they are labeled "EX", however, initiating events for Subsurface Operations are labeled "SSO" in Section 6.

The first initiator, EX-201, captures the potential for an impact of a heavy load onto the TEV. For example, a rockfall would be a heavy load onto the TEV. A rockfall can occur at any point in the emplacement process.

The second initiator, EX-202, relates to the potential for a waste package to be dropped or dragged during the emplacement process. Prior to emplacement, the base-plate of the TEV is extended, leaving the waste package and pallet to be support at a height directly above the invert. At this point, upon the failure of the four lifting screw jacks of the shield enclosure or the shearing of the lifting features, the waste package could hit the invert.

This event differs from EX-201 in that the challenge to the waste package is a drop rather than a projectile loading. A similar event can occur if the TEV, in moving away from the newly emplaced waste package, inadvertently raises the shield enclosure and engaging the pallet at one end only. As the TEV continues to move away, it drags the pallet and waste package, leading to an eventual drop of the waste package from the pallet onto the invert.

The third initiator, EX-203, encompasses the potential direct impact onto the waste package if the TEV shield doors are prematurely activated when the TEV is in proximity to a previously emplaced waste package. An example identified of this event is a spurious signal which would activate the TEV door control at the wrong time. The impact to the waste package is in the form of a vertical pinching load to the side of the waste package which differs from the loadings of a drop or impact onto the TEV.

EX-204 is the fourth initiator, which relates to the movement of the TEV in the emplacement ate drift. Waste packages are emplaced in close proximity to each other, and an error in control at this point can lead to the TEV running directly into an emplaced waste package. An example of this initiator is a spurious signal which would activate the TEV to continue moving at full operational speed instead of stopping.

The final initiator, EX-205 describes the potential for a collision of the TEV causing an impact to the waste package. An example of this event would be the derailment of the TEV due to a piece of rock on the track.

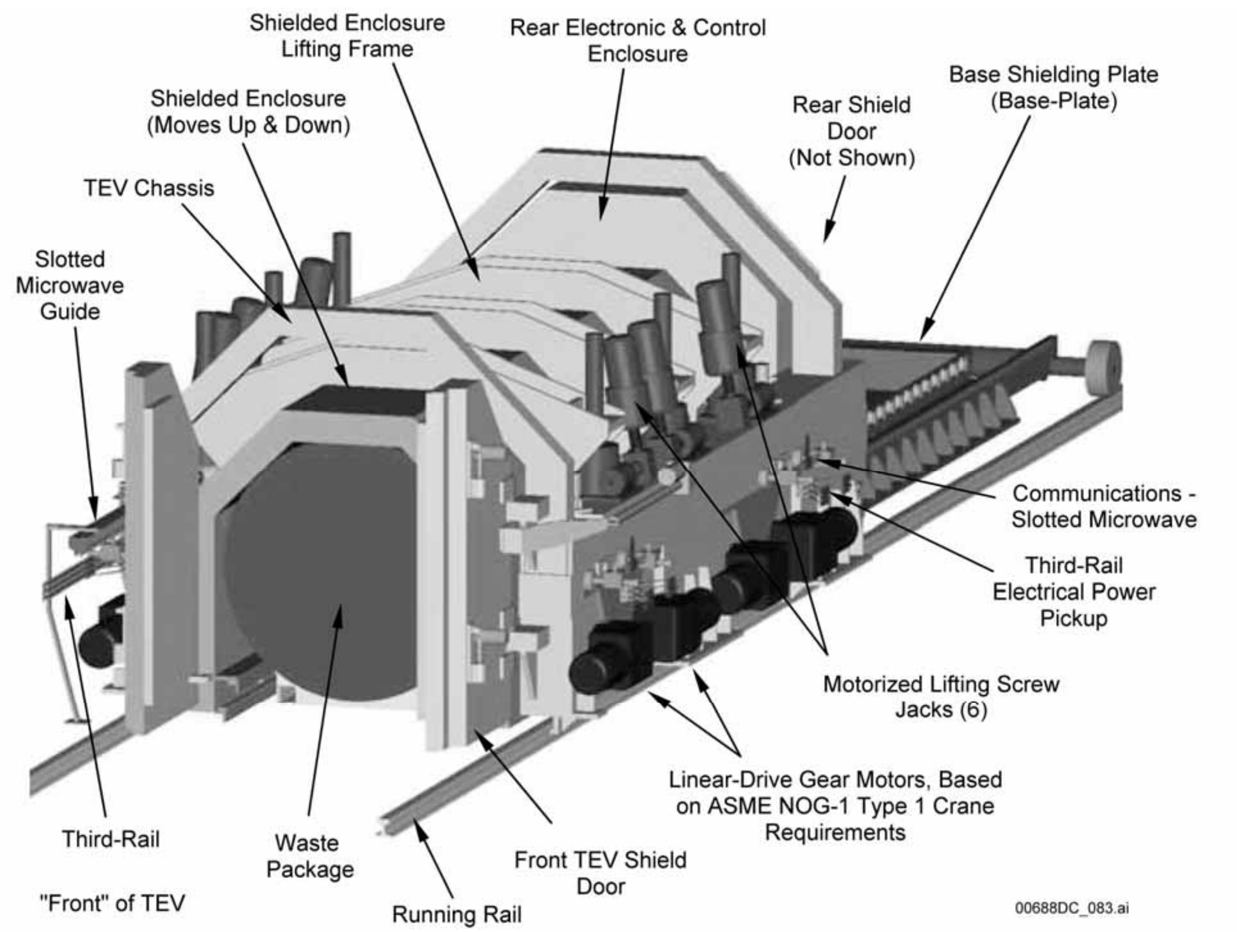
Each set of initiating events in the MLD is similarly developed for other parts of the MLD and evaluated. The level at which initiating events are identified is the highest level for which the same system response event tree applies. Lower levels provide failure events associated with the initiating event. .

4.3.4.3 HAZOP Evaluation Development

In addition to the MLD development, an independent study of the processes identified in the PFD is conducted by a team of subject matter experts, analysts, and operations personnel. This is a HAZOP evaluation (Section 4.3.1.3), which is employed to support the MLD development to assure that the facility (or operations area) operations is well understood and that comprehensive identification of initiating events is accomplished. The team evaluates each node in the PFD using a set of HAZOP evaluation parameters and deviations, and the results of the HAZOP evaluation are compared to the results of the MLD development. Any initiating events that are identified in the HAZOP evaluation, but not already identified in the MLD are added and assigned an MLD index number for traceability. Thus, the MLD becomes the conduit for events identified in the HAZOP evaluation, and not previously identified, for inclusion in the ESDs. The HAZOP evaluation is not used for any other purpose in this analysis. The detailed breakdown of the initiating events from the MLD into contributing failure modes is achieved in fault trees as part of the quantification of the event sequences.

To demonstrate this process for Subsurface Operations, activities involved in the emplacement of the waste package within an emplacement drift are examined (shown on the MLD as "Exposure during emplacement in emplacement drift" (Figure 9). As discussed previously, emplacement activities are identified under Node 4 in the PFD. The evaluation operations for Node 4 are provided in the PFD of Figure 7. Movement is one parameter of concern for TEV operations. Deviations from normal operational movement (e.g., movement that is too far, too little, the wrong direction, becomes stuck) are considered, and postulated causes (e.g., human or mechanical failure), consequences (e.g., radioactive release resulting from waste package impact), and potential preventive/mitigative design features are identified.

Figure 10 depicts the TEV with specific callouts for its individual components. Upon examination of the figure, the actions specified in the HAZOP evaluation such as "extend base-plate" or "lower shield enclosure," and other deviations, can be visualized.



Source: Modified from (Ref. 2.2.34), Figure 1.

Figure 10. Illustration of the Transport and Emplacement Vehicle

Referring to Table 7, the parameter “Movement” signifies the movement of the TEV and the parameter "Direction" refers to movement direction of the front of the TEV. The deviations identified are based on these HAZOP evaluation guidewords, identified for this parameter as “More” (moved too far); “Less” (moved too little) and "Reverse" (the direction is the logical opposite of the intended direction). Note that these occurrences and the consequences are only postulated at this point and not yet quantified.

- The deviation “More” (in Node Item Number 4.9) indicates that the TEV moved farther than expected. If the TEV is in proximity to an emplaced waste package, this could result in a collision and damage to the waste package.

- The deviation “Less” (in Node Item Number 4.10) indicates that the TEV moved too little (less than expected) during emplacement. There are however, no safety consequences identified for this deviation as stopping short of the emplacement position does not provide an opportunity for collision or other impact to a waste package.

- The “Reverse” deviation (in Node Item Number 4.12) for this operational parameter could impact safety because, if the TEV moves in the wrong direction, (when it should be moving towards an emplaced waste package) could result in a collision with an access door resulting in damage to a waste package.

In addition, for operations associated with this node, the HAZOP evaluation also presented several deviations that are specific to the TEV and for which no standard HAZOP evaluation guidewords exist. One example of a miscellaneous "Other than" guideword for a Movement parameter/deviation is derailment (Node Item Number 4.3).

For every operational node, each deviation for each parameter in the HAZOP evaluation is assessed likewise. Any other relevant information is captured in the notes column. Deviations for which hypothetical safety consequences are identified are then assigned MLD index numbers to correlate the information to a specific event on the MLD. For example, the deviation involving the drop of the waste package (Node Item Number 4.14) is assigned the MLD index number EX-202, and the derailment during movement into the drift (Node Item Number 4.3) is assigned the MLD index number EX-205. Referring again to the MLD, Figure 9, these MLD index numbers are denoted for the two initiating events. Such correlations between the HAZOP evaluation and MLD confirm the comprehensiveness of the MLD and increases confidence that the significant event sequences are identified and developed.

Table 8 is provided to illustrate the interrelationship of the information between the PFD, MLD, and the HAZOP evaluation for the example analysis. The table presents the deviation, event cause and consequence and notes whether the deviation was originally included in the MLD or added later to the MLD as a result of the HAZOP evaluation. In this example, no additional initiating events were identified by the HAZOP for inclusion in the MLD because all deviations not in the MLD had no safety consequences.

Table 7. Example Hazard and Operability Evaluation for Exposure during Emplacement in Emplacement Drift (Partial Analysis)

Node Item Number	Parameter	Deviation Considered	Postulated Cause	Hypothetical Consequence	Potential Prevention/Mitigation Design of Operational Feature	Note	Related MLD Identifier
Facility/Operation: Subsurface				**Process:** Waste Package Emplacement Operations			
Node 4: Emplace Waste Package in drift				**Process/Equipment:** TEV, Waste Package, Rail			
Guidewords: No, More, Less, Reverse, Other Than, As Well as				**Consequence Categories:** Radioactive Release, Lack of Shielding, Criticality			
4.1	Shielding	(Less or No) Damage of TEV shield enclosure	Rockfall	Direct exposure	1 - Design TEV 2 - Ground support system	Verify PEFA. Ground support system prevents rock movement.	EX-201
4.2	Emplacement access door open	(Less or No) Door not completely opened	Human failure or mechanical failure	Potential release of radioactive material due to collision	1 - TEV design 2 - Emplacement access door design 3 - Procedures and training	Emplacement access door independently controlled by operator.	EX-204
4.3	Movement (into drift)	(Other Than) Derailment	Obstructions on rail or mechanical failure	Potential radioactive release direct exposure	1 - Training and procedures 2 - TEV design 3 - Rail design	Validate with PEFA. TEV shielding can potentially be deformed due to roll over.	EX-205
4.4	Movement (into drift)	(No) TEV stuck in doorway	Mechanical failure	No safety consequence		Increase exposure time to emplacement access door close.	N/A
4.5	Emplacement access door close	(Other Than) Inadvertent closure of emplacement access door while TEV in doorway	Human failure or mechanical failure	Potential release of radioactive material due to collision	1 - Procedures and training 2 - TEV design	Validate with PEFA.	EX-201
4.6	Position calibration	(Other Than) Miscalibrates position	Mechanical failure	Potential release of radioactive material due to collision	1 -Procedures and training 2 - TEV design	TEV carries diverse positional sensors and cameras. Result is collision with a WP.	EX-204
4.7	Shielding (door open)	(Less or No) Door not completely opened	Mechanical failure	Potential release of radioactive material due to collision of door with WP in drift	1 - TEV design		EX-204
4.8	Extend (base-plate)	(No or Less) Does not extend	Mechanical failure	No safety consequence			N/A
4.9	Movement (to emplacement point)	(More) TEV moves too far	Mechanical failure	Potential release of radioactive material due to collision of TEV door with WP in drift or drift itself	1 - TEV design 2 - WP design 3 - Procedures and training	Operator observing emplacement and stop TEV if necessary.	EX-204
4.10	Movement (to emplacement point)	(Less) TEV moves too little	Mechanical failure	No safety consequence			N/A
4.11	Speed	(More) TEV moves too fast	Mechanical failure	No safety consequence		Precursor to damaging collision with WP.	N/A
4.12	Direction	(Reverse) TEV goes backwards instead of forwards	Mechanical failure	Potential release of radioactive material due to collision with emplace access door	1 - TEV design 2 - WP design 3 - Procedures and training		EX-204
4.13	Lower (WP)	(Other Than) Asymmetrical lowering	Screw jack failure	No safety consequence			N/A
4.14	Lower (WP)	(Other Than) Drop	Mechanical failure	Potential radioactive release	1 - Design of TEV and WP	Verify maximum drop of 1ft	EX-202
4.15	Lower (WP)	(Less or No) Not lowered enough - WP partially unloaded	Mechanical failure	No safety consequence		Precursor to potential WP damage due to dragging while backing TEV out.	EX-202
4.16	Lower (WP)	(Less or No) Not lowered enough - WP not unloaded	Mechanical failure	No safety consequence		Precursor to bringing WP back out, however the TEV is inspected on the way out.	N/A

Source: Original

Table 8. Example Interfaces between the Master Logic Diagram and Hazard and Operability Evaluation for Exposure during Emplacement in Emplacement Drift

MLD Index #	Deviation	Event Cause	Consequence	Originally Included in MLD [a]
EX-201	(Less or No) Damage of TEV shield enclosure	Rockfall	Direct exposure	Y
EX-201	(Other Than) Inadvertent closure of emplacement access door while TEV in doorway	Human failure or mechanical failure	Potential release of radioactive material due to collision	Y
EX-202	(Other Than) Drop	Mechanical failure	Potential radioactive release	Y
EX-202	(Less or No) Not lowered enough - WP partially unloaded	Mechanical failure	No safety consequence	Y
N/A	(Less or No) Not lowered enough - WP not unloaded	Mechanical failure	No safety consequence	N
EX-204	(Less or No) Door not completely opened	Human failure or mechanical failure	Potential release of radioactive material due to collision	Y
N/A	(No) TEV stuck in doorway	Mechanical failure	No safety consequence	N
EX-204	(Other Than) Miscalibrates position	Mechanical failure	Potential release of radioactive material due to collision	Y
EX-204	(Less or No) Door not completely opened	Mechanical failure	Potential release of radioactive material due to collision of door with WP in drift	Y
N/A	(No or Less) Does not extend	Mechanical failure	No safety consequence	N
EX-204	(More) TEV moves too far	Mechanical failure	Potential release of radioactive material due to collision of TEV door with WP in drift or drift itself	Y
N/A	(Less) TEV moves too little	Mechanical failure	No safety consequence	N
N/A	(More) TEV moves too fast	Mechanical failure	No safety consequence	N
EX-204	(Reverse) TEV goes backwards instead of forwards	Mechanical failure	Potential release of radioactive material due to collision with emplace access door	Y
N/A	(Other Than) Asymmetrical lowering	Screw jack failure	No safety consequence	N
EX-205	(Other Than) Derailment	Obstructions on rail or mechanical failure	Potential radioactive release direct exposure	Y

NOTE: [a] The HAZOP evaluation did not identity any additional initiating events to the existing MLD.
TEV = transport and emplacement vehicle; HAZOP = hazard and operability; MLD = master logic diagram.

Source: Original

4.3.4.4 Event Sequence Diagram Development

After the HAZOP evaluation and MLD results are correlated and the MLD is complete, analysts group initiating events by initiator types, system response, and waste form. Based on this grouping ESD development can begin.

As detailed in Section 4.3.2.1 and as shown in Figure 11, the ESDs are a graphical communication tool to aid the understanding of the initiating events and the later development of the event trees. An ESD is read left to right: initiating events (circles), through pivotal events (success or failure) (rectangles), to end states (hexagons). The small circles on the left are descriptions that are summarized or paraphrased from one or more initiating events identified in the MLD. More than one MLD initiating event may be represented by a single small circle because events and system responses from different operational nodes are often the same.

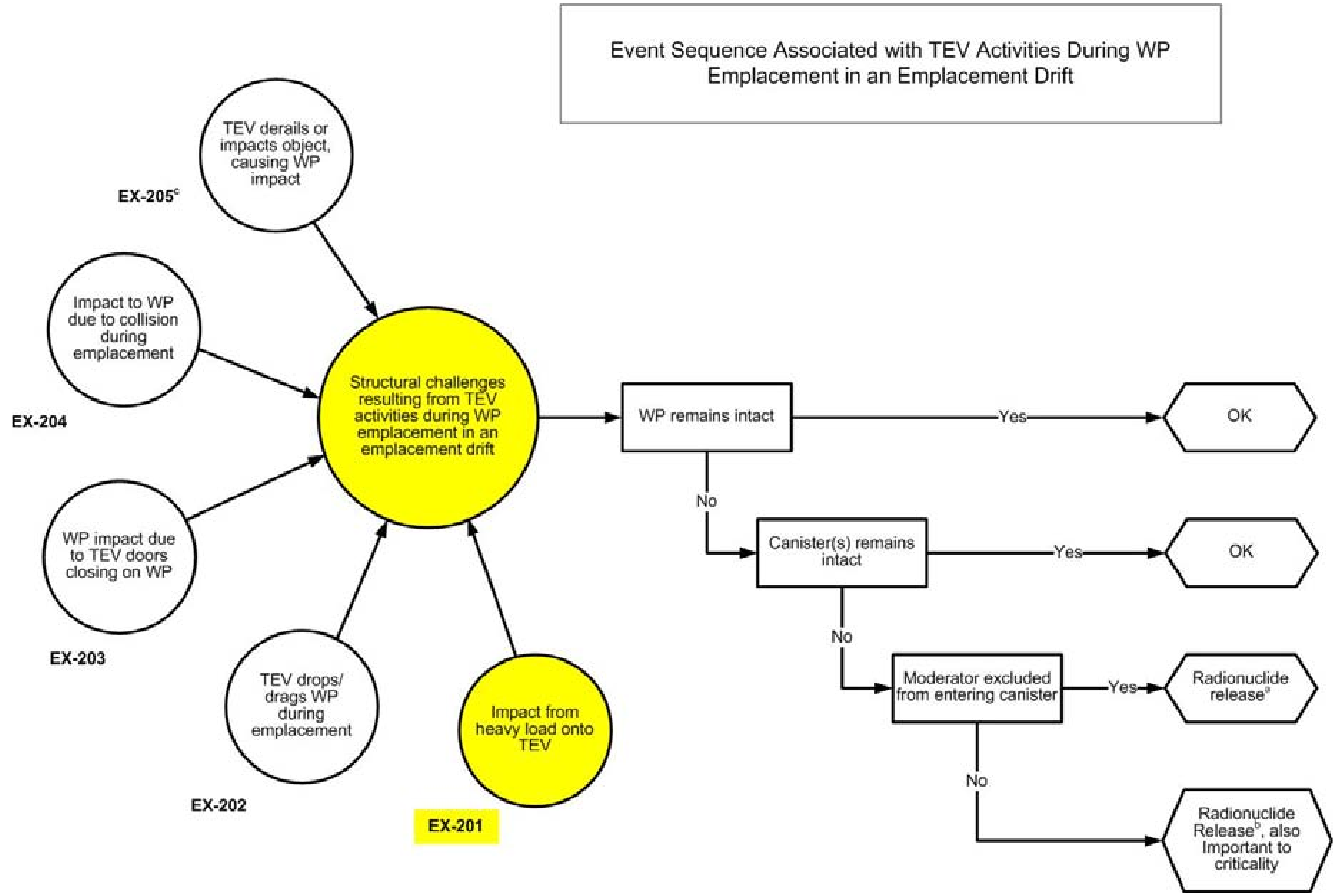
The set of small circles on an ESD shares the same system responses (pivotal events), but each small circle has a unique set of probabilities for these system responses. Refer also to Section 4.3.2.2.

If events are grouped for a small circle on an ESD, the relevant MLD index numbers are listed adjacent to the small circle. Table 8 provides a brief description of the initiating events encompassed in the small circle “Impact from heavy load onto TEV” (Figure 11). Following the flow of the ESD to the right, the small circles point to a central, large circle. The large circle represents the aggregate initiating event. Each small circle on an ESD can be considered a subset of the large circle.

The possibility that the waste package might breach or remain intact is the first pivotal event. As discussed in the *Subsurface Reliability and Event Sequence Categorization Analysis* (Ref. 2.4.1), categorization of initiating events is based on the aggregate (i.e., large circle).

The probability of occurrence of an event sequence is the product of the initiating event frequency and pivotal event conditional probabilities. The separation into small circles, however, is necessary because the conditional probability of pivotal events in the system response event tree differs for each small circle. To obtain the proper event sequence frequency, therefore, it is necessary to quantify the event sequences emanating from each small circle.

Continuing to the right, the path from the large circle is the logical progression of an event sequence through each pivotal event (displayed as boxes). For the initiating events in Figure 12, the analyst considers the possible events that might follow. For example, if a mechanical challenge to the canister occurred, what could happen? The canister might breach, or it might remain intact. This is an important distinction, and the analyst identifies this as the first pivotal event.



NOTE: [a] "Radionuclide release" describes a condition where radioactive material has been released from the container creating an inhalation or ingestion hazard which is accompanied by the dose received from emersion in the plume, and direct exposure. "Direct exposure" is defined that condition where individuals are directly exposed to the radiation beam streaming through areas where shielding has been compromised.

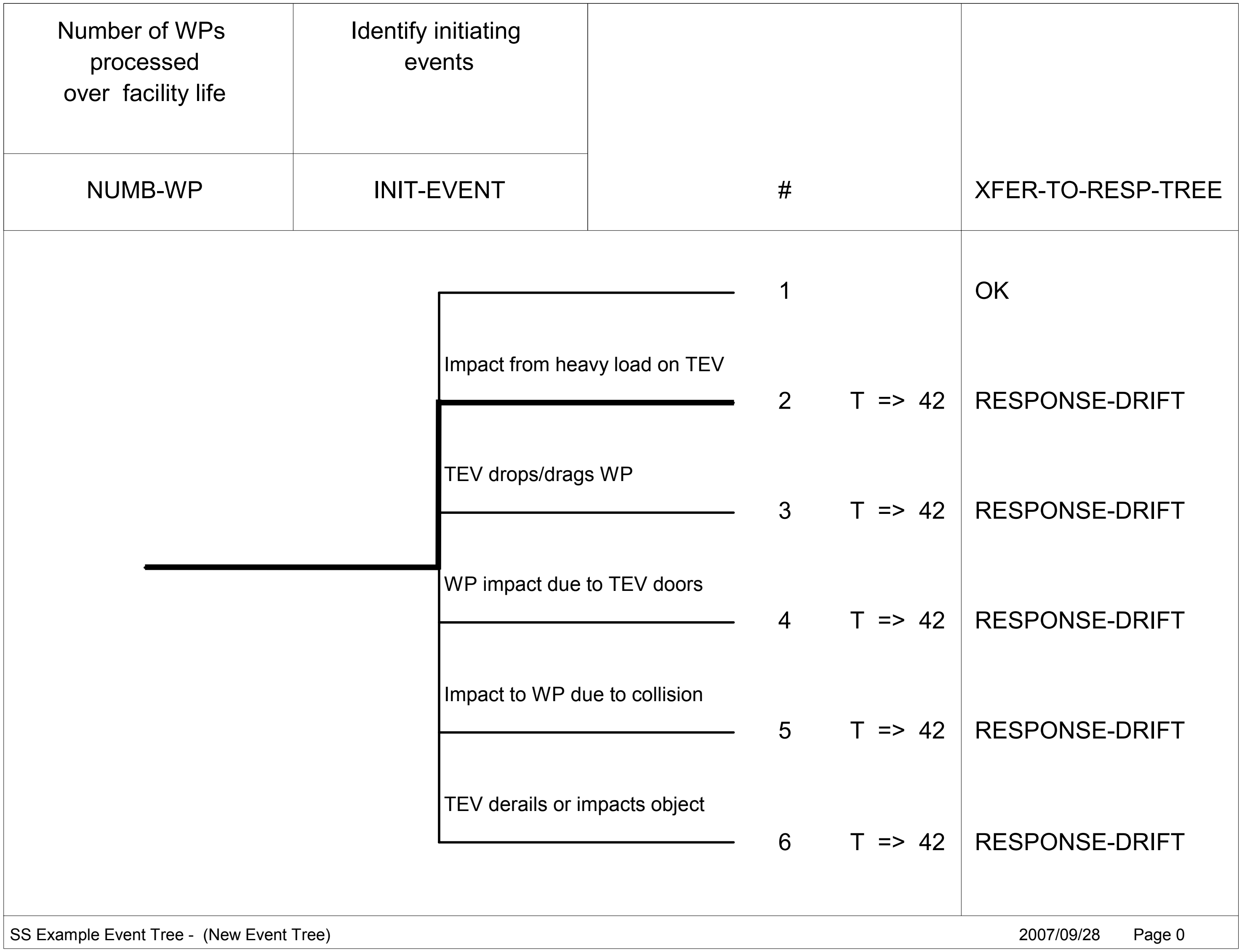
"Radionuclide release, also important to criticality" describes a condition in which (a) the containment boundaries, such as canister and waste package containment, have been compromised, releasing radioactive material; and (b) liquid moderator is present and may enter the canister .

Example Facility (EX) numbers next to the smaller circles are references to the example master logic diagram (MLD)

[b] TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Figure 11. Example Event Sequence Diagram for Exposure during Emplacement in Emplacement Drift with Emphasis on Impact from heavy load onto TEV (EX-201)



NOTE: INIT = initiating events; NUMB = number; RESP = response; SS = subsurface; T = transfer; TEV = transport and emplacement vehicle; WP = waste package; XFER = transfer.

Source: Original

Figure 12. Initiator Event Tree for Example of Emplacement in an Emplacement Drift

The analyst looks at the success and failure of this first pivotal event to determine either a next pivotal event or, if no subsequent pivotal event is identified, then an end state. Following the success branch for waste package containment in the example after the initiating event (Figure 3), given the waste package remains intact, radioactive material cannot be released. If the waste package remains intact, the end state is “OK” (end state #1, Figure 13). If the waste package does not remain intact, the condition of the canister is examined. If the canister remains intact, the end state is again “OK” (end state #2, Figure 13), if not, a release has occurred and the end state is “Radionuclide Release, Unfiltered” (end state #3, Figure 13). This process is continued for each pivotal event, considering paths for success and failure for each, leading either to one or more consecutive pivotal events or to an end state. Explanatory annotations on the ESD are included by the analyst to ensure that the meaning of each pivotal event is unambiguous. In the ESD, the analyst follows this logical progression for each path, identifying canister as the next system response. Also identified is a unique pivotal event that represents a condition, moderator ingress, which is used as the basis for the identification of event sequences as important to criticality.

The overall series of pivotal events are described as follows:

- Waste Package Containment. Success of waste package containment precludes a release.

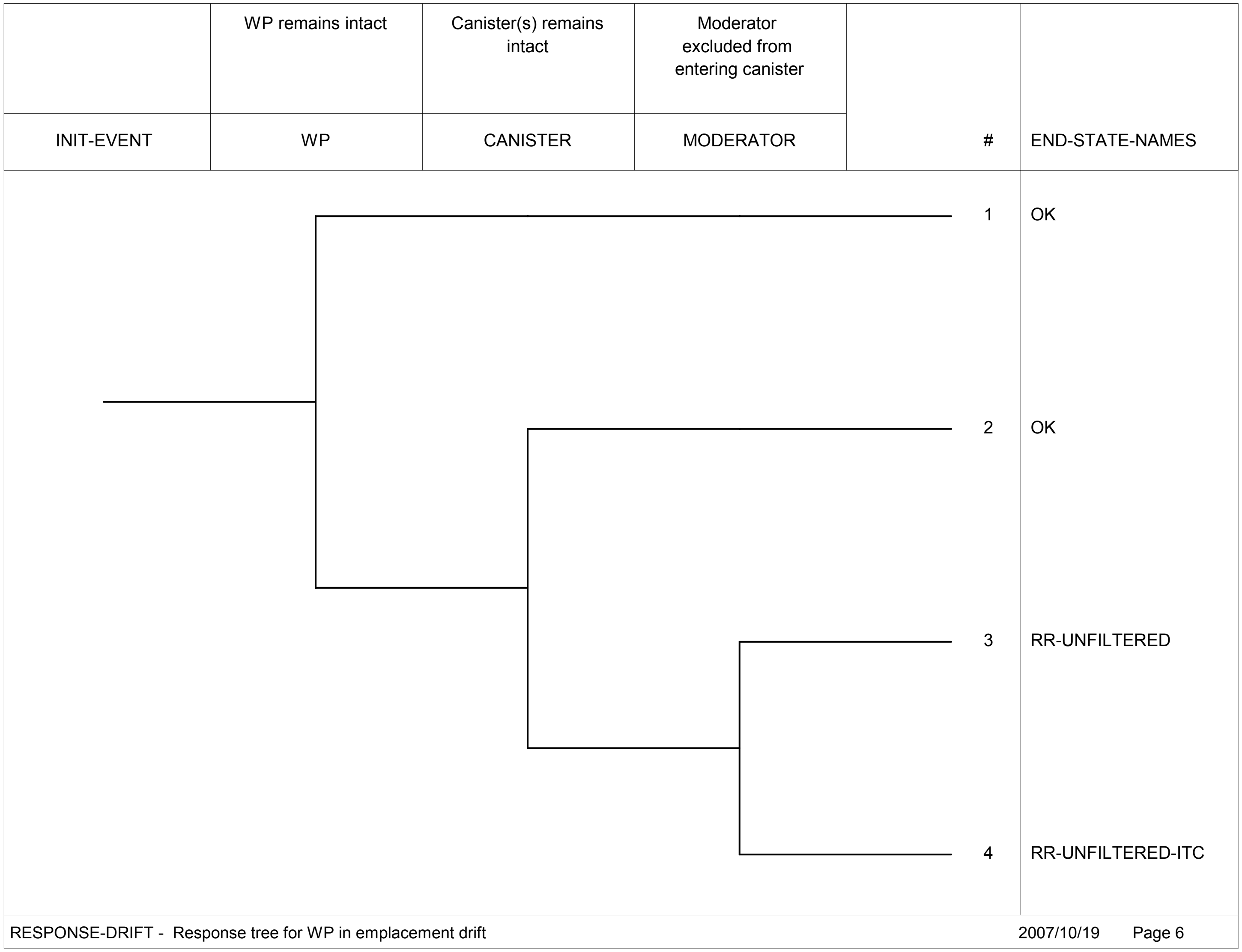
- Canister Containment. Success of canister containment precludes a release.

- Moderator Ingress. If a condition arises in which a moderator (e.g., water from a fire suppression system) is present, but is successfully isolated from the waste form by, for example, the canister’s containment barrier or if a moderator is not present, then a release important to criticality is avoided. If a moderator is present and able to contact the waste form, a potential for possible criticality exists. Note that failure to prevent moderator ingress does not imply an inevitable criticality event, but rather indicates that further analysis must be done to show either that the event sequence will not result in criticality or that the event sequence is beyond Category 2.

4.3.4.5 Event Tree Development

Event trees developed from the ESDs are graphical logic models used for quantitative evaluation of event sequences. There is a direct correlation from the small circles, boxes, paths, and end states on the ESD to the initiating events, pivotal events, paths, and end states on the event trees for the same sequence.

For the example, the analyst uses SAPHIRE computer software to set up the models. Initiating event frequency and probability values are input into the model later for quantification.



NOTE: DE = direct exposure; INIT = initiating; ITC = important to criticality; RR = radioactive release; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Figure 13. System Response Event Tree for Example of Emplacement in an Emplacement Drift (Page 2)

Table 9 lists the initiating events for the ESD developed in Figure 11 and the associated initiating event. Each small circle on the ESD in Figure 11 is represented by a branch on the initiator event tree (Figure 12). The label on a small circle corresponds to the label on the initiator event tree. Each branch is expanded further in the system response event tree (Figure 13), using success/failure criteria for each pivotal event. The pivotal events shown on the top row of Figure 13 correspond to the pivotal events in Figure 11. In Figure 12, the first branch in an initiator event tree is the branch that represents absence of the initiating event. It is an artifact of how event trees must be represented in SAPHIRE. Each initiating event in Figure 13 transfers to the example system response event tree of Figure 13 at the location call Init-Event. The convention used to develop the remaining branches of the ET is that the upper branch of a pivotal event represents success (or a desirable outcome) and the lower branch represents failure (or an undesireable outcome).

Table 9. Initiating Event Descriptions for Example ESD

MLD Index Number	Initiating Event Text from MLD
EX-201	IMPACT FROM HEAVY LOAD ONTO TEV
EX-202	TEV DROPS/DRAGS WP DURING EMPLACEMENT
EX-203	WP IMPACT DUE TO TEV DOORS CLOSING ON WP
EX-204	IMPACT TO WP DUE TO COLLISION DURING EMPLACEMENT
EX-205	TEV DERAILS OR IMPACTS OBJECT, CAUSING WP IMPACT

NOTE: MLD = master logic diagram; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

5. LIST OF ATTACHMENTS

6. BODY OF CALCULATION

6.1 INITIATING EVENTS ANALYSIS

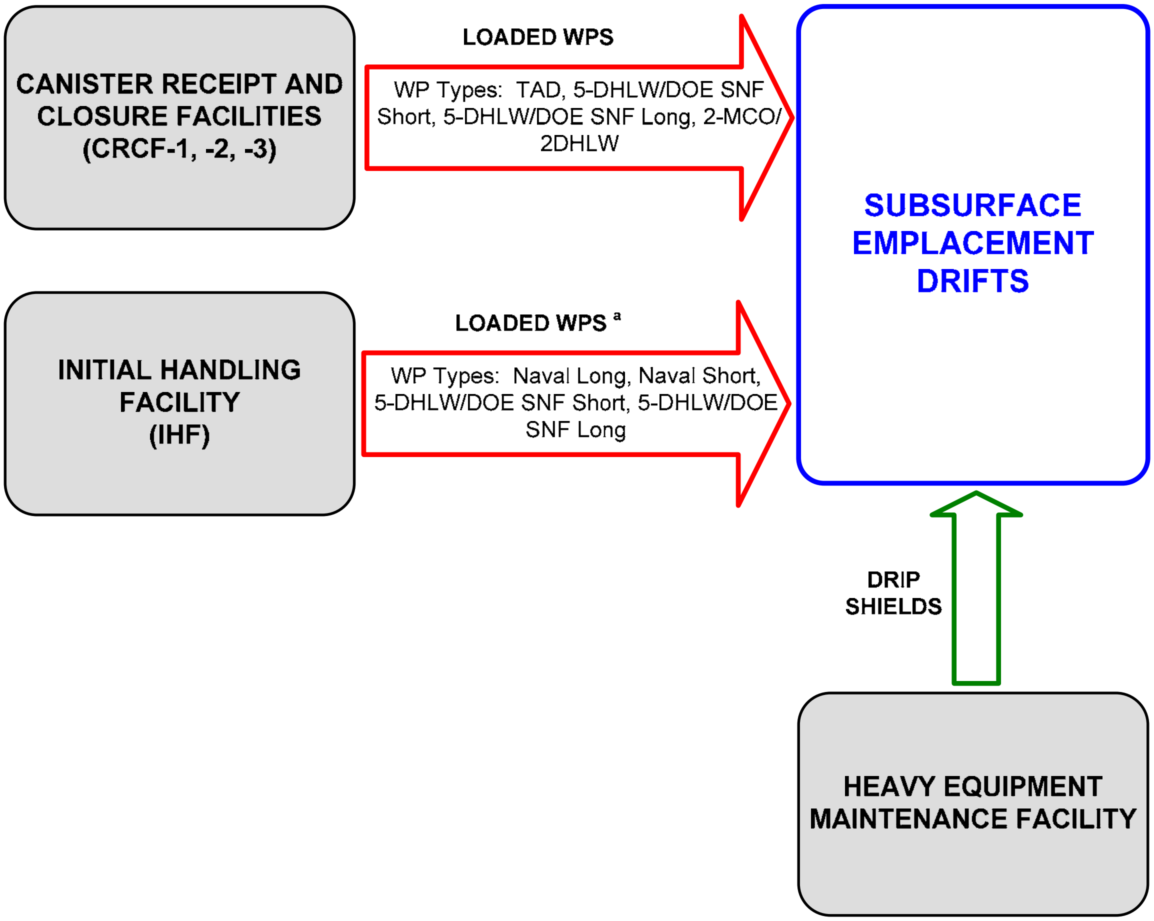
6.1.1 Introduction

Initiating events are identified for the YMP using MLDs that are verified with a HAZOP evaluation as described in Section 4. Each phase of the Subsurface Operations was analyzed to ensure that a comprehensive list of initiators was identified. These initiators are identified at a level for which, historical data exists, expert opinion can be obtained, or a fault tree model of causes can be developed based on equipment design and intended operations (e.g., human versus automated control). The initiating events identified in this analysis stem from: (1) external events, which are identified in *Monitored Geologic Repository External Initiating Events Screening Analysis* (Ref. 2.2.15), including natural phenomena such as tornado, earthquakes, flooding, lightning, etc., and (2) internal events, which include events that could occur randomly within the facility (or operations area). Events such as mechanical or electromechanical equipment failure (e.g., TEV motor failure), human failure events associated with the operations of the systems or components (e.g., collision with the TEV due to human failure), and fires or flooding events are also included. These initiating events are depicted in the MLDs.

6.1.2 Overview of Facility Process

Consistent with the methodology discussed in Sections 4.3.1.1 and 4.3.4.1, this section contains a brief overview of the Subsurface Operations. The overview provides the basis for the identification of initiating events and the development of event sequences. Operational details are presented at a level that is intended to be sufficient, for development of the MLD, the HAZOP evaluation, and the ESDs. Attachments A and B provide supplemental details regarding equipment and operations that is useful to understand some of the potential initiating events and the subsequent event sequences. The layout of the subsurface emplacement drifts and the surface facilities arrangement in the GROA are shown in Figures A-1 and A-5 (in Attachment A), respectively.

Subsurface Operations provide the handling capability for waste packages for a portion of the U.S. Department of Energy (DOE)–managed nuclear waste stream. As illustrated earlier in Figure 6, waste packages (containing waste canisters) are transported from one of the three CRCFs or from the IHF for emplacement into drifts within the underground operations area. This flow of waste packages is shown in Figure 14. The mode for waste package transport for emplacement is the TEV; a rail-based remote-operated vehicle specially designed for the task (Figure 10). The TEV accepts one of six waste package configurations resting on either a short or long pallet. It is shielded to allow only a limited dose at the surface of the shield enclosure. The TEV is also designed to operate in the range of environments both on the surface and in the subsurface, during transit and within the emplacement drift.



NOTE: [a] The 5-DHLW/DOE SNF WPs loaded in the IHF do not have DOE SNF loaded into the WP.
CRCF = Canister Receipt and Closure Facility; DHLW = defense high-level radioactive waste; DOE SNF = U.S. Department of Energy spent nuclear fuel; IHF = Initial Handling Facility; MCO = multicanister overpack; TAD = transport, aging, and disposal canister; WP = waste package.

Source: Original

Figure 14. Subsurface Operations – Generalized Input and Output Diagram

Subsurface emplacement operations are designated to start with the TEV engaging a waste package within a waste handling facility at the loadout station and extend to transit, and the eventual emplacement in the subsurface. In addition to transit and emplacement of the waste packages, Subsurface Operations do encompass other processes as well. A significant multi-year activity which is part of Subsurface Operations is the emplacement of drip shields over each of the waste package by a remote gantry, the drip shield emplacement gantry (DSG).

Further, other Subsurface Operations include (1) the operational period after waste emplacement and prior to the emplacement of drip shields, where the waste package is nominally at-rest in an emplacement drift, termed the post-emplacement period; and (2) activities associated with recovery or movement of waste packages under normal operations from one drift to another or to return the package to the surface. Concurrent with post-emplacement activities, other operations include ventilation, maintenance and performance confirmation.

The summary of Subsurface Operations continues with Section 6.1.2.1, and the major operations for waste package emplacement and drip shield emplacement are organized according to the nodes, which are indicated in the PFD (Figures 15 and 16). For the study, the five nodes were defined:

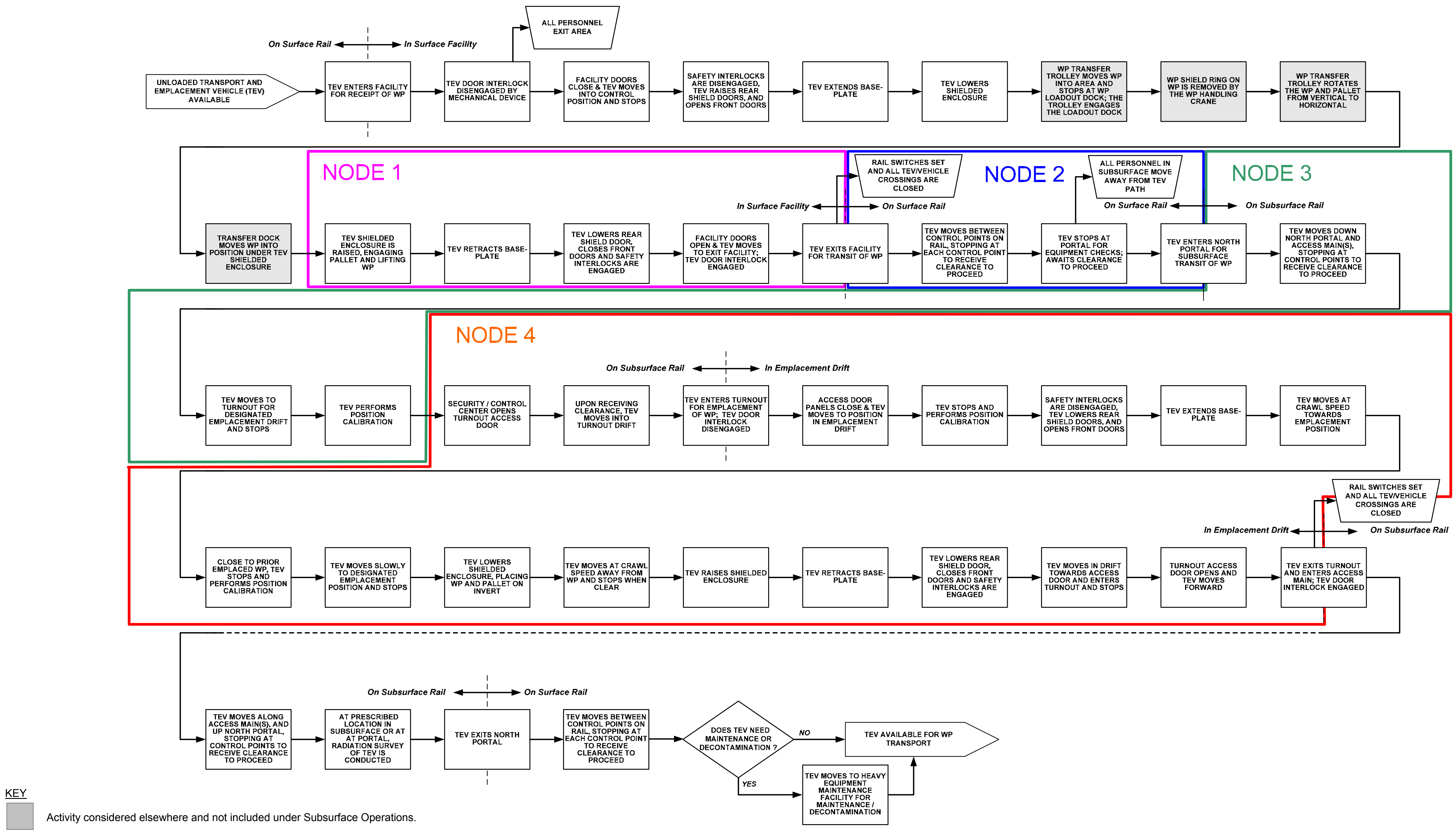
1. Waste package loadout
2. TEV on surface rail
3. Subsurface transit
4. Waste package emplacement operations
5. Drip shield emplacement operations.

For these nodes, the summary for emplacement of waste packages and drip shields is based primarily on the Level 3 mechanical handling block flow diagram for the these operations. The specific pages of the block flow diagram that are used as primary sources for each node are cited at the end of each node's operational description. Attachment B provides more details on the various Subsurface Operations.

6.1.2.1 Node 1: Waste Package Loadout

Prior to the start of Subsurface Operations, an unloaded TEV (i.e., without a waste package) enters the surface nuclear facility, and the facility shield doors and confinement doors are closed and secured. Also this time, workers exit the waste package Loadout Room. The interior shield door is raised and a WPTT enters the loadout room, and engages the loadout dock. The waste package and pallet, carried in a vertical orientation, is rotated to the horizontal. The loadout station moves the waste package and pallet into proper position under the TEV.

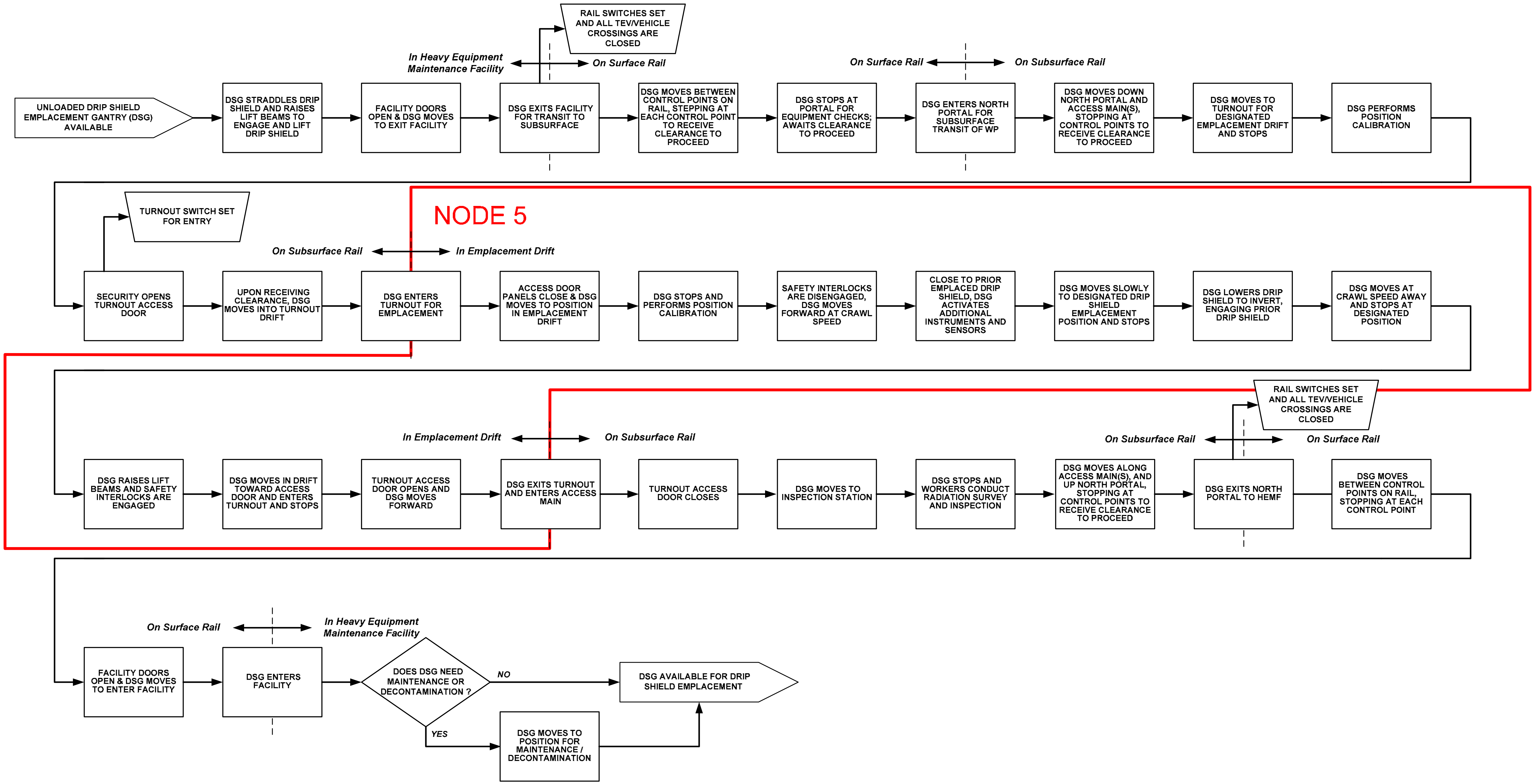
Subsurface Operations start when the waste package and pallet are in the proper position on the loadout station, and the TEV is remotely commanded from the facility control room to raise the shield enclosure. The enclosure engages the base of the pallet as it rises, and lifts the waste package; the enclosure continues to raise the pallet to travel height. The TEV then engages the transportation shot bolts, locking the shield enclosure into travel position. The TEV then retracts its base-plate, and closes and locks the front and rear shield doors, which completely encases the waste package in shielding.



NOTE: [a] Diagram is predicated upon the process of loading of TEV by the carriage retrieval assembly at the loading dock during loadout in the facility.
[b] The WP is to be clean prior to loading into the TEV.
TEV = transport and emplacement vehicle; WP = waste package.

Source: Modified from Ref 2.2.55 and Ref. 2.2.34.

Figure 15. Process Flow Diagram for Nodes 1 to 4 for Subsurface Operations



NOTE: TEV = transport and emplacement vehicle; WP = waste package.

Source: Modified from Ref 2.2.55 and Ref. 2.2.34.

Figure 16. Process Flow Diagram for Node 5 for Subsurface Operations

The facility shield door is then remotely opened and the loaded TEV moves backward along the TEV rail system and exits the loadout room and the facility (if the TEV is in a CRCF, it must first pass through a loadout vestibule with a roll-up door to be completely outside). The rail at this point is a branch line connecting the facility to the main line which in turn allows movement to the North Portal. As the TEV exits the facility, an electromechanical switch is activated which disables the ability of the TEV to unlock the front shield doors during transit. Also, at this time all rail crossings are closed and rail switches are rotated into proper position for TEV movement.

The activities of this node are illustrated in the *Waste Package Emplacement Mechanical Handling System Block Flow Diagram Level 3* (Ref. 2.2.55) and described in *Mechanical Handling Design Report: Waste Package Transport and Emplacement Vehicle* (Ref. 2.2.34, Section 2.5.1).

6.1.2.2 Node 2: TEV on Surface Rail

The operations for this node include the transit of the TEV containing a waste package along the dedicated surface rail from outside a waste handling facility to the North Portal (the only operations entrance into the subsurface). TEV operations are directed by on-board PLCs to move to from control point to control point. At each control point the TEV stops to await an affirmative signal from central control to continue to the next point. The TEV is also always under observation by workers in the Central Communication and Control Facility (CCCF) and they can stop the TEV if any off-normal condition is detected.

Along the route, the TEV moves from the branch line from the facility through a switch onto the main (trunk) line. The main rail line passes to the northwest of operations area, alongside the waste handling and supporting facilities. Depending on the starting point, the TEV encounters various access roadway crossings. The TEV passes through the rail switch traveling from the branch line onto the main line, and through other rail switches as other branch lines join the main line. Further, as the TEV must enter an emplacement drift front first, the TEV may reverse direction to enter the North Portal in the correct orientation.

The activities of this node are illustrated in the *Waste Package Emplacement Mechanical Handling System Block Flow Diagram Level 3* (Ref. 2.2.55) and described in *Mechanical Handling Design Report: Waste Package Transport and Emplacement Vehicle* (Ref 2.2.34, Section 2.5.2).

6.1.2.3 Node 3: Subsurface Transit

In the subsurface, the loaded TEV travels from the North Portal to a selected emplacement drift turnout, where the TEV stops and calibrates its position. As on the surface, TEV operations are directed by on-board PLCs to move the TEV from control point to control point. Using cameras and on-board instruments, the TEV is under observation by workers in central control and these operators can stop the TEV if any off-normal condition is detected.

Along the route, the TEV moves first down the decline of the North Ramp (the steepest grade in the operating facility) and then along the access mains (large tunnels) to the emplacement drift. The subsurface route passes through rail switches as the access main divides into various segments. While access into the entrance of the North Portal is restricted, workers may be present at various points within the subsurface for maintenance, security, or for in situ monitoring and testing associated with performance confirmation. The activities of this node are illustrated in the *Waste Package Emplacement Mechanical Handling System Block Flow Diagram Level 3* (Ref. 2.2.55) and described in *Mechanical Handling Design Report: Waste Package Transport and Emplacement Vehicle* (Ref. 2.2.34, Section 2.5.2).

6.1.2.4 Node 4: Waste Package Emplacement Operations

Upon receiving clearance from operators in the CCCF and security stationed at the North Portal, the access door to the emplacement drift is opened. The TEV is then authorized to proceed through the turnout drift switch and through the access door threshold, entering the selected emplacement drift turnout. After the TEV clears the doorway, the access door is closed by central control. During this movement, an electromechanical switch is activated (as in Node 1) which enables the TEV to unlock the front shield doors, permitting the emplacement operation.

The TEV moves to a specific location in the drift and then stops. There it performs a position calibration and after receiving clearance, it opens the front and rear shield doors and extends its base-plate. Then, the TEV moves forward at a crawl speed to a position close to the emplacement location. It then moves very slowly to the emplacement location and again stops. The shield enclosure is then lowered to place the pallet and waste package on the emplacement drift's invert (base).

The TEV moves at a crawl speed away from the waste package to a predetermined distance from the waste package and stops. At this point it raises the shield enclosure, extends the transportation shot bolts, retracts the base-plate and closes both shield doors. Thereafter, it proceeds to move toward the access door. As the TEV approaches the emplacement access door, it stops. The access door is opened, and it is commanded to proceed into the access door threshold and back into the emplacement drift turnout. The emplacement access door is closed, completing the operations in this node.

The activities of this node are illustrated in the *Waste Package Emplacement Mechanical Handling System Block Flow Diagram Level 3* (Ref. 2.2.55) and described in *.Mechanical Handling Design Report: Waste Package Transport and Emplacement Vehicle* (Ref. 2.2.34, Section 2.5.3).

6.1.2.5 Node 5: Drip Shield Emplacement Operations

As illustrated in Figure 15, each drip shield is transported from the Heavy Equipment Maintenance Facility (HEMF) to an emplacement drift along the TEV rail system using the DSG. Like the TEV, the DSG moves along the surface rail system, into the subsurface through the North Portal and down the North Ramp. It continues along access mains into the emplacement turnouts and finally, into the emplacement drifts. Control of the DSG is based on PLCs and is similar to the TEV. The DSG moves from control point to control point and then stops, awaiting a confirmation signal to proceed. Until this time, the DSG is not associated with waste forms and no initiating events are identified..

Operations relevant to the node start after the DSG has received clearance from central control and security, and the access door to the emplacement drift is opened. The DSG is then authorized to proceed through the turnout drift switch and through the access door threshold, entering the selected emplacement drift turnout. After it clears the doorway, the access door is closed by the CCCF.

Traveling through the emplacement drift, the DSG moves to a specific location and stops. It then performs a position calibration. After receiving clearance, it moves forward at a crawl speed, and activates additional instrumentation for final positioning. The DSG then moves to the designated drip shield emplacement location and stops. Once the correct position is achieved, the gantry lowers the lift beams, which lowers the drip shield into place until the drip shield engages the previously emplaced drip shield interlock (if present) and the drip shield base rests upon the steel frame of the emplacement drift invert.

The DSG then lowers its lifting features to its travel height and moves at a crawl speed away from the newly emplaced drip shield to a predetermined distance and stops. Upon confirmation of emplacement status, it moves towards the emplacement access door. Once it reaches the access door, it again stops. The access door is opened and the gantry passes through the doorway. Once through, the access door closes, and it stops for inspection and monitoring. The DSG then proceeds along the rail line to the surface and returns to the HEMF for a new drip shield or repair.

The activities of this node are illustrated in the *Drip Shield Emplacement Block Flow Diagram Level 3* (Ref. 2.2.25) and described in *Concept of Operations for the Drip Shield Gantry* (Ref. 2.2.21, Section 4.1).

6.1.2.6 Ventilation and Other Operations during the Post-Emplacement Period

During the post-emplacement period, various activities are conducted in the Subsurface Operations area. For the entire preclosure period, emplacement drifts are ventilated to cool the waste packages and maintain the repository thermal limits, including waste package surface temperatures. In the emplacement area, airflow is drawn through the subsurface by fans located on the surface, at the top of the exhaust shafts. Automated regulators located in the emplacement access turnout bulkheads control the airflow into each of the emplacement drifts. Filtration is provided as part of the ventilation system. However, the ventilation system may be out-of-service for 30 consecutive days during this period without violating fuel and waste package thermal limits.

In addition, several other operations occur in the subsurface during the post-emplacement period. These operations include performance confirmation, waste operational monitoring, as well as security and maintenance activities. These activities require personnel to be in the access mains and other non-emplacement drifts of the operational area at different times for performance confirmation in situ testing, and rail and support maintenance.

Further, as part of the closure process, various activities are conducted to prepare the Subsurface for postclosure, in addition to the emplacement of drip shields. These activities involve the placement of backfill and seals in various openings, excluding emplacement drifts, and the removal of non-committed material from non-emplacement areas. Again, these activities require personnel to be in the access mains and other non-emplacement drifts of the operational area at different times.

These activities are briefly discussed in *Yucca Mountain Repository Concept of Operations* (Ref. 2.2.59, Attachments I, N, and O), in *Subsurface Construction and Emplacement Ventilation* (Ref. 2.2.63), and in Attachment B.

6.1.2.7 Construction Operations

For most of the emplacement period – and concurrent with the storage of waste packages within emplacement drifts for Panels 1 through 3 – subsurface construction activities are ongoing to expand the operational area of the repository. Subsurface emplacement operations interface with construction work. Subsurface construction methods involve both mechanical excavation methods (i.e., tunnel boring machines and road headers) and explosive-based methods (drill-and-blast). The subsurface construction area is separated from the emplacement operations area by isolation barriers, termed bulkheads. Bulkheads prevent personnel from the construction areas from access to the emplacement operations area and are moved as the operations area expands. Further, the bulkheads help isolate the construction ventilation from the operations side ventilation. To supplement this barrier, the construction ventilation system is designed to be entirely separate from the emplacement operations side. Further, the construction ventilation system is maintained with a positive pressure and the emplacement side is maintained with a negative-pressure, in the event of the failure of either system, airflow is from the construction side into the emplacement side.

These activities are briefly discussed in *Yucca Mountain Repository Concept of Operations* (Ref. 2.2.59, Sections 3.16, 3.17, and I.4.1.3.3), in *Subsurface Construction and Emplacement Ventilation* (Ref. 2.2.63), and in Attachment B.

6.1.2.8 Waste Package Recovery

It may be necessary to move a waste package (or a limited number of waste packages) from one emplacement drift to another or to return a waste package to the surface as a part of normal operations. This process is termed the recovery of a waste package or packages. As the process does not involve an off-normal condition of the waste package, the recovery operations are essentially the reverse of emplacement and transit operations discussed for Nodes 1 to 4, and involve the use of the TEV. Operations involving off-normal events such as recovery of a dropped waste package or removing a rockfall from an emplacement drift are evaluated elsewhere and not included in this analysis.

Recovery is briefly described in *Mechanical Handling Design Report: Waste Package Transport and Emplacement Vehicle* (Ref. 2.2.34, Section 2.5.5).

6.1.3 Identification of Initiating Events

The identification of initiating events is completed by constructing the MLD and supplementing it with a HAZOP evaluation. The methodologies for the MLD and HAZOP are described in Sections 4.3.1.1 and 4.3.1.2, respectively. The MLD diagrams and the HAZOP evaluation deviations for Subsurface Operations for internal events (excluding construction-related hazards) are provided in Attachment D and E, respectively. Construction hazards are evaluated in *Construction Hazards Screening Analysis* (Ref. 2.4.2).

External hazards are first screened as applicable to Subsurface Operations (as described in Section 4.3.3) and then the applicable hazards are further developed in the MLD and associated ESDs and event trees. Thirteen categories of external events are identified as potentially applicable to a repository, as listed in Table 10 and incorporated into the MLD structure as shown in Attachment D.

Table 10. Listing of Potential External Event Categories

Category No.	External Event Category Description [a]	Comments
1	Seismic events	---
2	Non-seismic geologic activity (including landslides, avalanches)	---
3	Volcanic activity	---
4	High winds/tornadoes (including wind effects from hurricanes)	---
5	External floods	---
6	Lightning	---
7	Loss of power events	---
8	Loss of cooling capability event (non-power cause, including biological events)	---
9	Aircraft crash	No Events Identified [b]
10	Nearby industrial/military facility accidents (including transportation accidents)	No Events Identified [c]
11	Onsite hazardous materials release	---
12	External fires (including forest fires, grass fires)	---
13	Extraterrestrial activity (including meteorites, falling satellites)	---

NOTE: [a] External events are further developed in Ref. 2.4.1.
[b] Based on Ref. 2.2.29.
[c] Based on Ref. 2.2.62.
[d] The loss of cooling capability event category includes the occurrence of extreme outdoor temperatures.

Source: Original

As an aid for the identification of internal hazards for Subsurface Operations, prior hazard studies were reviewed for applicability. In particular, two calculations, *Internal Hazards Analysis for License Application* (Ref. 2.2.14, Sections 6.6.5 and 6.6.9) and *DBE/Scenario Analysis for Preclosure Repository Subsurface Facilities* (Ref. 2.2.65) were reviewed. Other general sources were also examined for applicability, but little risk analysis work is available in the open literature for facilities similar to Subsurface Operations. All applicable internal events from this review of existing literature were incorporated into the MLD.

A list of initiating events identified by the MLD and HAZOP evaluation is provided in Table 10 for external events and Table 11 for internal events.

To facilitate ESD development, a unique identification number ("MLD Identifier") has been assigned to each initiating event as shown in Attachment D. The identifier consists of "SSO-" to identify the event as part of Subsurface Operations, followed by a three- or four-digit number. The last two digits of the identification numbers uniquely identify events on each page of the MLD. The first one or two digits specify the MLD page number.

Table 11. List of Internal Initiating Events

MLD Identifier	General Event Description	MLD Figure No.	HAZOP Evaluation Table No.	ESD Figure No.
SSO-201	Impact from heavy load onto TEV	D-2	---	SSO-ESD-01
SSO-202	TEV drops WP during loading	D-2	E-2	SSO-ESD-01
SSO-203	WP impact due to collision with facility structure or equipment	D-2	E-2	SSO-ESD-01
SSO-204	WP impact due to TEV shield doors closing on WP	D-2	---	SSO-ESD-01
SSO-205	WP impact due to facility shield door closing or failure	D-2	E-2	SSO-ESD-01
SSO-301	Impact from heavy load onto TEV	D-3	---	SSO-ESD-02
SSO-302	TEV drops WP during transit	D-3	---	SSO-ESD-02
SSO-303	Impact on TEV during transit	D-3	---	SSO-ESD-02
SSO-304	Thermal impact due to loss of TEV movement	D-3	E-3	SSO-ESD-04
SSO-305	Impact due to TEV derailment or collision with object	D-3	E-3	SSO-ESD-02
SSO-401	Impact from heavy load onto TEV	D-4	E-4	SSO-ESD-02
SSO-402	TEV drops WP during transit	D-4		SSO-ESD-02
SSO-403	Thermal impact due to loss of TEV movement	D-4	E-4	SSO-ESD-04
SSO-404	Impact due to TEV derailment or collision with object	D-4	E-4	SSO-ESD-02
SSO-501	Impact from heavy load onto TEV	D-5	E-5	SSO-ESD-03
SSO-502	TEV drops/drags WP during emplacement	D-5	E-5	SSO-ESD-03
SSO-503	WP impact due to TEV doors closing on WP	D-5	E-5	SSO-ESD-03
SSO-504	Impact to WP due to collision during emplacement	D-5	E-5	SSO-ESD-03
SSO-505	TEV derails or impacts object, causing WP impact	D-5	E-5	SSO-ESD-03
SSO-601	Impact from heavy load onto WP	D-6	---	SSO-ESD-03
SSO-701	Impact from heavy load onto WP	D-7	---	SSO-ESD-03

Table 11. List of Internal Initiating Events (Continued)

MLD Identifier	General Event Description	MLD Figure No.	HAZOP Evaluation Table No.	ESD Figure No.
SSO-702	Impact on emplaced WP due to collision	D-7	---	SSO-ESD-03
SSO-901	Inadvertent TEV door opening	D-9	E-2, E-3, E-4	SSO-ESD-04
SSO-902	Inadvertent TEV door opening	D-9	E-4	SSO-ESD-04
SSO-903	Prolonged worker proximity to TEV	D-9	E-3, E-4	SSO-ESD-04
SSO-1001	Inadvertent entry into drift	D-10	---	SSO-ESD-04
SSO-F1201	TEV fire effects waste form on surface rail	D-12	---	SSO-ESD-05
SSO-F1202	TEV fire effects waste form on subsurface rail	D-12	---	SSO-ESD-05
SSO-F1203	TEV fire effects waste form in emplacement drift	D-12	---	SSO-ESD-05

NOTE: HAZOP = hazard and operability evaluation; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

For example, "SSO-301" means "the first initiating event on the page 3 of the MLD" and "SSO-1203" means "initiating event 03 on page 12 of the MLD." The identification convention is modified for internal fires and external events by inserting a prefix "F" or "E" (respectively) before the page number. Thus, "SSO-F1202" means internal fire initiating event 02 on page 12 of the MLD.

6.2 DEVELOPMENT OF INTERNAL EVENT SEQUENCES

6.2.1 Introduction

Using the MLD as a basis, a set of ESDs is identified for Subsurface Operations. Using the methods described in Section 4.3.2.1, these ESDs are constructed using the initiating events identified in the MLD. The resulting ESDs are presented in Attachment F (Figures F-1 through F-5).

Sections 6.2.2 through 6.2.6 describe the logical flow of each ESD, from the initiating event, through the pivotal events, to the end state. In order to clearly understand the ESD logic, both the descriptive text and the resulting ESD graphic should be considered.

The following descriptive text for each ESD provides the following information:

- A summary description of each event sequence as embodied in the ESD
- Internal events addressed by the ESD together with specific examples
- Pivotal event descriptions and the associated logic.

For Subsurface Operations, five ESDs were identified. The ESDs in some cases represent a grouping of several processes or nodes (Figure 15 and 16) that can be accurately represented by a single ESD. For example, the initiating events for transit of the TEV with a waste package on the surface are (to a large degree) repetitive of the initiating events associated with the transit in the subsurface and are represented by a single ESD (SSO-ESD-02). In constructing this ESD, several initiating events are grouped to be considered as a single initiator (i.e., as the same small circle). For initiating events that have been grouped together, the MLD index number of each initiator is listed adjacent to the relevant initiating event (small circle) for traceability (Figure E-2).

6.2.2 SSO-ESD-01: TEV Activities Inside the Facility (IHF or CRCF) in the Waste Package Loadout Area

6.2.2.1 Summary Description

ESD-01 encompasses all activities in the loadout area of a waste handling facility (the IHF or CRCF) after the TEV has engaged the waste package pallet through the TEV exit from the facility with a waste package. This ESD is shown in Figure F-1. In more detail, ESD-01 includes the loading of the waste packages inside the TEV, the subsequent opening of facility shield door (and other doors if present) and transit of the TEV from the loadout station to outside of the facility, passing through the Loadout Vestibule traveling along the TEV rail system. The activities are analyzed under Node 1 of the PFD and are shown in Figure 15.

This ESD involves a single waste package within the confines of a shielded TEV. At the initial stages of the process, when the facility shield door is closed, the facility provides confinement with a HEPA exhaust through the HVAC. The TEV only provides shielding of the waste package and does not provide confinement.

6.2.2.2 Initiating Events and Examples

Five initiating events in Figure F-1 are identified from the MLD shown in Figure D-2. For quantification purposes, these initiators (represented by small circles) are collected together (represented by the large circle). The initiating events are as follows:

1. Impact from heavy load onto the TEV/waste package
2. Drop of waste package from TEV during loading
3. Waste package impact due to collision with facility structure or equipment
4. Waste package impact due to TEV shield doors closing on a waste package
5. TEV/waste package impact due to facility doors closing or failure on TEV.

An example of the first initiating event, the impact of a heavy load onto the TEV, is the event when the Waste Package Loadout Room crane drops a waste package shield ring or an empty waste package onto the TEV. A shield ring is removed from the loaded waste package by crane just prior to the start of TEV activities. Loading of empty of waste packages into a facility occurs in the same room as the loading of the TEV and loading could occur simultaneously on the second loadout station present in the CRCF concurrent with TEV activities.

An example of the second initiating event is the drop of the waste package by the TEV immediately after lifting the pallet and package which is caused by the failure of the lifting features (or lift system). An example of the third initiating event is derailment of a TEV by irregularities in the track leading to an impact with a facility wall. An instance of the fourth initiating event is the inadvertent activation of the TEV shield doors as the waste package is loaded into the TEV, and the doors impacting the sides of the waste package. Finally, an example of the fifth initiating event is the activation of the shield doors prematurely as the TEV is exiting the facility, and close upon the TEV in the threshold.

These groups of initiating events are summarized by an aggregate initiating event, which is represented by the large circle in the ESD. The large circle represents a structural challenge resulting from TEV activities inside a facility in the waste package loadout area, including the Loadout Vestibule.

6.2.2.3 Pivotal Events - System Response

The pivotal events shown in the ESD represent the system response to the structural challenge. After the initiating event challenge has occurred, the first pivotal event asks whether the containment boundary of the waste package remains intact. Determining whether or not the containment boundary of the waste package remains intact may be probabilistic in that the event involves uncertainties in both the load imposed on the waste package (and TEV) and the strength of the waste package (and the protection provided by the TEV shield enclosure). If the containment boundary remains intact, no radioactive release occurs. However, there remains the question whether or not the shielding provided by the TEV or the facility remains intact, as posed by the next pivotal event (e.g. an impact may compromise the TEV shielding). If the shielding remains intact, there is no exposure of personnel to radiation and the end state is "OK." Otherwise, the event sequence terminates in an end state entitled direct exposure to radiation.

If the containment boundary of the waste package does not remain intact (i.e., along the path of the negative answer to the question posed by the first pivotal event), whether or not a radionuclide release occurs depends on whether or not the canister containment boundary remains intact. Determining whether or not the containment boundary of the canister remains intact may be probabilistic in that the event involves uncertainties in both the load imposed on the canister and the strength of the canister. If the canister containment remains intact, radionuclide release is avoided, but a direct exposure occurs if both the TEV shielding is breached and shielding doors are open to allow personnel exposure. Otherwise, the containment boundaries of both the waste package and the canister have been breached and a radionuclide release is inevitable.

The subsequent pivotal events provide further characterization of each potential event sequence regarding the availability of a HVAC confinement and the potential for moderator intrusion. First, a pivotal event asks whether HVAC confinement is maintained. In addition to whether or not the HVAC system is operating at the time of the release, this question includes maintenance of building confinement. If HVAC confinement is maintained over the mission time, the release is considered a filtered release and the consequence analysis may take into account the filter efficiency. If HVAC confinement is not maintained, the release is considered to be unfiltered.

The remaining pivotal event provides further delineation of the event sequences by asking whether or not moderator is prevented from entering the breached canister. With a yes condition (that is, in the absence of moderator intrusion), the filtered or unfiltered release is represented by the “Radionuclide release” end state. In the negative case, that is, if moderator enters the breached canister, the corresponding event sequences terminate in either a filtered or an unfiltered radionuclide release that must be further evaluated with respect to criticality (which is indicated as “also important to criticality”). Note that, “also important to criticality” means that event sequences tagged as such, that are found to be Category 1 or Category 2 in the subsequent categorization analysis, are evaluated to determine criticality. Evaluation of criticality is not required for event sequences that are beyond Category 2.

In summary, for each waste form and each initiating event group (small circles), the ESD delineates seven event sequences:

1. Waste package containment and shielding remain intact ("OK" i.e., no radiation exposure)

2. Waste package containment remains intact, but shield deformation causes direct exposure

3. Waste package containment fails, canister containment remains intact, but deformation of the TEV shielding causes a direct exposure

4. Waste package containment fails, canister containment fails, HVAC confinement is maintained, and moderator intrusion is prevented, resulting in a filtered radionuclide release

5. Waste package containment fails, canister containment fails, HVAC confinement fails, and moderator intrusion is prevented, resulting in an unfiltered radionuclide release

6. Waste package containment fails, canister containment fails, HVAC/ventilation confinement is maintained, and moderator intrusion is not prevented, resulting in a filtered radionuclide release, also important to criticality

7. Waste package containment fails, canister containment fails, HVAC/ventilation confinement fails, and moderator intrusion is not prevented, resulting in an unfiltered radionuclide release, also important to criticality.

6.2.3 SSO-ESD-02: TEV Activities During Transit

6.2.3.1 Summary Description

ESD-02 encompasses all activities associated with the transit of a waste package carried on a pallet within the TEV, from the TEV's exit from a facility to the arrival of the loaded TEV at the start of the selected emplacement drift turnout. This ESD is shown in Figure F-2. In more detail, ESD-02 includes the TEV traveling along the surface rail system, the passing through rail switches and vehicular crossings to reach the North Portal. After surveys at the North Portal, the loaded TEV descends the North Ramp to the emplacement level and travels along the access mains using the subsurface rail system, eventually reaching the designated turnout. These activities are analyzed under Node 2 and Node 3 of the PFD, and are shown in Figure 15.

This ESD involves a single waste package within the confines of a shielded TEV. En route, the TEV provides shielding of the waste package but does not provide confinement as the TEV shield enclosure is not airtight.

6.2.3.2 Initiating Events and Examples

Four types of initiating events in Figure F-2 are identified as those that can lead to a release from the MLD shown on Figures D-3 and D-4. For quantification purposes, these initiators (represented by small circles) are collected together (as represented by the large circle).

The initiating events are as follows:

1. Impact from heavy load onto TEV
2. TEV drops the waste package during transit
3. Impact on TEV during transit
4. Impact due to TEV derailment or collision with object.

An example of the first initiating event is a rockfall onto the TEV while the TEV is traveling in an access main. An example of the second initiating event is the drop of the waste package by the TEV caused by the concurrent extension of the TEV base-plate initiated by a spurious signal and the failure of the TEV lift system. An example of the third initiating event is the impact of a speeding service vehicle striking the side of the TEV at a vehicular crossing. Finally, an instance of the fourth initiating event is the derailment of a TEV attempting to pass through a closed switch leading to impact with a berm or other barrier.

The groups are summarized by a generic initiating event, which is represented by the large circle in the ESD. The large circle represents a structural challenge resulting from TEV activities during transit on the surface from a waste handling facility to the start of the emplacement drift turnout.

6.2.3.3 Pivotal Events - System Response

The pivotal events shown in the ESD represent the system response to the structural challenge. After the initiating event challenge has occurred, the first pivotal event asks whether the containment boundary of the waste package remains intact. Determining whether or not the containment boundary of the waste package remains intact may be probabilistic, in that, the event involves uncertainties in both the load imposed on the waste package and TEV and the strength of the waste package and TEV shield enclosure. If the containment boundary remains intact, no radioactive release occurs. However, there remains the question whether or not the waste package shielding remains intact, as posed by the next pivotal event. If the shielding remains intact, there is no exposure of personnel to radiation and the end state is “OK”. Otherwise, the event sequence terminates in a direct exposure to radiation.

If the containment boundary of the waste package does not remain intact (i.e., along the path of the negative answer to the question posed by the first pivotal event), whether or not a radionuclide release occurs depends on whether or not the canister containment boundary remains intact. Determining whether or not the containment boundary of the canister remains intact may be probabilistic in that, the event involves uncertainties in both the load imposed on the canister and the strength of the canister. If the canister containment remains intact, radionuclide release is avoided, but a direct exposure occurs due to a loss of shielding caused by waste package breach. In the event that waste package containment is lost, it is implied that the TEV shielding is lost, as well as the impact must penetrate or crush the TEV in order to damage the waste package. The event also presumes that workers may be near the TEV route on the surface or in the subsurface. Otherwise, the containment boundaries of both the waste package and the canister have been breached and a radionuclide release is inevitable.

The remaining pivotal event provides further delineation of the event sequences by asking whether or not moderator is prevented from entering the breached canister. With a yes condition (that is, the absence of moderator intrusion), the unfiltered release is represented by the "Radionuclide release" end state. In the negative case, that is, if moderator enters the breached canister, the corresponding event sequences terminate in either an unfiltered radionuclide release that must be further evaluated with respect to criticality (which is indicated as "also important to criticality"). Note that, "also important to criticality" means that event sequences tagged as such, that are found to be Category 1 or Category 2 in the subsequent categorization analysis, must be demonstrated to be subcritical. Demonstration of sub-criticality is not required for event sequences that are beyond Category 2.

In summary, for each waste form and each initiating event group (small circle), the ESD delineates five event sequences:

1. Waste package containment and shielding remain intact ("OK" - i.e., no radiation exposure)

2. Waste package containment remains intact, but loss of shielding causes direct exposure

3. Waste package containment fails, canister containment remains intact, but loss of shielding causes direct exposure

4. Waste package containment fails, canister containment fails, and moderator intrusion is prevented, resulting in an unfiltered radionuclide release

5. Waste package containment fails, canister containment fails, and moderator intrusion is not prevented, resulting in an unfiltered radionuclide release, also important to criticality.

6.2.4 SSO-ESD-03: TEV Activities within the Emplacement Drift

6.2.4.1 Summary Description

ESD-03 encompasses all activities that occur within the emplacement drift, including waste package emplacement, drip shield emplacement and the storage period between these activities (i.e. during the post-emplacement period). This ESD is shown in Figure F-3. In more detail, ESD-03 includes waste package emplacement activities which involve: the TEV entrance into the emplacement drift (passing through the emplacement access doors), the transit of the loaded TEV to the emplacement position (including the opening of the TEV shield doors and extension of the base-plate), the emplacement of the waste package on the emplacement drift invert, and the eventual transit of the unloaded TEV out of the emplacement drift. The second group of activities (that of drip shield emplacement), involves the movement of drip shields into the emplacement drift and over the waste packages by the DSG. It also involves movement of the DSG to exit the drift, after the drip shield has been placed. Finally, the ESD includes potential events while the waste package is at rest in the emplacement drift without the cover of drift shields. The waste package emplacement and drip shield emplacement activities are analyzed under Node 4 and Node 5 (respectively) of the PFD and are shown in Figures 15 and 16.

This ESD involves one or more waste packages within an emplacement drift, together with the waste package, being carried by a TEV (prior to emplacement) for emplacement activities. As noted in *Subsurface Facility Radiation Zone Classification* (Ref. 2.2.46), the emplacement drift is an R5 radiation zone[4] with shielding to the access main provided by the curvature of the turnout drift. As shown in Figure A-4, the curved geometry of the turnout drift prevents direct shine at the entrance of the turnout drift and hence into the access main. Therefore, the turnout access door is <u>not</u> a shield door but only controls access into the turnout and emplacement drifts.

6.2.4.2 Initiating Events and Examples

Six categories of initiating events in Figure F-3 are identified which encompass eight MLD identified events. For quantification purposes, these initiators (represented by small circles) are collected together (as represented by the large circle).

The initiating events are as follows:

1. Impact of heavy load onto TEV
2. TEV drops or drags waste package during emplacement
3. Impact of heavy load onto waste package
4. Waste package impact due to TEV doors closing on waste package
5. Direct impact to waste package due to collision
6. TEV derails or impacts object causing waste package impact.

An example of the first initiating event is a spurious signal activating the emplacement access door to close on the TEV while the TEV is traveling through the threshold. An example of the second initiating event is the drop of the waste package by the TEV due to a failure of the TEV lift system just prior to emplacement. During the movement to position the waste package for emplacement, the TEV base-plate is extended and the waste package is in a raised position. An example of the third initiating event is a rockfall onto the waste package at rest in the emplacement drift. An instance of the fourth initiating event is the inadvertent activation of the TEV shield doors as the TEV approaches an emplaced waste package, and the doors impact the sides of the waste package. An example of the fifth initiating event is the direct impact on a waste package by the TEV moving too far during emplacement or in the wrong direction as the

[4] This is the highest radiation rating and is categorized as "limited or no occupancy, access is not normally allowed." The definition of radiation zones is provided in (Ref. 2.2.38, Table 4.10.3-1)

TEV exits the emplacement drift. Finally, an instance of the last initiating event is the derailment of a TEV by wheel failure leading to impact with the rock wall of the emplacement drift.

The groups are summarized by an aggregate initiating event, the large circle in the ESD. The large circle represents a structural challenge resulting from activities in an emplacement drift.

6.2.4.3 Pivotal Events - System Response

The pivotal events shown in the ESD represent the system response to the structural challenge. After the initiating event challenge has occurred, the first pivotal event asks whether the containment boundary of the waste package remains intact. Determining whether or not the containment boundary of the waste package remains intact may be probabilistic in that the event involves uncertainties in both the load imposed on the waste package and the strength of the waste package (a protection provided by the TEV, if applicable). If the containment boundary remains intact, no radioactive release occurs.

If the containment boundary of the waste package does not remain intact (i.e., along the path of the negative answer to the question posed by the first pivotal event), whether or not a radionuclide release occurs depends on whether or not the canister containment boundary remains intact. Determining whether or not the containment boundary of the canister remains intact may be probabilistic in that the event involves uncertainties in both the load imposed on the canister and the strength of the canister. If the canister containment remains intact, radionuclide release is avoided. Otherwise, the containment boundaries of both the waste package and the canister have been breached and a radionuclide release is inevitable.

The remaining pivotal event provides further delineation of the event sequences by asking whether or not moderator is prevented from entering the breached canister. With a yes condition (that is, the absence of moderator intrusion), the unfiltered release is represented by the “Radionuclide release” end state. In the negative case, that is, if moderator enters the breached canister, the corresponding event sequences terminate in either an unfiltered radionuclide release that must be further evaluated with respect to criticality (which is indicated as “also important to criticality”). Note that, “also important to criticality” means that event sequences tagged as such, that are found to be Category 1 or Category 2 in the subsequent categorization analysis, must be demonstrated to be subcritical. Demonstration of sub-criticality is not required for event sequences that are beyond Category 2.

No direct exposures were identified for this ESD due to the location of the events. No personnel are present in the emplacement drift during normal operations due to the radiation zone classification.

In summary, for each waste form and each initiating event group (small circle), the ESD delineates four event sequences:

1. Waste package containment and shielding remain intact ("OK" – i.e., no radiation exposure)

2. Waste package containment fails, canister containment remains intact ("OK" – i.e., no radiation exposure)

3. Waste package containment fails, canister containment fails, and moderator intrusion is prevented, resulting in an unfiltered radionuclide release

4. Waste package containment fails, canister containment fails, and moderator intrusion is not prevented, resulting in an unfiltered radionuclide release, also important to criticality.

6.2.5 SSO-ESD-04: Loss or Lack of Shielding

6.2.5.1 Summary Description

ESD-04 encompasses all activities that can occur due to loss or lack of shielding, but do not present a structural challenge to the waste package. This ESD is shown in Figure F-4. As such, ESD-04 includes all activities where workers can be exposed due to event sequences such as during the transit of the TEV on the surface and in the subsurface, as well as, when the TEV exits a facility to move a waste package to emplacement.

This ESD includes event sequences that arise due to: an exposure to a single waste package within the TEV, to the inadvertent opening of the TEV shield doors or, due to the prolonged worker proximity to the TEV. Also included, are event sequences that arise due to an exposure to a number of waste packages in an emplacement drift due to the inadvertent worker entry into the drift.

6.2.5.2 Initiating Events and Examples

Four types of initiating events in Figure F-4 are identified from the MLD shown on Figures D-3, D-4, D-9 and D-10. For quantification purposes, these initiators (represented by small circles) are collected together (as represented by the large circle).

The initiating events are as follows:

1. Loss of TEV movement induces thermal impact on shielding
2. Inadvertent TEV door opening
3. Prolonged worker proximity to TEV
4. Inadvertent entry into drift.

An example of the first initiating event is a power loss of the third rail, halting the TEV, which in turn may allow the shielding to overheat over time. The TEV's neutron shielding is composed of a borated, hydrogenous synthetic polymer, NS-4-FR (Table A-2). This material has a continuous operating temperature limit of 150^{o}C (300^{o}F) (Ref. 2.2.66, P. II-5), which may be challenged if the TEV heats up over a period of time. An example of the second initiating event is the inadvertent opening of the TEV shield doors (while in travel on the surface or in the subsurface) by a spurious signal, thereby exposing a worker. An example of the third initiating event is continuous worker presence close to the TEV as it travels from a facility to an emplacement drift. An instance of the fourth initiating event is the inadvertent entry of worker into an emplacement drift in the case of impaired visibility (due to dust, smoke, etc.) or due to an emergency.

The groups are summarized by an aggregate initiating event, the large circle in the ESD. This large circle represents a challenge resulting from loss or lack of shielding.

6.2.5.3 Pivotal Events - System Response

After the exposure has occurred, no subsequent pivotal event is identified and the event sequence terminates in a direct exposure to radiation of the worker. Considerations as to whether worker protection (including shielding and procedural controls) is present to mitigate the direct exposure, is included as part of the probability of the initiating event.

In summary, for each waste form and each initiating event group (small circle), the ESD delineates one consequence:

- Failure of the shielding or failure to adhere to procedural safety controls causes direct exposure.

6.2.6 SSO-ESD-05: Localized Internal Fire

6.2.6.1 Summary Description

ESD-05 encompasses all the event sequences that arise due to an impact to the waste package due to a localized internal fire. This ESD is shown in Figure F-5. ESD-05 includes all Subsurface Operations where a localized fire could occur. Specifically, it includes fire-initiated event sequences that arise within the TEV control compartment during transit or in an emplacement drift, and also includes the potential for fires in a DSG control box during drip shield emplacement.

Note that fires originating near or in a TEV, as the TEV is inside a facility, are considered as part of the specific facility fire evaluations and are not duplicated in this analysis. A large areal internal fire is not analyzed. It is not considered credible due to the ability of the TEV to avoid or move away from an initiating fire induced by a cause external to the TEV, and the general lack of combustibles along the TEV track on the surface and along access mains in the subsurface. The potential for a fire in an adjacent facility affecting the TEV in transit is not considered credible due to the significant clearance distances from facilities shown in Figure A-5, a conclusion which is consistent with other fire analyses (Ref. 2.2.47).

As fire is not considered in the HAZOP evaluation, no related activity node is identified for fire.

This ESD includes event sequences that arise due to a localized fire within the TEV carrying a single waste package, as well as event sequences that arise in a TEV or DSG due to a localized fire that can impact a number of waste packages in an emplacement drift.

6.2.6.2 Initiating Events and Examples

Three initiating events in Figure F-5 are identified from the MLD shown in Figure D-12. For quantification purposes, these initiators (represented by small circles) are collected together (as represented by the large circle).

The initiating events are as follows:

1. TEV fire effects waste form on surface rail
2. TEV fire effects waste form on subsurface rail
3. TEV fire effects waste form in emplacement drift.

An example of the first initiating event is an overheating of an electrical power box in the TEV and igniting a cable fire as the TEV is traveling on the surface rail. An example of the second initiating event is a short-induced fire in the TEV as the TEV descends the North Ramp. An instance of the third initiating event is the failure of the cooling system of a DSG control box, allowing ignition of control wires and inducing a fire.

The groups are summarized by an aggregate initiating event, the large circle in the ESD. This large circle represents structural challenges resulting from internal fires.

6.2.6.3 Pivotal Events - System Response

The pivotal events shown in the ESD represent the system response of the waste package system to the challenge of a fire. After the initiating event challenge has occurred, the first pivotal event asks whether the containment boundary of the waste package remains intact. The availability of mobile fire suppression equipment is not considered in the analysis. Determining whether or not the containment boundary of the waste package remains intact may be probabilistic in that, the event involves uncertainties in both the load imposed on the waste package and the strength of the waste package. If the containment boundary remains intact, no radioactive release occurs. However, there remains the question whether or not the shielding during transit provided by the TEV remains intact, as posed by the next pivotal event. If the shielding remains intact, there is no exposure of personnel to radiation and the end state is "OK". Otherwise, the event sequence terminates in a direct exposure to radiation.

If the containment boundary of the waste package does not remain intact (i.e., for a negative answer to the question posed by the first pivotal event), whether or not a radionuclide release occurs depends on whether or not the canister containment boundary remains intact. Determining whether or not the containment boundary of the canister remains intact may be probabilistic in that the event involves uncertainties in both the load imposed on the canister and the strength of the canister. If the canister containment remains intact, radionuclide release is avoided, but an end state of direct exposure is assigned. If the fire is severe enough to damage the waste package, it is modeled as severe enough to compromise shielding provided by the TEV. For the occurrence of a fire in an emplacement drift, there is no potential for exposure of workers. The emplacement drift is an R5 radiation zone, and no personnel are present in the emplacement drift during normal operations due to this classification. Therefore, no direct exposure can occur if shielding is lost.

Otherwise, the containment boundaries of both the waste package and the canister have been breached and a radionuclide release is inevitable. The TEV does not provide containment. The remaining pivotal event provides further delineation of the event sequences by asking whether or not moderator is prevented from entering the breached canister. With a yes condition (that is, the absence of moderator intrusion), the unfiltered release is represented by the "Radionuclide release" end state. In the negative case, that is, if moderator enters the breached canister, the corresponding event sequences terminate in either an unfiltered radionuclide release that must be further evaluated with respect to criticality (which is indicated as "also important to criticality"). Note that, "also important to criticality" means that event sequences tagged as such that are found to be Category 1 or Category 2 in the subsequent categorization analysis must be demonstrated to be subcritical. Demonstration of sub-criticality is not required for event sequences that are beyond Category 2.

In summary, for each waste form and each initiating event group (small circle), the ESD delineates five event sequences:

1. Waste package containment and shielding remain intact ("OK" - i.e., no radiation exposure)

2. Waste package containment remains intact, but loss of TEV shielding causes direct exposure

3. Waste package containment fails, canister containment remains intact, but loss of waste package shielding causes direct exposure

4. Waste package containment fails, canister containment fails, and moderator intrusion is prevented, resulting in an unfiltered radionuclide release

5. Waste package containment fails, canister containment fails, and moderator intrusion is not prevented, resulting in an unfiltered radionuclide release, also important to criticality.

6.3 EVENT TREES

Event trees were developed for each ESD discussed above, with no differentiation for the type of waste forms involved in the process. The structure allows for a straightforward transposition of ESDs into event trees. The methodology for the transposition of ESDs to event trees is described in Section 4.3.2.3. For each ESD, there is a set of two corresponding event trees, one for the initiating events and the other for the corresponding system responses. No distinction is made for the waste form that is contained in the waste package. Table G-1 shows the correlation between event trees in Attachment G and ESDs in Attachment F.

7. RESULTS AND CONCLUSIONS

This analysis constitutes a systematic examination of Subsurface Operations and identifies and develops potential internal event sequences (excluding construction-related hazards) that could occur in Subsurface Operations during the preclosure period. The results of this analysis are:

- A set of MLDs for the Subsurface Operations (Attachment D), which identifies potential internal initiating events for event sequences
- A set of ESDs for the Subsurface Operations (Attachment F),which graphically depicts the event sequences that may be initiated by the initiating events identified in the MLD
- A set of event trees (Attachment G), which translate the ESDs into a convenient form for future event sequence quantification and categorization

ATTACHMENT A
SUBSURFACE LAYOUT AND DIAGRAMS

A1 SUBSURFACE LAYOUT AND OPENINGS

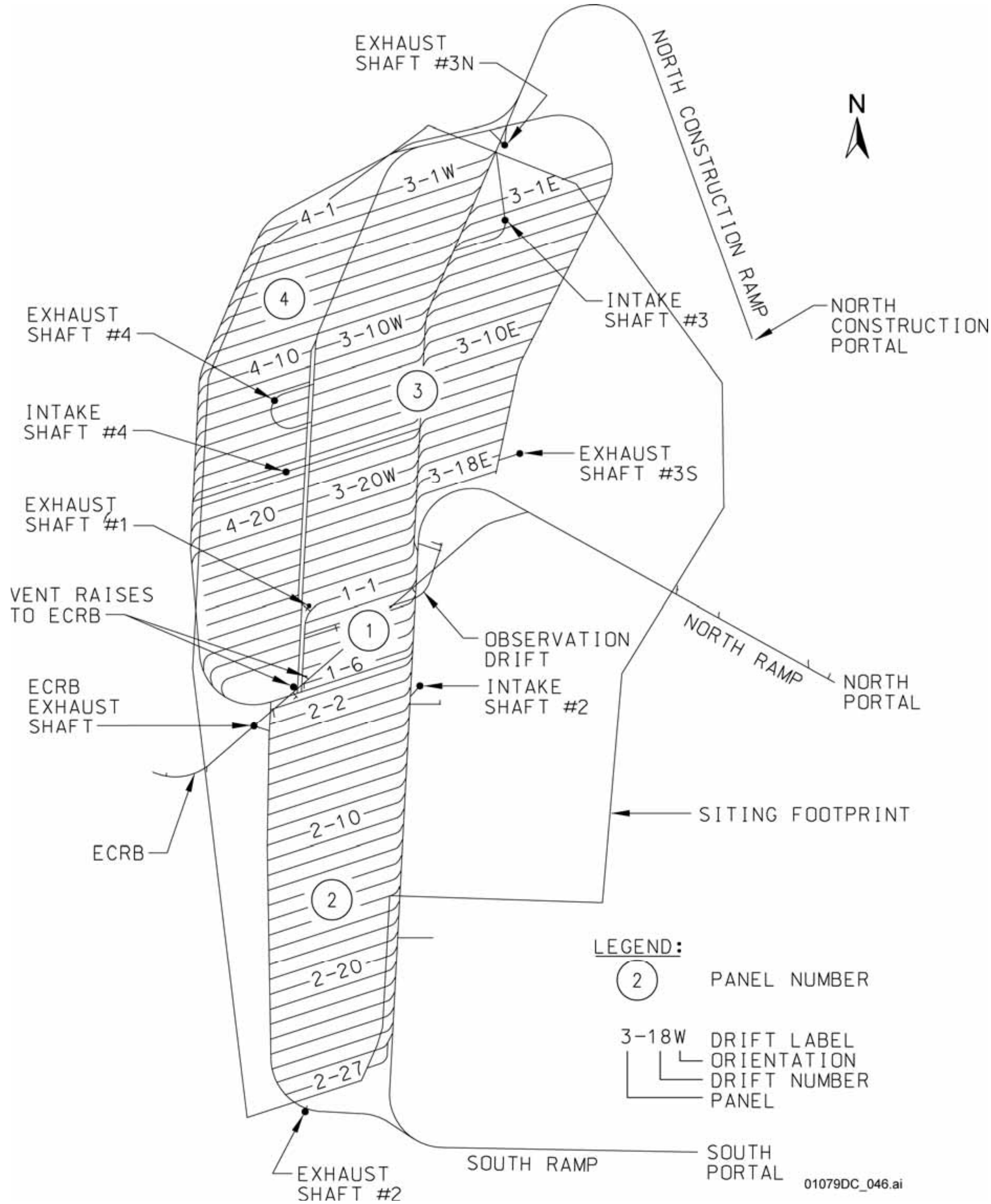
The layout for the underground facility is shown in Figure A-1 and is discussed in detail in two calculations, *Underground Layout Configuration* (Ref. 2.2.10) and *Underground Layout Configuration for LA* (Ref. 2.2.54). The nuclear waste is stored underground in emplacement drifts that are located a minimum of 125 m (410 ft) below the surface in volcanic rock formations (Ref. 2.2.10, Section 7.1.7. The layout of the Subsurface Facility is divided into four regions, or panels, encompassing 108 emplacement drifts (tunnel sections), with a total effective length for emplacement of 65.3 km (40.6 miles) (Ref. 2.2.54, Section 7.5.1).

Each emplacement drift is essentially a horizontal circular tunnel with a nominal diameter of 5.5 m (18 ft). Emplacement drifts are spaced apart nominally 81 m (266 ft) center to center (Ref. 2.2.54, Table 1, and are driven through the host rock by a tunnel boring machine (TBM). The base of the emplacement invert is framed in metal and filled with gravel ballast to provide a level surface for the rail system and for emplacing the waste packages (Ref. 2.2.40).

The subsurface area is reached by ramps (declines) from the surface, with the major access point for emplacement being the North Portal at the head of the North Ramp (Figures A-2 and A-3). From the North Portal, the North Ramp slopes down to the Subsurface facility elevation at an average -2.15% grade (i.e., slope) (Ref. 2.2.54, Section 6.2.1), which is the largest decline for Subsurface emplacement operations. Other ramps (i.e., the North Construction Ramp and the South Ramp) provide construction access.

Travel to emplacement drifts within the subsurface is provided by larger diameter excavations, termed access mains. Three access mains interface between the North Ramp and the emplacement drifts. These access mains as well as the ramps are circular openings, nominally 7.6 m (25 ft.) in diameter and are also excavated by the TBM. Travel distances in the subsurface (i.e., from the North Portal to an emplacement drift along these access mains) vary from about 3,000 to 7,200 m (9,800 to 23,600 ft). The travel paths to various points and panels are shown in *Repository Subsurface Transport and Emplacement Vehicle (TEV) Routes Details* (Ref. 2.2.41). Grades along the access mains are small and are typically 1.35%, varying from 1.04% to 1.45% with positive inclines to access Panels #1 and #2, and declines to access Panels #3 and #4.

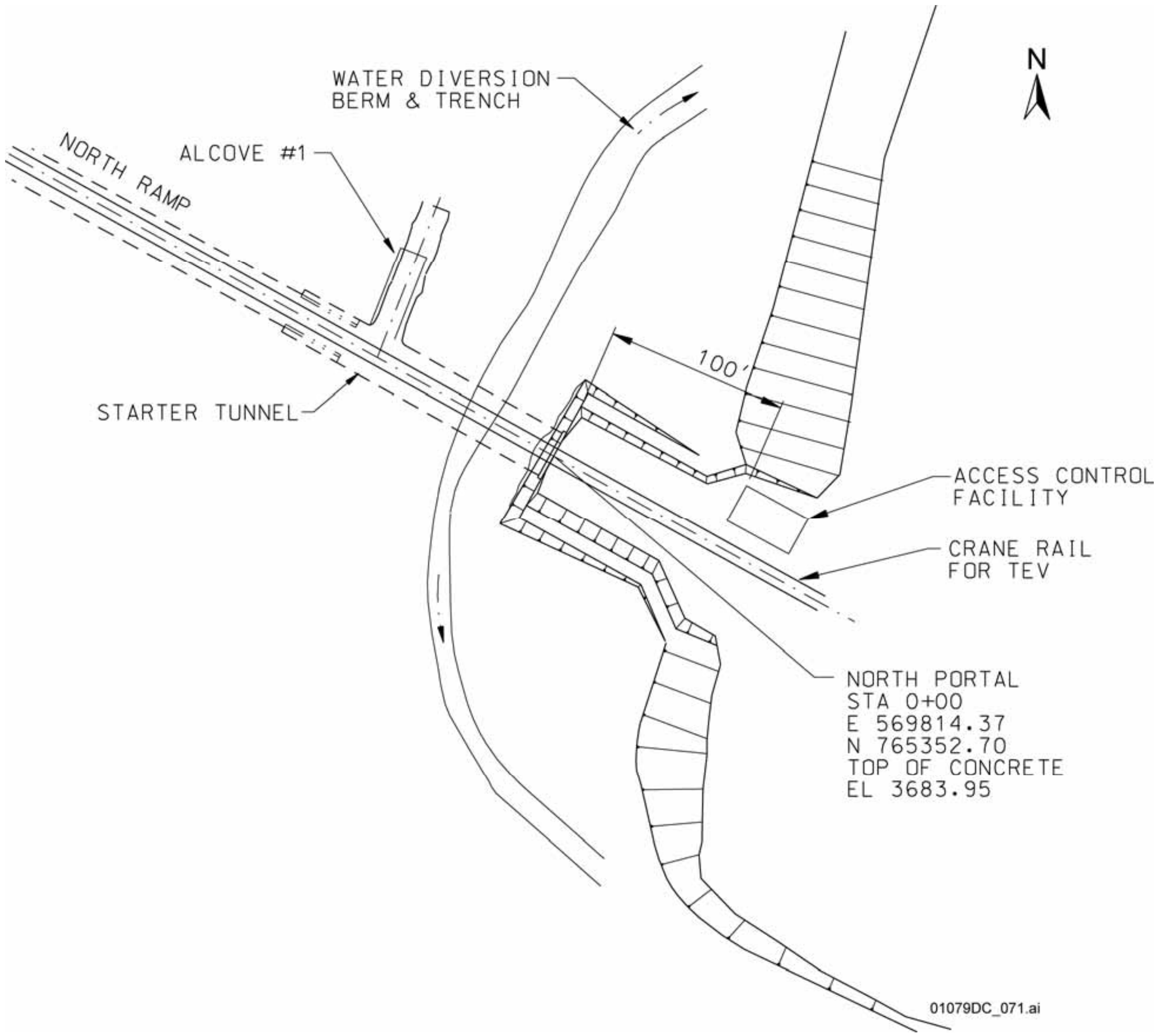
The transition between the larger-diameter access mains to the smaller, 5.5 m (18 ft) diameter emplacement drifts is provided by turnout drifts. A turnout is approximately 110 m (362 ft) in length (Figure A-4), variable in diameter, and contains the turnout rail switch to change from the access main rail to the emplacement rail. The turnouts are also curved to eliminate the direct radiation exposure (shine) from emplaced waste packages to the access main. Each turnout contains an access door bulkhead to control entry into the drift and provide ventilation controls for the drift; it does not provide shielding. The turnout is excavated in parts, with the initial portion created by drill and blast and methods in order to provide a launch chamber to enable the excavation of the remainder of the turnout and the emplacement drift by a TBM.



NOTE: ECRB = Enhanced Characterization of the Repository Block Drift.

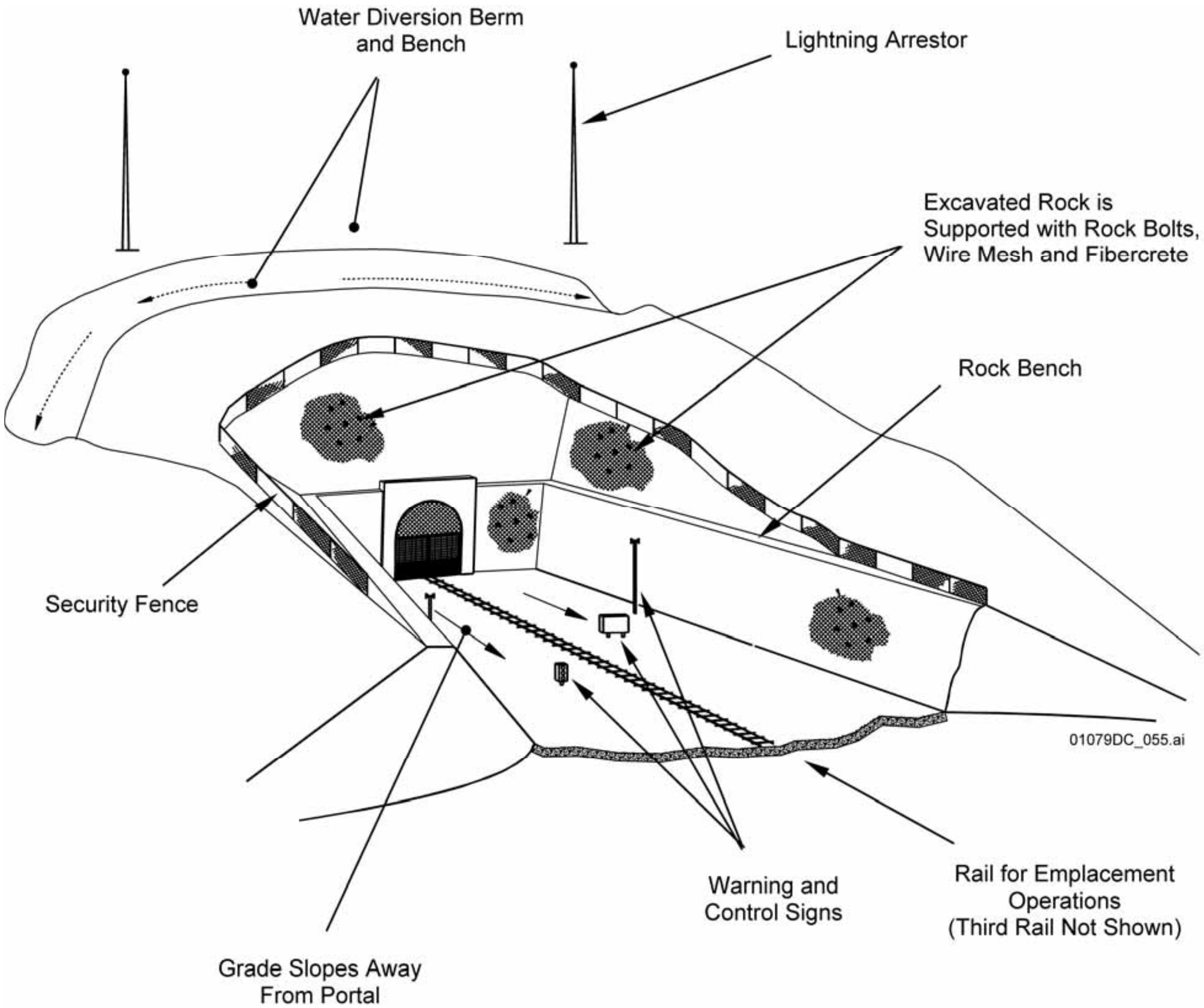
Source: Modified from (Ref. 2.2.54, Figure 11).

Figure A-1. Subsurface Layout of Repository



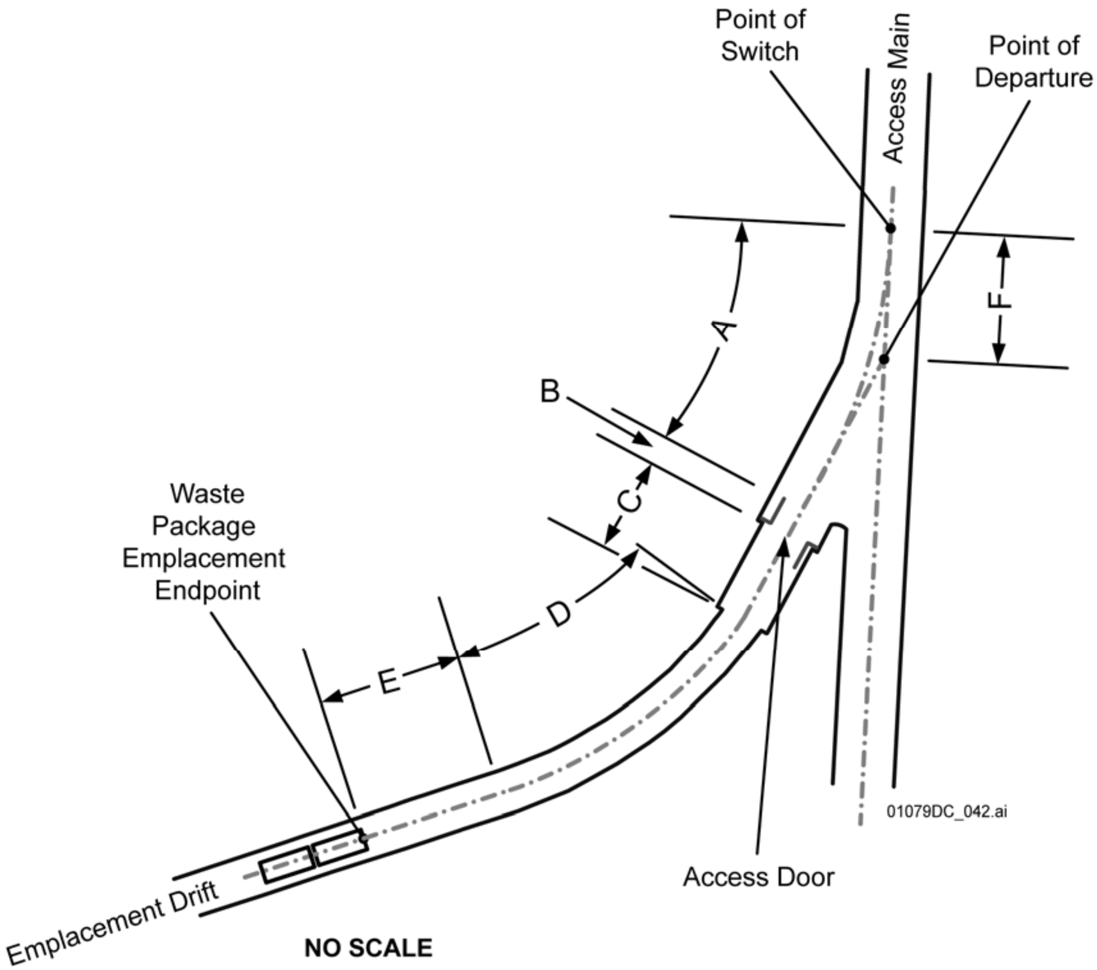
Source: Modified from ((Ref. 2.2.37, Figure 2).

Figure A-2. North Portal Plan View – During Emplacement



Source: Modified from (Ref. 2.2.13).

Figure A-3. Illustration – North Portal Isometric View



Identifier	Description	Typical Dimension (m)	Typical Dimension (ft)
A	Rail turnout segment	37.8	124
B	Turnout bulkhead segment	3.7	12
C	TBM launch chamber segment	12.0	39
D	Turnout curve (Radius = 61.0 m)	38.6	127
E	TEV alignment segment	18.3	60
F	Distance to point of departure segment	15.4	51
---	Total Turnout Distance (= A + B + C + D + E)	110.4	362

NOTE: TBM = tunnel boring machine; TEV = transport and emplacement vehicle.

Source: Modified from Ref. 2.2.52, Attachment I, Ref. 2.2.51, Figure 3 and Ref. 2.2.42.

Figure A-4. Typical Geometry of Turnout Drift - Plan View

Subsurface ventilation is provided by exhaust mains which are connected to the emplacement drifts; the exhaust mains are in turn connected to exhaust shafts. A total of six exhaust shafts are provided with four large-diameter (8 m, 26 ft) exhaust shafts and two small-diameter (5 m, 16 ft) exhaust shafts. The shafts are excavated by mechanical and/or drill and blast methods, and lined with concrete. Two ventilation fans are located at the top of each exhaust shaft to pull air from the ramps and three large diameter (8 m, 26 ft) intake shafts through the emplacement drifts and to ambient air. Ventilation flow into individual drifts is regulated by the access door ventilation system at the entrance of each emplacement drift. In addition, part of the Enhanced Characterization of the Repository Block Drift used for exploration of the subsurface is incorporated into the ventilation system.

A2 SURFACE RAIL

Subsurface Operations are defined in this analysis to encompass the transit of the waste package along the surface rail from the IHF and the CRCF to the North Portal. As shown in Figure A-5, the travel distance to the North Portal varies with each facility. The travel distance to the North Portal ranges from approximately 660 m (2170 ft) from CRCF 1, to approximately1350 m (4430 ft) from CRCF 3. The IHF is about 690 m (2250 ft) distant from the North Portal along the rail line. These travel distances consider the necessity to reverse direction during transit to achieve the correct orientation for emplacement operations.

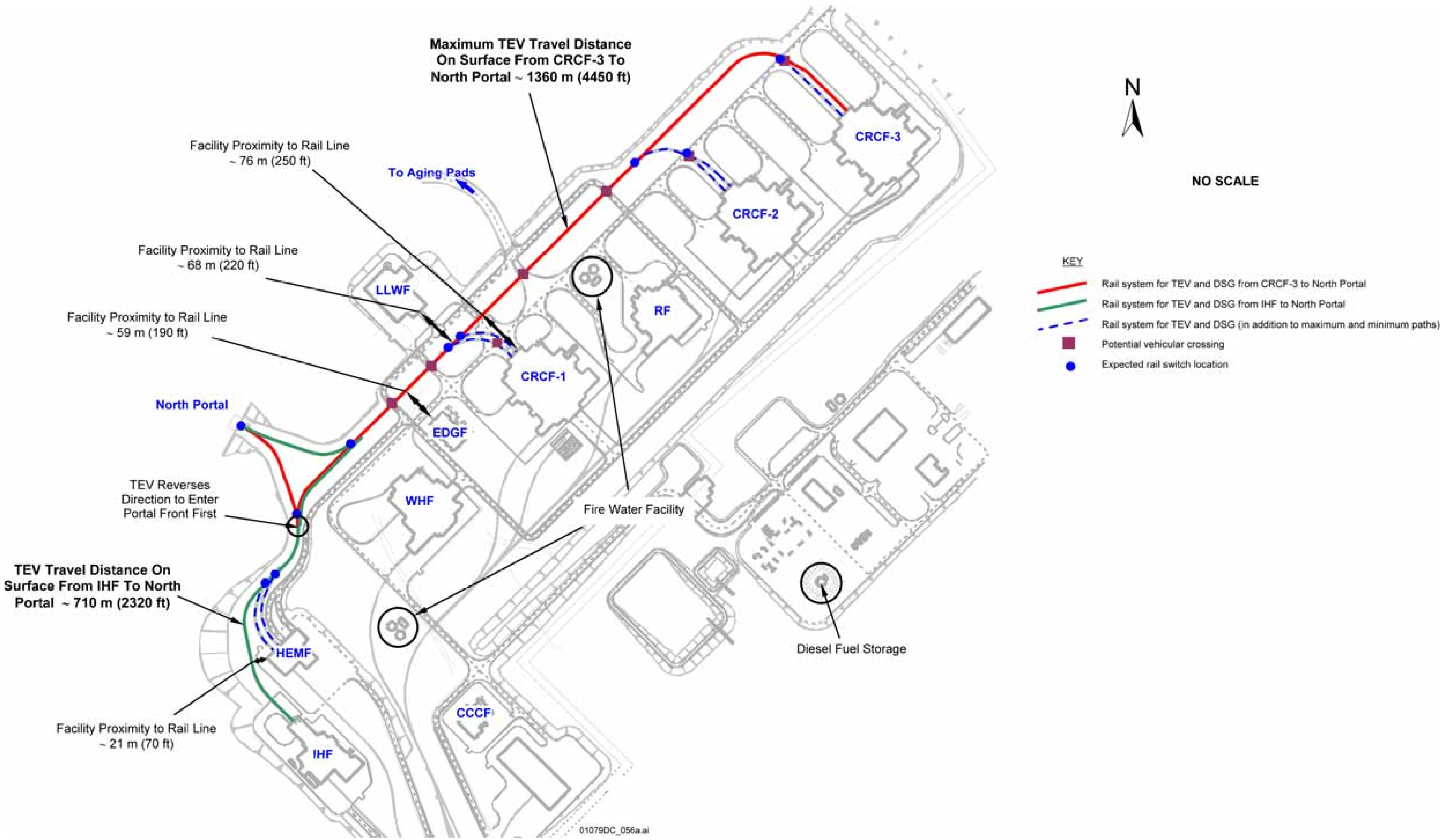
The rail line maintains a substantial distance from all handling facilities in the GROA, with the closest approach of the rail line to a handling facility is approximately 76 meters (250 ft) occurring at CRCF 1. The closest approach to other facilities is 21 m (70 ft) occurring along the transit from the IHF. In addition, the surface transit operations will cross several roadways including the transit path to and from the handling facilities and the Low-Level Waste Facility. The rail line will also cross the path taken by the site transporter to the aging pads.

A3 MAJOR SUBSURFACE SYSTEMS AND EQUIPMENT

Aside from the underground openings described in the previous section, the following systems and components are located in the Subsurface Facility:

Waste Package and Emplacement Pallet—Waste packages are emplaced in the subsurface, each containing canisterized nuclear waste. A nuclear waste canister (or several canisters) is placed into a cylindrical waste package which is then welded closed within a surface handling facility prior to transport into the subsurface. The waste package provides containment to prevent or limit the introduction of a moderator into the disposed waste form, and to prevent or limit the release of radionuclides into the environment.

The waste canisters within the waste packages contain one of several waste forms, including: (1) SNF in transportation, aging, and disposal (TAD) canisters; (2) canistered U.S. Department of Energy (DOE) SNF, including canistered naval SNF; and (3) canistered HLW from prior commercial and defense fuel-reprocessing operations.



NOTE: Distances shown are scaled from source drawing.
The TEV will need to reverse its orientation prior to entry into North Portal for access to most emplacement drifts. Therefore, the need to proceed into the switch south of portal to reverse direction is shown as part of the maximum travel distance.
CRCF = Canister Receipt and Closure Facility; CCCF = Central Control Center Facility; DSG = drip shield emplacement gantry; EDGF = Emergency Diesel Generator Facility; HEMF = Heavy Equipment Maintenance Facility; IHF = Initial Handling Facility; LLWF = Low-Level Waste Facility; RF = Receipt Facility; TEV = transport and emplacement vehicle; WHF = Wet Handling Facility; WP = waste package.

Source: Modified from Ref. 2.2.61.

Figure A-5. Estimated Surface Rail Distance and Rail Clearances from Facilities

The waste package itself consists of a single design with several configurations to accommodate the different types and sizes of the waste canisters; there are six distinct waste package sizes (Table A-1):

1. TAD Waste Package (holding a TAD canister containing either 21-PWR (pressurized water reactor) fuel assemblies or 44-BWR (boiling water reactor) fuel assemblies)

2. 5-DHLW/DOE Short (DHLW = defense high-level radioactive waste)

3. 5-DHLW/DOE Long

4. 2-MCO/2-DHLW

5. Naval Short

6. Naval Long.

Approximately 12,000 waste packages of various sizes will be emplaced in the repository (Ref. 2.2.69. The general waste package design consists of two concentric cylinders in which the canisters are placed (Ref. 2.2.48). The inner vessel is stainless steel Type 316 (UNS S31600); the sides of this cylinder are 51 mm (2 in) in thickness (Ref. 2.2.49). The outer corrosion barrier is Alloy 22 (UNS N06022), a corrosion-resistant, nickel-based alloy, and cylinder side is 25 mm (1 inch) in thickness. The top of the waste package has both a welded outer lid and an inner lid or shield plug. The weight of a waste package ranges from 44.9 to 80.8 metric tons (49.5 to 89.1 short tons) (Ref. 2.2.34, Table 1).

Within the emplacement drift and above the invert, each waste package rests upon a composite metal frame or pallet. The pallet consists of two V-shaped supports of Alloy 22 (UNS N06022), which are tied together by stainless steel tubes (UNS S31600) (Figure A-6). To prevent damage to the waste package, the waste package is handled solely using this pallet, to ensure that the handling equipment does not make direct contact with the waste package during normal Subsurface Operations.

Transport and Emplacement Vehicle (TEV)—To transport the waste package and pallet into the subsurface, a shielded, remotely-operated vehicle is used, termed a TEV and is described in the *Mechanical Handling Design Report: Waste Package Transport and Emplacement Vehicle* (Ref. 2.2.34). The TEV is illustrated in Figures A-7 and A-8. The TEV is a rail-based, metal-wheeled vehicle which travels from the surface handling facilities and directly into the emplacement drift, to emplace the waste package. The TEV is powered by a third rail and contains programmable logic controllers (PLCs) for localized control of the device, with only general oversight from a central control

Table A-1. Nominal Waste Package Inventory and Dimensions

<table>
<tr><th>No.</th><th>Waste Package Configuration</th><th>Estimated Nominal Quantity [g]</th><th>Nominal WP Length (m [ft])</th><th>Nominal WP Diameter (m [ft])</th><th>Description of Configuration</th></tr>
<tr><td>1</td><td>TAD WP [a]</td><td>7483</td><td>5.85 [19.19] [h]</td><td>1.96 m [6.44]</td><td>WP with TAD canister</td></tr>
<tr><td>2</td><td>5 DHLW Short / 1 DOE SNF Short [b]</td><td>1207</td><td>3.70 [12.13]</td><td>2.13 [6.98]</td><td>WP containing five short HLW glass canisters and one short DOE SNF canister</td></tr>
<tr><td>3</td><td>5 DHLW Long / 1 DOE SNF Long [c]</td><td rowspan="3">1862</td><td rowspan="3">5.30 [17.40]</td><td rowspan="3">2.13 [6.98]</td><td>WP containing 5 long HLW glass canisters and one long DOE SNF canister</td></tr>
<tr><td>4</td><td>5 DHLW Long / 1 DOE SNF short [c]</td><td>WP containing 5 long HLW glass canisters and one short DOE SNF canister</td></tr>
<tr><td>5</td><td>5 DHLW Long [c]</td><td>WP containing 5 long HLW glass canisters</td></tr>
<tr><td>6</td><td>2 MCO / 2 DHLW [d]</td><td>210</td><td>5.28 [17.32]</td><td>1.83 [6.01]</td><td>WP containing 2 multi-canister over packs and 2 long HLW glass canisters</td></tr>
<tr><td>7</td><td>1 Naval Short [e]</td><td>90</td><td>5.22 [17.11]</td><td>1.96 [6.44]</td><td>WP containing 1 short naval canister</td></tr>
<tr><td>8</td><td>1 Naval Long [f]</td><td>310</td><td>5.85 [19.19]</td><td>1.96 [6.44]</td><td>WP containing 1 long naval canister</td></tr>
<tr><td></td><td>Total WP</td><td>11,162</td><td>---</td><td>---</td><td>Nominal number of WPs - all configurations</td></tr>
</table>

NOTE: [a] Source for dimensions: Ref. 2.2.49, dimensions rounded to the nearest 0.01 m (0.01 ft).

[b] Source for dimensions: Ref. 2.2.20. Dimensions rounded to the nearest 0.01 m (0.01 ft).

[c] Source for dimensions: Ref. 2.2.19. Dimensions rounded to the nearest 0.01 m (0.01 ft).

[d] Source for dimensions: Ref. 2.2.18. Dimensions rounded to the nearest 0.01 m (0.01 ft).

[e] Source for dimensions: Ref. 2.2.36. Dimensions rounded to the nearest 0.01 m (0.01 ft).

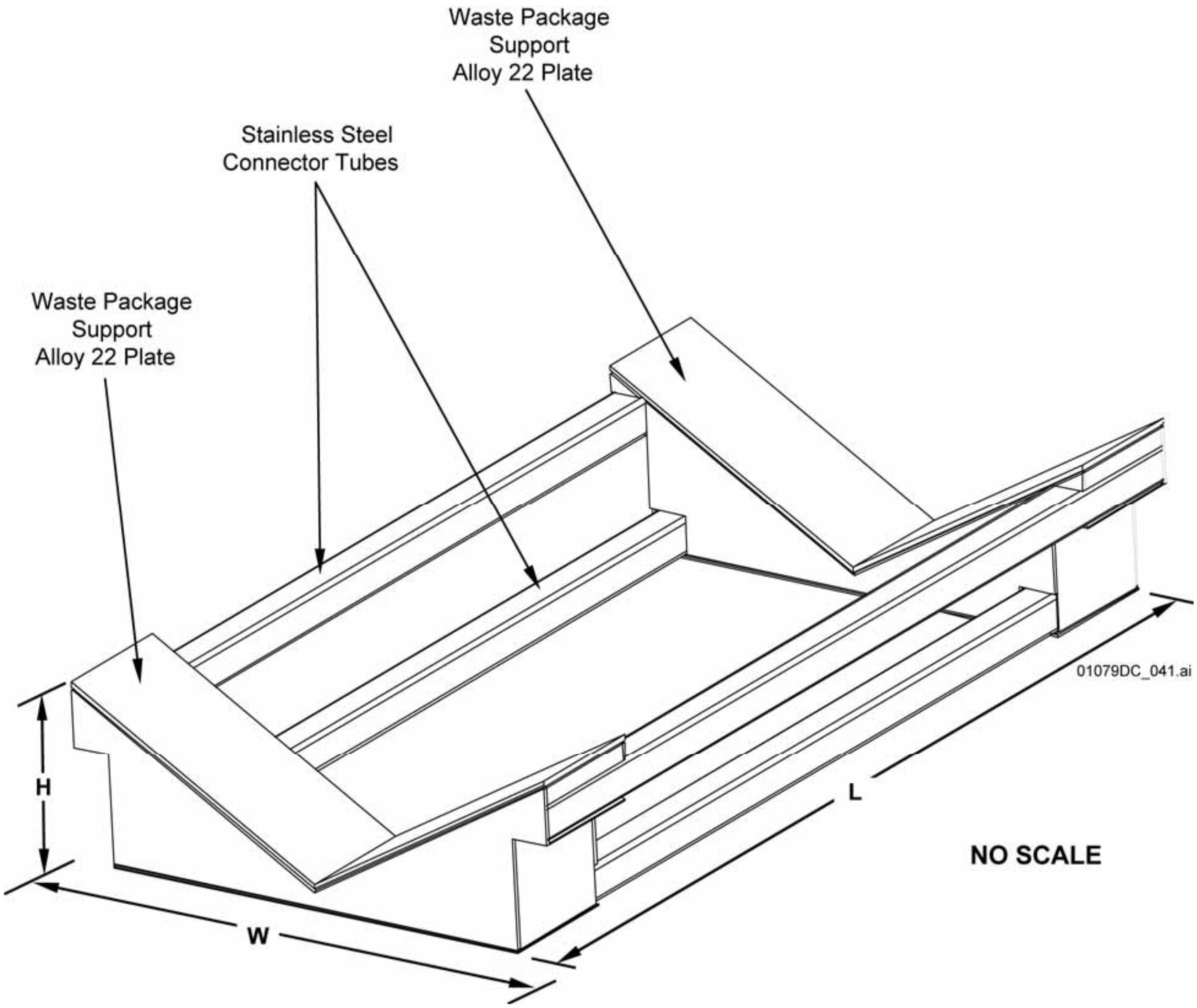
[f] Source for dimensions:Ref. 2.2.35. Dimensions rounded to the nearest 0.01 m (0.01 ft).

[g] Source for nominal quantities is Ref. 2.2.69, Unit Cell, Item 1

[h] Approximately 166 TAD WP may require an increase in length of 0.46 m (1.5ft), or a total length of 6.31 m (20.69 ft).

DOE SNF = U.S. Department of Energy spent nuclear fuel; DHLW = defense high-level radioactive waste; MCO = multicanister overpack; TAD = transportation, aging, and disposal canister; WP = waste package.

Source: Original

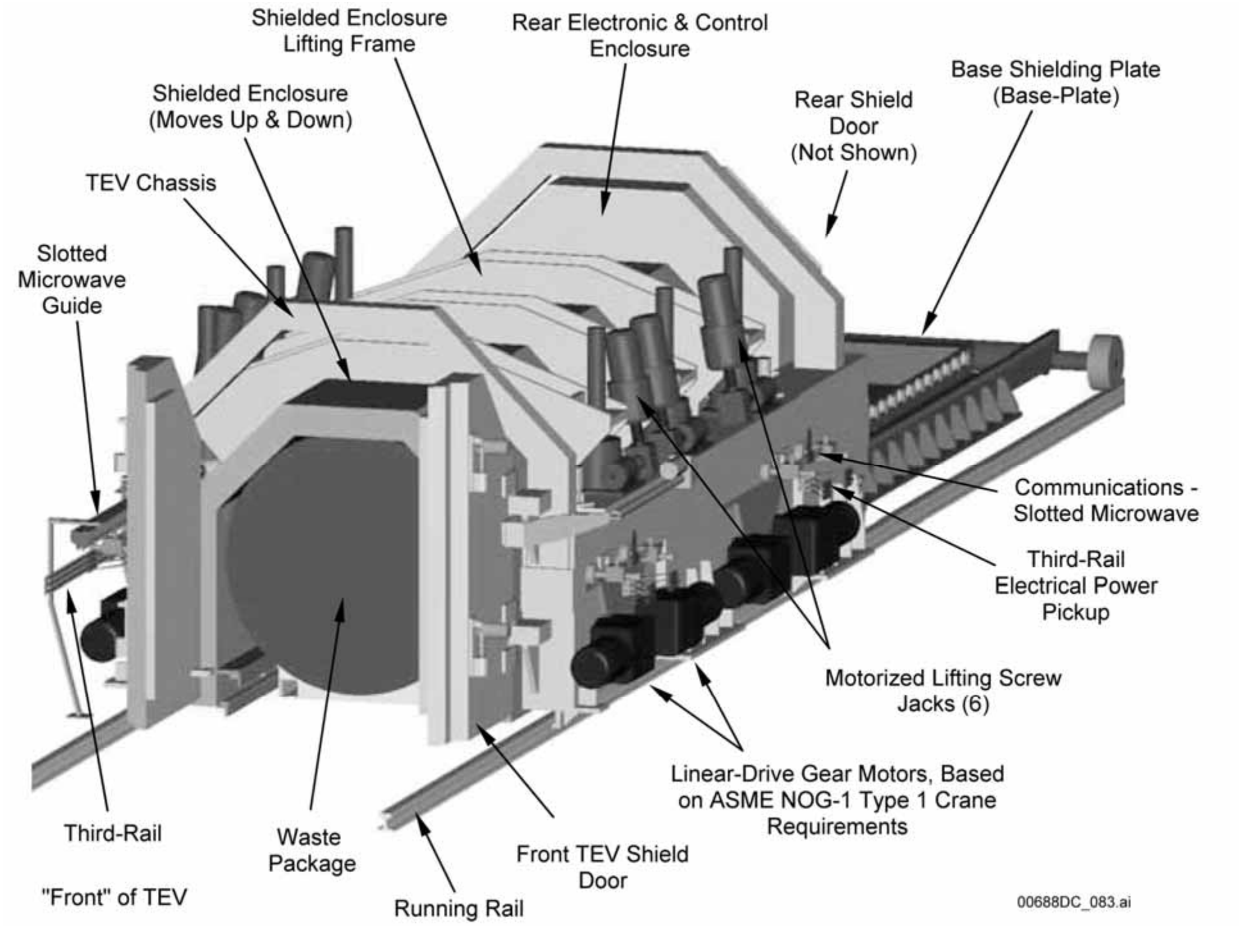


Description	Typical Dimensions (H × W × L)	Nominal Weight
Short pallet	0.73 × 2.15 × 2.50 m [2.4 × 7.1 × 8.2 ft]	1.73 metric ton [1.9 short ton]
Long pallet	0.73 × 2.15 × 4.15 [2.4 × 7.1 × 13.6 ft]	1.97 metric ton [2.2 short ton]

NOTE: Dimensions and weight from Ref. 2.2.9 and Ref. 2.2.7; dimensions rounded to the nearest 0.01 m or 0.1 ft.

Source: Modified from Ref. 2.2.8.

Figure A-6. Illustration of a Waste Package Emplacement Pallet



NOTE: [a] Approximate TEV nominal dimensions (H x W x L) = 3.4 x 4.7 x 9.0 m (11.1 x 15.3 x 29.7 ft) (With base-plate retracted).

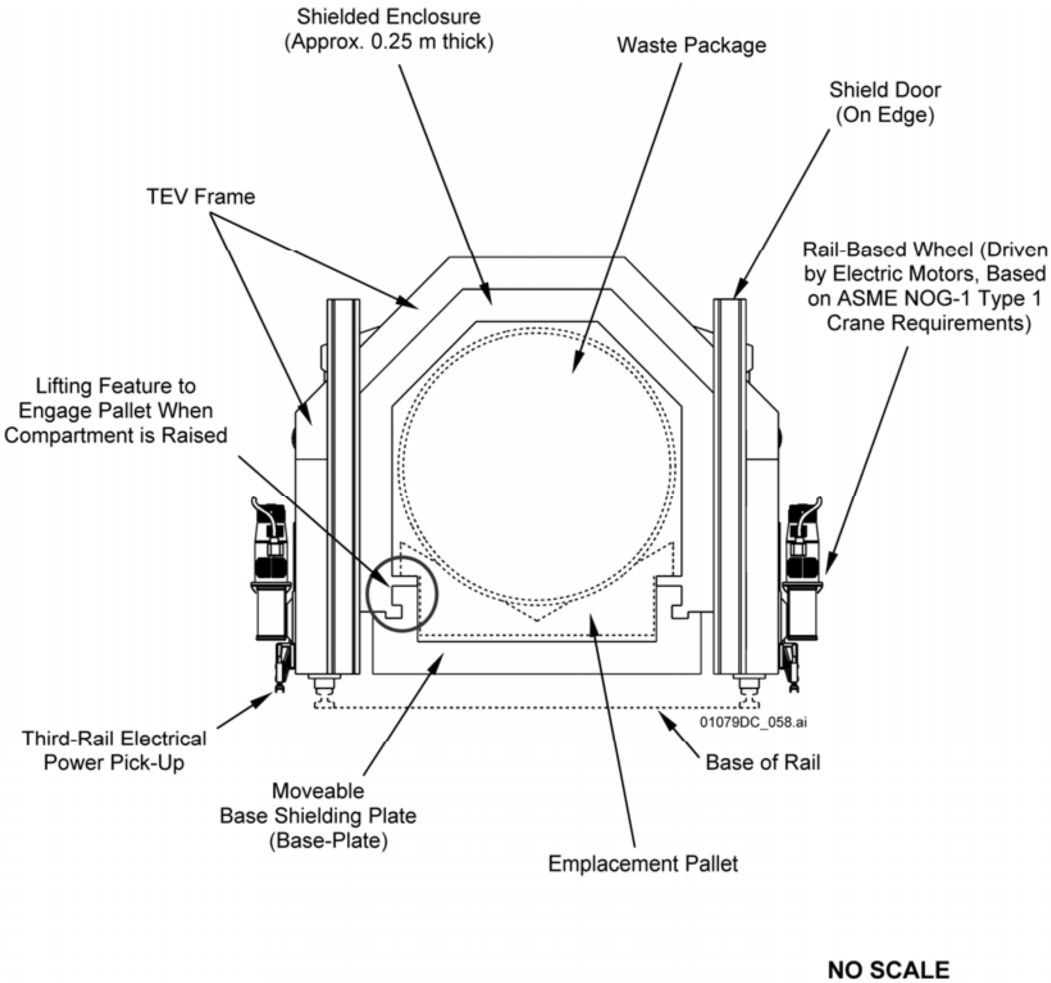
[b] Approximate TEV length with extended base-plate (operating envelope) = 18.3 m (60.0 ft).

[c] Approximate weight = (unloaded) 164 metric tons (181 short tons) and (loaded) 247 metric tons (272 short tons).

[d] Cameras, lights and other instrumentation are not shown.

Source: Modified from Ref. 2.2.34.
Nominal dimensions from Ref. 2.2.50.

Figure A-7. Illustration of Transport and Emplacement Vehicle (TEV) in Emplacement Drift



Source: Modified from Ref. 2.2.28, View B.

Figure A-8. Illustration of a Section through Front of the Transport and Emplacement Vehicle (TEV) Carrying a Waste Package

The TEV has eight wheels (four on each side) each driven by an electric motor (Figure A-7). To limit derailment, the wheels on one side of the vehicle are double-flanged (Ref. 2.2.34), Section 3.3.5. Disc brakes are integral to the motors on each wheel. In addition, the TEV has a separate braking system (sometime termed a "parking brake"), independent of the wheel brakes, which can be used to stop the TEV in the event of a failure of the wheel brakes *(*(Ref. 2.2.34, Section 3.3.3). To lower and raise the TEV shielded enclosure, six screw jacks are mounted on the TEV exterior, with the front and rear jacks used in normal operations and two central jacks acting as backup units. The maximum speed of the electric motors conforms to ASME NOG-1-2004. 2005. *Rules for Construction of Overhead and Gantry Cranes (Top Running Bridge, Multiple Girder)* (Ref. 2.2.4). The TEV travels on 171 lb crane rail with a gauge of 3.35 m (11 ft), installed in accordance with the requirements of ASME NOG-1 2004, 2005.

The PLCs and other electronic controls of the TEV are housed in a separate equipment compartment, positioned externally at the rear of the TEV shielded enclosure. This compartment houses a number of sub-enclosures that will contain the control and instrumentation components with duplicate equipment to provide defense in depth. Each sub-enclosure is totally enclosed to provide fire protection and protection against internal explosions. The overall compartment also contains a HVAC unit to maintain the operating environment for the control instrumentation, as well as a fire detection system that will activate the on-board fire suppression system, should fire be detected within this compartment.

The TEV has approximately 0.25 m (10 in) of shielding, constructed with a layered metal/polymer composite and formed (Table A-2). Radiologically, the TEV shield enclosure is not airtight, but the shielding prevents a dose rate in excess of 100 mrem/hr at 30 cm (11.81 in) from the external accessible surfaces, based on design requirements *Project Design Criteria Document* (Ref. 2.2.38, Table 4.10.1-1). In contrast, the dose rate from the base of a unshielded waste package is approximately 356 rem/hr, decreasing to 99 rem/hr from the top and 220 rem/hr radially, measured at a distance of 1 m (3.2 ft) ((Ref. 2.2.11, Tables 6.1-3 and 6.1-5. To provide cooling for the shielding, a fan circulates air within the TEV. The air intake for this fan is shown at the top of the unit, (Ref. 2.2.56) and no filtration of the exhaust air is identified.

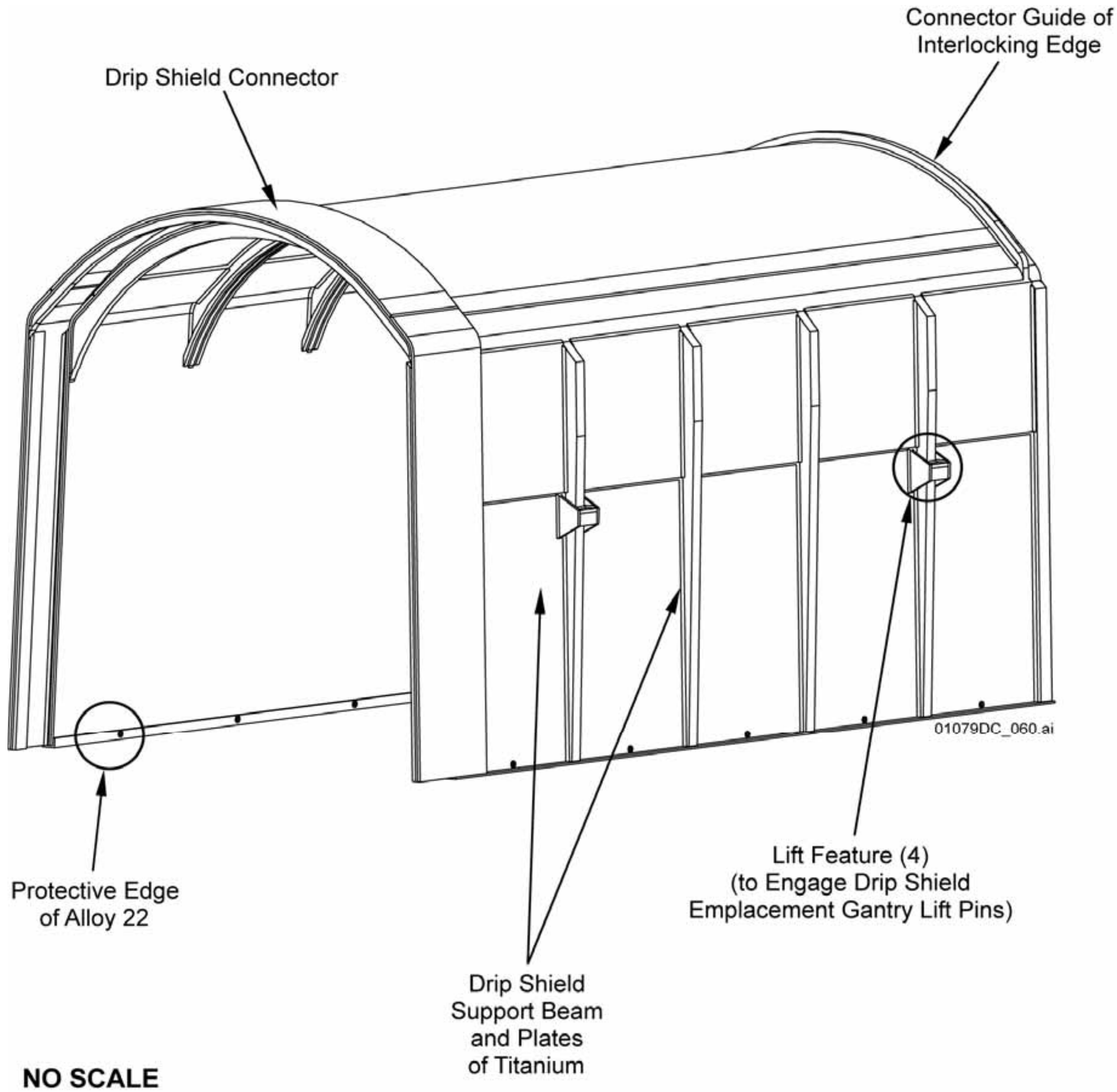
Drip Shield–Just prior to closure of the Subsurface Facility, drip shields are placed over the waste packages within the emplacement drifts (Ref. 2.2.31, Ref. 2.2.32, and Ref. 2.2.33). The drip shields are to prevent any seepage entering the drift from dripping onto the waste packages after repository closure. A drip shield has an inverted U shape, and is composed of titanium alloys (UNS R56404 and UNS R52400) with a protective base edge of Alloy 22 (Figure A-9). A drip shield segment is approximately 2.9 m (9.5 ft) high and 5.8 m (19 ft) long (Ref. 2.2.31). Each drip shield segment is designed to interlock with a previously emplaced drip shield segment, and when properly interlocked, the drip shield does not contact the emplacement pallet, the waste package, the rock wall or the runway beams of the invert.

Table A-2. TEV Shielding Configuration

Component	Material	Layer Thickness (mm / in)
Inner layer	Austenitic stainless steel, SS316L (UNS S31603)	38 / 1.5
Gamma shield	Depleted Uranium	38 / 1.5
Structural steel	Austenitic stainless steel, SS316L (UNS S31603)	13 / 0.5
Neutron shield	Synthetic polymer material, NS-4-FR	152 / 6.0
Outer layer	Stainless steel, SS3316L	13 / 0.5
Total shielding thickness		254 / 10.0

NOTE: Material layers start with inner material at the top of the list and the outer layers down the list.

Source: Modified from Ref. 2.2.34, Table 3. Shielding order has reversed the thickness for layers #1 and #3 from configuration shown in Ref. 2.2.17.

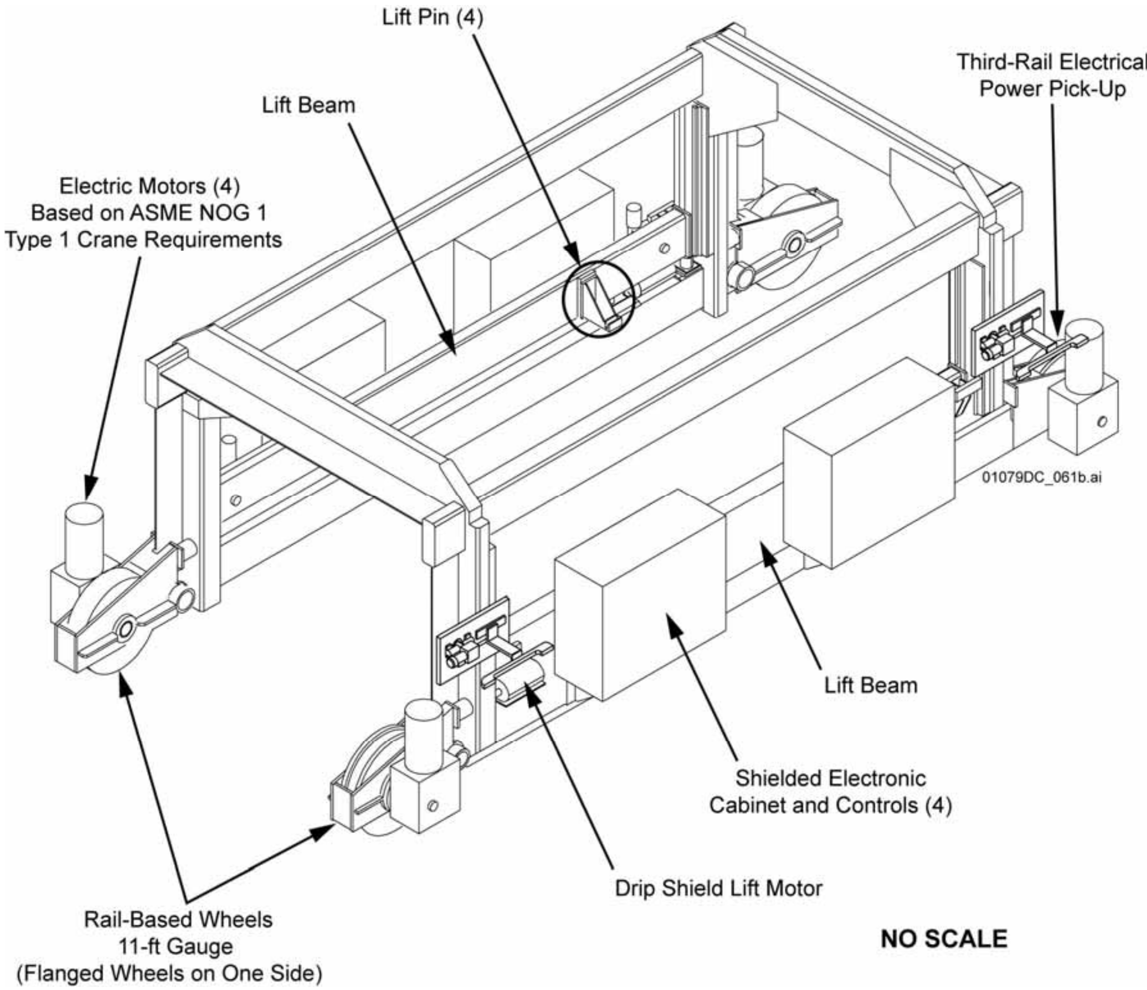


NOTE: [a] Approximate shield dimensions (H x W x L) = 2.9 x 2.5 x 5.8 m (9.5 x 8.3 x 19.1 ft).
[b] Approximate weight = 5 metric tons (5.5 short tons).

Source: Modified from *Interlocking Drip Shield Configuration* (Ref. 2.2.31).
Dimensions and mass from Ref. 2.2.32 and Ref. 2.2.33.

Figure A-9. Interlocking Drip Shield – Isometric View

Drip Shield Emplacement Gantry (DSG)—Drip shields are transported from the Heavy Equipment Maintenance Facility (HEMF) on the surface to each emplacement drift by the drip shield emplacement gantry (DSG). Similar to the TEV, the DSG is a rail-based metal-wheeled vehicle, powered by a third rail. However, the DSG is without shielding as it does not transport waste, and therefore is more of an open-framed vehicle than a TEV (Figure A-10). The DSG also contains PLCs for localized control of the gantry, and operates with only general oversight from a central control.



NOTE: Approximate gantry dimensions (H x W x L) = 3.2 x 4.7 x 9.2 m (10.6 x 15.3 x 30.3 ft).
Lights, cameras and other instrumentation are not shown.
Approximate weight (unloaded) = 48 metric tons (53 short tons).

Source: Modified from Ref. 2.2.27.
Nominal dimensions from Ref. 2.2.60.

Figure A-10. Drip Shield Emplacement Gantry (DSG)

The frame of the DSG is a steel structure designed to support its own weight and the weight of the drip shield. The DSG raises lift beams up to engage lifting pin assemblies on the drip shield and raise the shield into a carry position.

Each of the DSG wheels is directly driven by an electric motor. Integral brake motors work in a fail-safe configuration, which automatically activates if either a brake support system or the power fails. Gantry motors, including the lifting drive motors, and any other operating components of the DSG, are electrically operated and controlled (Ref. 2.2.21, Section 4.5). Motors and gearboxes are sealed against environmental effects.

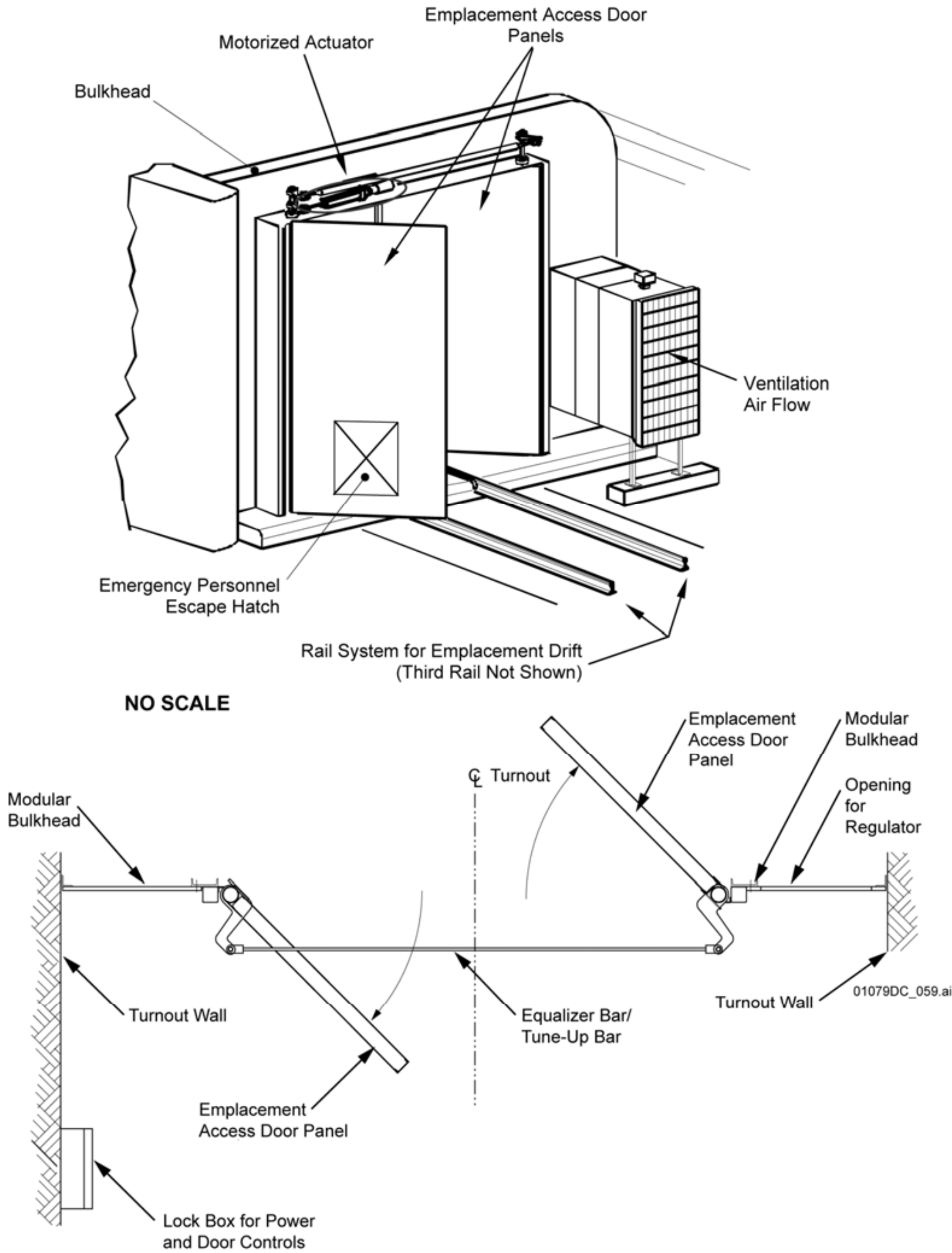
The PLCs and other electronic controls of the DSG are housed in separate equipment compartments (boxes) positioned at the sides of DSG (Figure A-10). Each compartment is insulated and contains equipment to maintain the operating environment for the control instrumentation, together with a fire suppression system (Ref. 2.2.21, Sections 4.5.2 and 4.5.6).

Turnout Bulkhead and Emplacement Access Door—At the entrance to each emplacement drift is a framed barrier wall, termed a turnout bulkhead. The bulkhead contains the emplacement access door as well as ventilation openings and controls for the emplacement drift. The emplacement access door controls access to the high radiation area of the emplacement drift and also restricts airflow into the emplacement drift; it does not provide shielding. The access door is composed of two panels which open in opposite directions rotationally from the outside edges (Figure A-11). The door can be operated locally or from the central control.

Rail System—Both the TEV and the DSG use the same rail system for Subsurface Operations. The running rail of this system consists of a 171 lb (weight per linear yard) (85 kg/m) crane rail with a gauge of 11 ft (3.35 m). Power for operation is provided by a third rail, mounted alongside the railway track. The third rail is on the side of the DSG as shown in *Emplacement and Retrieval Drip Shield Emplacement Gantry Mechanical Equipment Envelope* (Ref. 2.2.27), and at the side of the TEV (*Mechanical Handling Design Report: Waste Package Transport and Emplacement Vehicle* (Ref. 2.2.34). On the surface, the running rail is directly-anchored (i.e., without ties) to a concrete pad extending along the alignment.

In the subsurface, the rail differs between access mains and emplacement drifts; typical rail sections for the TEV subsurface transit is shown in Figure A-12. Within access mains and on ramps, the rail is anchored to a reinforced concrete slab poured on top of the existing or construction invert (Ref. 2.2.39). Within emplacement drifts, the rail is anchored to a steel frame anchored to the tunnel invert (base) (Ref. 2.2.40). The frame work is structured to provide direct support of the rails to the tunnel base, together with longitudinal members to support the rail and the drip shield, when emplaced. The space between the steel members is filled with gravel ballast.

Within the operating areas, the rail system terminates at various points in the subsurface including at the end of emplacement drifts and at isolation bulkheads. At isolation bulkheads and other points in the subsurface, the rail system can extend past the bounds of the operating area and physical barriers are required to prevent this occurence. To prevent the TEV or DSG from potentially impacting isolation barriers or running off the end of the emplacement drift, rail stops will be installed (Ref 2.2.34, Section 3.3.16). A rail stop is illustrated in Reference. 2.2.34 (Figure 42).

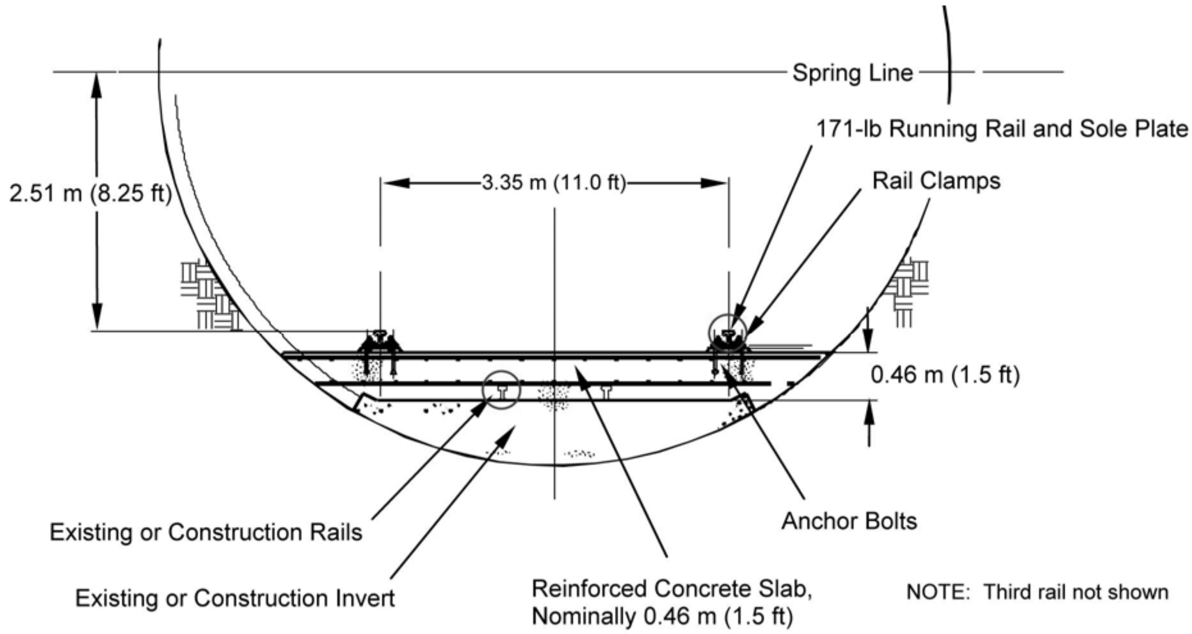


NOTE: [a] Approximate weight of door panels is 2.7 metric tons (3.0 short tons), and approximate overall dimensions (H x W) = 4.3 x 5.9 m (14.1 x 19.3 ft).

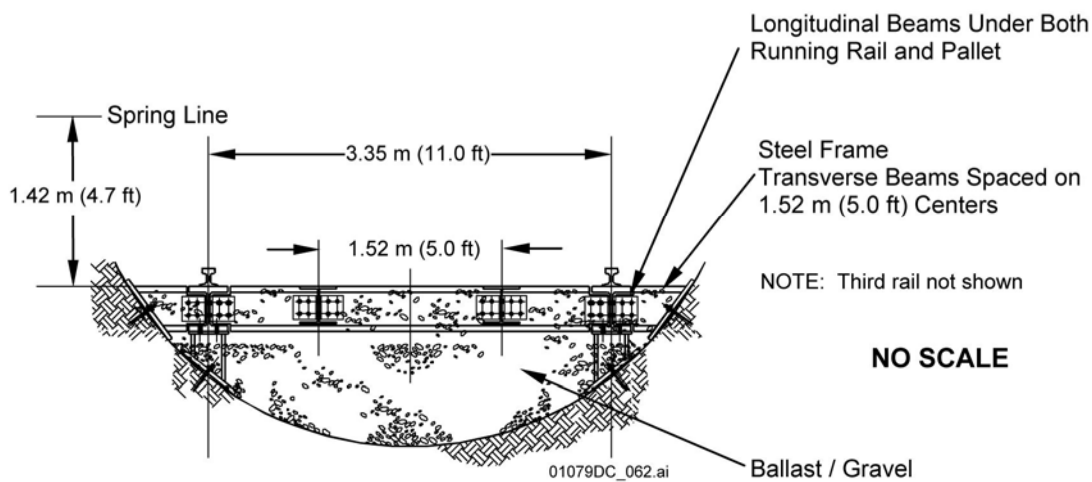
Source: Modified from Ref. 2.2.44 and Ref. 2.2.63, Figure 21.

Nominal weight from Ref. 2.2.26, p. 14; nominal dimensions based on Ref. 2.2.45 (*sizing of door opening*), increasing dimension to allow for framing, (Ref. 2.2.50, p.8).

Figure A-11. Isometric and Plan View of Typical Emplacement Access Door



(a) Rail Section - Access Main



(b) Rail Section - Emplacement Drift

Source: Modified from Ref. 2.2.40 and Ref. 2.2.39.

Figure A-12. Access Main and Emplacement Drift Rail

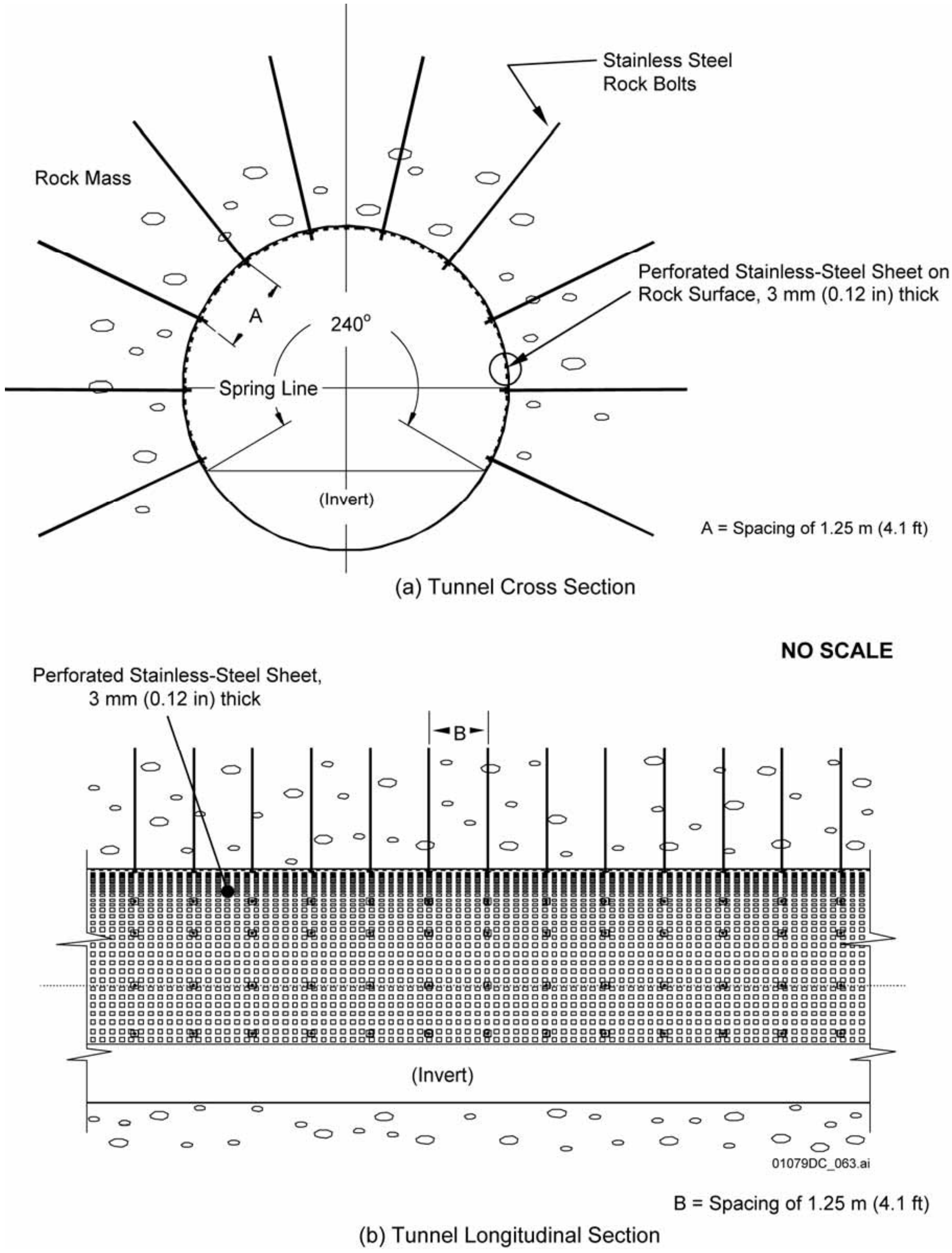
Ground Support—Underground openings are provided with support structures to ensure availability of these openings. The specific types of final ground support vary due to the requirements of the excavation type and the rock mass supported. Tunnel intersections in the subsurface along the access mains are supported with fully-grouted rock bolts, with steel-reinforced shotcrete and lattice girders used as necessary (Ref. 2.2.30, p. 223). Access mains and turnouts use fully-grouted rock bolts with heavy-duty welded wire mesh to support the rock mass. Supports in the emplacement drifts use stainless-steel expansion (friction) rock bolts together with perforated steel sheeting (Ref. 2.2.53) as shown in Figure A-13.

Utility Systems—Electrical and communications utility networks are present in the subsurface to power the TEV, controls and communications equipment (Ref. 2.2.59, pp. H-2 and I-14). Electrical supply and communication systems are also required in the subsurface for the ventilation controls and access door operation at the entrance of each emplacement drift. The electrical supply grid is also required to power the third rail for the rail system, for both the surface and the subsurface, together with associated electrical boxes, switches, controls, etc. In addition, a communication system is required for TEV and DSG operation. Standby diesel generators for the subsurface power system are located on the surface, south of the switchyard and at a substantial distance away from Subsurface Operations.

No gas, water or fuel utilities are present in the emplacement operation areas of the subsurface, and any utilities employed for construction in a specific panel area are isolated from emplacement operations (Ref. 2.2.59, pp. I-14 to I-17).

Ventilation Subsystems—The subsurface ventilation system consists of the development (construction) ventilation subsystem and the emplacement ventilation subsystem. The two independent subsystems provide for concurrent development/construction of the repository and waste emplacement. The two subsystems have independent airflow networks and fan systems that operate simultaneously.

To prevent the spread of any unlikely radioactive releases from the emplacement subsystem, the development subsystem is physically separated by isolation barriers as described in the *Basis of Design for the TAD Canister-Based Repository Design Concept* (Ref. 2.2.16, Section 22.1.1). The development ventilation subsystem is also operated as a positive pressure system and the emplacement ventilation subsystem is operated as a negative pressure system ((Ref. 2.2.16), Section 22.2.1.6). This combination ensures that a pressure differential between subsystems is maintained in the event that one subsystem shuts down. This ensures that any potential radioactive releases are contained on the emplacement side. The system ventilates the underground by circulating the ambient surface air throughout the subsurface development, subsurface emplacement areas, and subsurface non-emplacement areas and removes exhaust air.



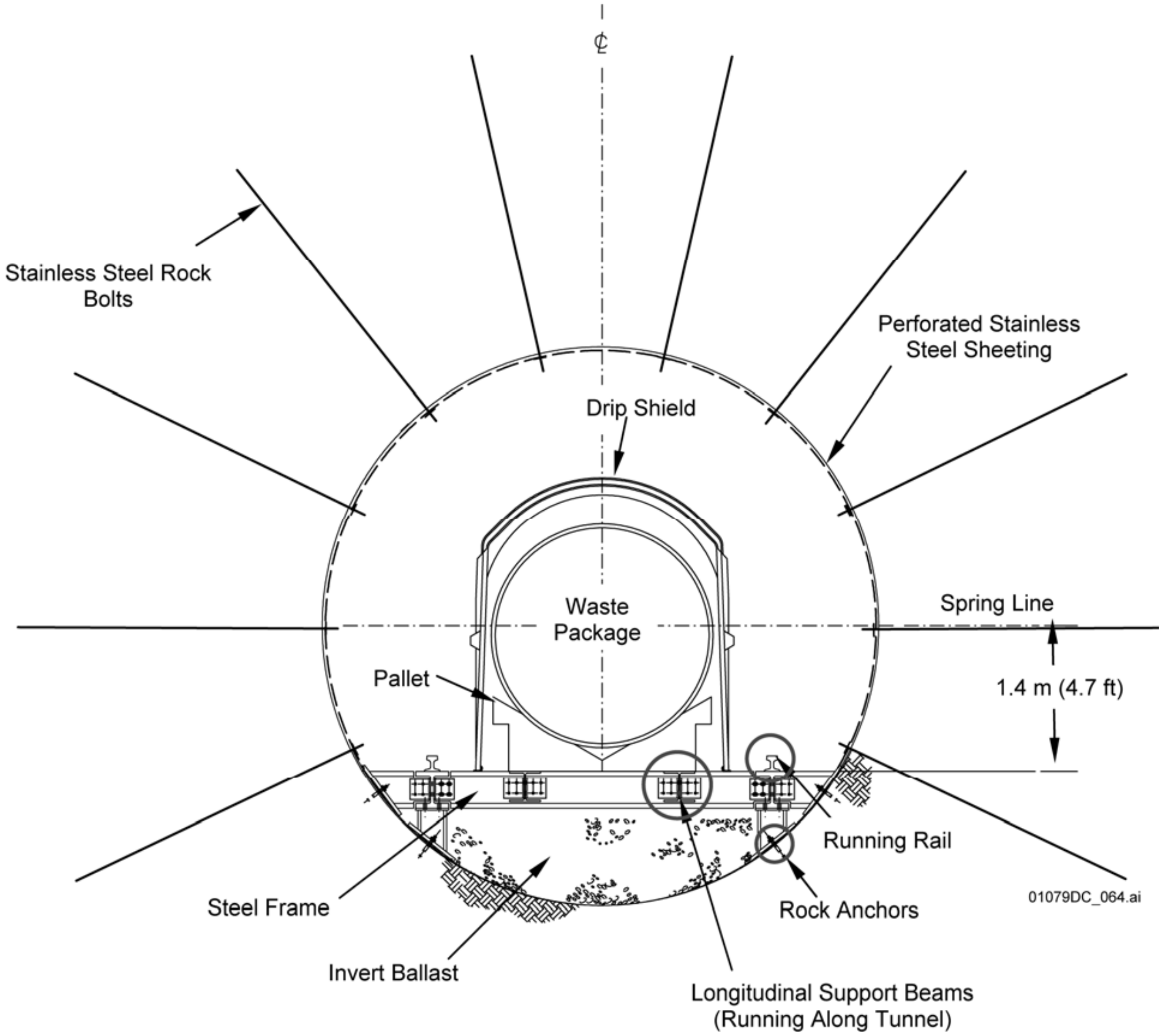
Source: Modified from *Typical Ground Support for Emplacement Drifts* (Ref. 2.2.53).

Figure A-13. Illustration of an Emplacement Drift Ground Support

For the emplacement areas, fans on the surface of exhaust shafts draw the air through the subsurface repository from the intake shafts and portals (Ref. 2.2.63, Section 6.3). Each exhaust shaft/raise contains two fans to ensure continuous operation if one of the fans is shut down for maintenance (Ref. 2.2.63, Figure 3). The volume of air required to cool the waste packages is approximately 15 m^3/s (530 ft^3/s) per emplacement drift (Ref. 2.2.63, Section 4.3.2). This flow rate is regulated by louvers in the emplacement access bulkhead panels (Figure A-11). In addition, other ventilation control devices such as barriers are used.

A4 FINAL CONFIGURATION PRIOR T0 CLOSURE

The final configuration of each emplacement drift after emplacing the drip shields is shown in Figure A-14. The pallet is supported by the longitudinal beams of the invert frame running the length of the drift. The rail sections are anchored directly over the longitudinal beams and the vertical members of the invert frame. The vertical members are anchored to the rock using rock anchors.



Source: Modified from Ref. 2.2.40, Ref. 2.2.53, and Ref. 2.2.24.

Figure A-14. Illustration of an Emplacement Drift after Drip Shield Emplacement

ATTACHMENT B
SUBSURFACE OPERATIONS SUMMARY

A brief summary of Subsurface Operations is presented in this attachment to provide a context for the PCSA of these operations. Subsurface Operations are defined as including all operations from the waste package transport vehicle's loading of a waste package in a handling facility on the surface, transit to the subsurface into the emplacement drift, and all operations within the emplacement drift and in the subsurface. The operational description is based primarily on *Mechanical Handling Design Report: Waste Package Transport and Emplacement Vehicle* (Ref. 2.2.34), together with relevant block flow diagrams, *Drip Shield Emplacement Block Flow Diagram Level 3* (Ref. 2.2.25) and *Waste Package Emplacement Mechanical Handling System Block Flow Diagram Level 3* (Ref. 2.2.55).

NOTE: The description of operations in this attachment and in Section 6.1.2 represents a cooperative effort involving PSCA facility leads, human reliability analysts, nuclear operations personnel, equipment reliability personnel and other engineering personnel. The PFD (shown in Figures 15 and 16) was developed while preparing the HAZOP study (Attachment E) describing these operations as it is a precondition for conducting the HAZOP. Furthermore, the specific processes described in Section 6.1.2 and in this attachment were discussed during the HAZOP meetings and in subsequent discussions among the above parties. This multi-disciplinary effort was led by the PCSA group and is documented herein.

B1 EMPLACEMENT OPERATIONS

Emplacement operations in the subsurface begin in Panel 1 and continue through Panel 4, covering a period of approximately 50 years as noted in the *Basis of Design for the TAD Canister-Based Repository Design Concept* ((Ref. 2.2.16, Section 2.2.2.7). Approximately 12,000 waste packages of various sizes are to be emplaced during this time period. As described in the following sections, the transport and emplacement operations for the different panels and waste package types are essentially identical.

Emplacement operations are conducted as waste packages become available, with a nominal rate of emplacement of one waste package per 8-hour shift, for a daily total of three waste packages emplaced per 24-hour day over an extended period. Excluding delays due to unplanned downtime, the resulting peak rate is 1,095 emplaced waste packages per year. Emplacement is conducted concurrently with other repository operations, such as maintenance, performance confirmation activities, and inspections. During transit, operational controls (including lights and alarms) exclude personnel from the waste package travel path.

The vehicle that conveys the waste package to the subsurface is the TEV (Attachment A). The TEV is a remotely-controlled, rail-based vehicle, which is powered by a third rail. It operates without an on-board crew, and is controlled by a PLC system housed at the rear of the vehicle. The TEV contains an array of instrumentation as shown on *WP Transport & Emplacement, Vehicle Process & Instrumentation Diagram (Sheet 1 of 3)* (Ref. 2.2.56), *WP Transport & Emplacement Vehicle Process & Instrumentation Diagram (Sheet 2)* (Ref. 2.2.57), and *WP Transport & Emplacement Vehicle Process & Instrumentation Diagram (Sheet 3)* (Ref. 2.2.58).

The TEV's progress is continuously monitored from a central control (i.e., the Central Control Center Facility).

B1.1 LOADOUT

Under the direction of an on-board PLC system and monitored from the Central Control Center Facility, the TEV is designed to remotely collect a waste package resting on an emplacement pallet from a waste handling facility on the surface and transport the container to the subsurface. The TEV receives waste packages from four facilities: the IHF and the CRCF 1, 2, and 3 facilities. For waste package loadout, the closed waste package is first transferred to the waste package loadout area of a waste handling facility on a waste package transfer trolley (WPTT), as shown in *CRCF-1 and IHF WP Transfer Trolley Mechanical Equipment Envelope Plan & Elevations - Sh 1 of 2* (Ref. 2.2.22). On the loading dock, the waste package is positioned horizontally, resting on the pallet at floor level, and centered between the TEV rails which allows for the proper alignment needed for TEV engagement (at the loadout station). The loadout configuration of the waste package and pallet is the same for all facilities.

Prior to staging the waste package at the loadout station, the facility loadout exterior doors are opened, the TEV enters the facility, and the exterior doors are closed. Prior to entering the facility, an electro-mechanical switch de-activates an interlock on the TEV, which allows the TEV shield doors to open. Upon exiting the facility, the interlock is activated, preventing the shield doors from opening until the TEV is ready to enter an emplacement drift. Personnel vacate the (Waste Package) Loadout Room and all shield doors and confinement doors are closed and secured. Next, the TEV moves forward to the loadout position, placing the vehicle directly over the loadout station. The TEV stops such that the TEV lifting features, integral to the shielded enclosure, are positioned to engage the waste package pallet lifting areas when the pallet and waste package are correctly positioned.

After receiving confirmation from control, the front shield door safety interlocks are disengaged; and the front shield doors are opened. Then the TEV raises its rear shield door and extends the base-plate from under the shielded enclosure. Subsequently, the lifting system (screw jacks) lift the shield enclosure to allow the transportation shot bolts to be retracted. Upon retraction of these bolts, the lifting system then lowers the shield enclosure to the proper collection height for the waste package and emplacement pallet.

A WPTT moves the waste package and pallet in a vertical position to the loadout station. The trolley engages the loadout dock, and the waste package shield ring is removed by the (waste package) handling crane. After the ring is removed, the WPTT rotates the waste package and pallet from vertical to horizontal, where the pallet and waste package rest on the waste package transfer carriage of the trolley (Ref. 2.2.23). In this process, the trolley's transfer carriage engages the docking station's carriage retrieval assembly. The carriage retrieval assembly contains a screw drive that moves the pallet and waste package horizontally from the trolley into the correct loading position under the TEV shielding. As the waste package is moved into position, cameras on the TEV record the waste package identification code to confirm the type of waste package loaded into the TEV. Once the pallet and waste package are properly positioned, the TEV shield enclosure is raised to its full travel height by the TEV's lifting features, engaging and raising the waste package and emplacement pallet into the TEV. The transportation bolts are engaged, and the shield enclosure is lowered to unload the jacks for transport. The base-plate is then retracted back under the shield enclosure and the rear shield door is lowered.

Subsequently, the TEV closes the TEV shield enclosure front doors, and engages all safety interlocks. The facility exterior shield doors are opened, and the TEV moves backward to exit the waste handling facility. As the TEV exits, a mechanical device engages an external switch on the TEV, which activates a mechanical interlock for the TEV shield doors, preventing a spurious signal from inadvertently opening the shield doors during transit.

B1.2 TRANSIT

TEV operations are defined within rail segments designated by control points within the software of the PLC system. The TEV travels within a defined rail segment between control points under PLC control. Stopping upon reaching a control point; the TEV proceeds to the next segment only upon receiving confirmation from central control. Upon a loss of power, the TEV is designed to stop, retain its load, and enter a locked mode; upon a restoration of power, the TEV stays in the locked mode until operator action is taken. Visual and auditory monitoring of TEV operations is performed by central control for all transit operations. The operator in central control has override control to stop the TEV in case of an emergency, and to provide authorization to proceed, but, can not activate or change settings of other operational controls, such as speed.

At an operating speed of approximately 2.7 km/hr (1.7 mph or 150 ft/min), the TEV moves along the surface track from the waste handling facility through a switch onto the main TEV surface rail line connecting all facilities to the North Portal. The TEV passes through a number of switches and sidings to reach the North Portal. The TEV continues along the main line and stops at the North Portal entrance for inspection and monitoring checks prior to descending the North Ramp (Ref. 2.2.34, Section 2.5.2).

The TEV passes through the North Portal and down the North Ramp and curve at the ramp base, to the repository level and through the central ramp switch at the low point of the system. The descent on the North Ramp is at an average -2.15% gradient, which upon exiting the ramp curve, flattens and subsequently rises at +1.35% to the south for Panels 1 and 2, (Ref. 2.2.10, Figure 3). The north ramp decline of -2.15% is the steepest grade of any access main used in emplacement.

The TEV will continue to proceed southward along the Panel 1 or 2 access main to an emplacement drift in Panels 1, 2 or 4. If the destination emplacement drift is within Panel 3, the TEV will stop and reverse direction, proceeding northward again through the central ramp switch, pass into the crossover to the Panel 3 access main, and through the Panel 3 switch, onto the Panel 3 access main track. If the destination emplacement drift is Panel 4, the TEV will enter the Panel 4 switch south of Panel 1 and then travel along the Panel 4 access main, traveling first westward and then northward. For all paths, the TEV continues along the appropriate access main until it stops at the switch in front of the access door of the selected emplacement drift. A single turnout switch system is positioned at an active emplacement drift and moved as this emplacement drift become filled, with the gap in the rails replaced with straight running rail. The switch system allows up to three emplacement drifts to be concurrently active at one time (i.e., a three-switch system).

B1.3 EMPLACEMENT

At the entrance of each emplacement drift is an emplacement access door, consisting of two panels to control entry. This access door has controls and electric motors necessary to open the two panels as well as an airflow regulator to control ventilation of the drift. The two door panels open in the opposite directions from one another.

After the TEV stops at the emplacement access door, various positional sensors and devices onboard (Ref. 2.2.34, Section 2.5.4) enable the TEV to calibrate and to establish a positional datum point. Once calibration is complete, the access door is opened and the TEV proceeds through. The access door closes immediately after the TEV has passed through the entryway. The TEV then passes into a curved tunnel segment (with a positive grade of approximately 1.75%) and then into a straight section of the turnout tunnel, eventually entering the emplacement drift proper which has a nominal grade of 0 %. Within the turnout is a mechanical device (arm) along the rail which engages an external switch on the TEV and releases a mechanical interlock, allowing the TEV shield doors to open. Potential radiation shine to the access main from the emplacement area is precluded due to the curved geometry of the turnout and operationally, waste packages are first emplaced at the far end of the emplacement drift to ensure that exposures to radiation for personnel working in the access mains remain as low as is reasonably achievable (ALARA).

The TEV proceeds down the turnout and enters the emplacement drift at its normal operational speed of approximately 2.7 km/hr (1.7 mph) to a predefined location, where it stops and confirms its location. Upon confirmation, the front shield door safety interlocks are disengaged, the TEV shield enclosure doors are opened, the rear shield door is raised, and the base-plate is retracted from under the shield enclosure. The lifting system raises the shield enclosure to engage the pallet with the lifting features and the transportation shot bolts are retracted into an unlocked position. The TEV now moves forward at a crawl speed, on the order of 4.6 m/min (15 ft/min), stopping at a position close to a previously emplaced waste package.

At this stage, additional on-board positional sensors and devices (e.g., lights, cameras, and ultrasonic sensors) are activated, and measurements are made to re-confirm the position of the TEV and the waste package it is carrying in relation to a previously emplaced waste package. The TEV then moves forward at a slower positioning speed (at approximately 0.46 m/min (1.5 ft/min), until the required final position is achieved. On-board cameras and sensors confirm the final position with central control; some minor movement may be required to achieve the desired position. When the correct position is achieved, the shield enclosure is lowered to its lowest position, placing the waste package and pallet on the emplacement drift invert structure.

The TEV is backed away at the positioning speed from the waste package and pallet to a predetermined distance from the emplaced waste package, and stops. The shield enclosure is raised to its travel height, the transportation bolts are extended, and the shield enclosure is lowered to its traveling position. The base-plate is retracted, the rear door is lowered, and the front doors are closed. The safety interlocks are engaged and the TEV travels in reverse back down the emplacement drift at the normal operating speed. As it approaches the main access door, the TEV again stops, the access door is opened, and the TEV passes into the access main.

B2 DRIP SHIELD EMPLACEMENT OPERATIONS

At the end of the preclosure period, interlocking drip shields are placed over the waste packages in each of the emplacement drifts. The function of the drip shield is to divert the moisture that drips from the drift walls, as well as the water vapor that condenses on the drip shield surface, around the waste packages and to the drift invert. This increases the longevity and prolongs the structural integrity of the covered waste package. Drip shield emplacement operations are similar to the waste package emplacement operations, and the emplacement operations within the different panels in the subsurface are essentially identical.

Drip shield emplacement operations are conducted as a continuous operation, with the rate of emplacement limited by travel times to and from the emplacement drifts, operational concerns, and maintenance downtime. Drip shields are placed over waste packages by using a DSG (Ref. 2.2.21), which is specifically designed to carry and lift a drip shield over emplaced waste packages to the correct location within an emplacement drift.

The operational configuration for the DSG is a single-car, remotely-controlled, rail-based vehicle, which is powered by a third rail. The DSG is controlled from central control without an on-board crew. The DSG operates on the same rail system as the TEV, and additionally, carries an auxiliary (battery) backup power system to provide a limited supply of power in the event that recovery operations are needed.

B2.1 DRIP SHIELD LOADING AND TRANSPORT

The DSG loads a drip shield for emplacement in the HEMF on the surface as noted in *Drip Shield Emplacement Block Flow Diagram Level 3* (Ref. 2.2.25). The remotely-controlled DSG then transports the drip shield from this facility on the surface, through the North Portal and down the North Ramp. The DSG and drip shield continues along the appropriate access main and stops at the turnout access door for the selected emplacement drift.

B2.2 DRIP SHIELD EMPLACEMENT AND GANTRY RETURN

After the DSG stops at the turnout access door, its positional sensors and devices enable it to calibrate and to establish a positional datum point. Once calibration is complete, the access door panels are opened and the DSG proceeds through the door, passing into the curved section of the turnout tunnel. The door closes immediately after the DSG has passed through.

The DSG proceeds down the remainder of the turnout and enters the emplacement drift at an operational transit speed of approximately 2.7 km/hr (1.7 mph or 150 ft/min) to a predetermined position, where the gantry stops, and re-confirms its location. The DSG moves forward at a slow speed, nominally 4.6 m/min (15 ft/min), to a predetermined position relative to the previously emplaced drip shield. Similar to the TEV, additional on-board positional sensors and devices are activated (e.g., lights, cameras, and ultrasonic sensors), and measurements are made to re-confirm to the position of the DSG and the drip shield it is carrying, in relation to a previously emplaced drip shield.

The DSG moves forward at a crawl speed, nominally 0.46 m/min (1.5 ft/min), until the required final position is achieved. On-board cameras and sensors report the final position to central control; some minor movement may be required to achieve the desired position. Once the correct position is achieved, the gantry lowers the lift beams, lowering the drip shield. The drip shield engages the previously emplaced drip shield interlock (if present), and rests upon the steel frame of the emplacement drift invert.

The emplacement gantry lowers its lifting features to its travel height and moves at a crawl speed away from the newly emplaced drip shield to a predetermined distance and stops. Upon confirmation of emplacement status, the gantry slowly accelerates to the full operational speed towards the emplacement drift access door. Once the gantry reaches the access door, the gantry again stops. The access door is opened and the gantry passes through the doorway. Once through, the access door closes, and the DSG stops for inspection and monitoring.

The gantry next proceeds along the rail line to the surface and returns to the HEMF. If the inspection and monitoring results are within the required limits, the gantry is loaded with another drip shield to start another drip shield emplacement procedure. If not, the gantry proceeds to the maintenance area within the HEMF for repair and/or decontamination.

The resulting final drift configuration with the drip shield over the waste package is shown in Figure A-14.

B3 CONSTRUCTION OPERATIONS

Construction operations onsite occur concurrently with emplacement operations during a portion of the preclosure period. A variety of construction methods are employed and excavation methods will differ between the surface and subsurface activities. The impact of construction operations are of concern to preclosure safety regarding their interface or effect on waste handling operations.

In the subsurface, the excavation of emplacement drift turnouts, ventilation shafts and raises, stations, and test alcoves is accomplished using common drill and blast techniques[1] or by mechanical excavators (Ref. 2.2.43, Table 4.1-1). Explosives or fuels are not stored in the subsurface prior to use, but are issued from storage magazines on the surface as needed. Shafts/raises are constructed using drill and blast excavation or boring machines. Access mains and emplacement drifts are mechanically excavated using TBMs.

Surface construction is expected to use primarily mechanical excavators, but explosives may be used and stored in designated stockpiles on the surface in the construction area. Operations may also employ fuel depots and other stockpiles which can potentially explode.

Construction utilities include electrical power, compressed air lines and communication and monitoring lines as well as water lines. Ventilation ducting is also necessary. Water lines are installed in construction areas (and removed after construction) as mechanical excavations use water for dust control.

[1] Drill and blast methods employ explosives to excavate rock.

B3.1 BOUNDARIES AND ISOLATION BARRIERS

On the surface, boundaries are designed to isolate personnel movement between nuclear operations and construction areas. Surface nuclear operations are located at the North Portal and construction operations are located at both the South Portal and the North Construction Portal. Berms, fences and other barriers are employed, as appropriate, to clearly designate construction and waste handling areas, in addition to security measures.

Subsurface work areas are separated with engineered bulkheads (isolation barriers) in the intake and exhaust mains. In addition, separate utility systems are provided, to ensure that there are no penetrations through the isolation barriers. These utility systems include power, ventilation, communication, emergency notification, and data acquisition.

The subsurface isolation barriers are designed to accommodate the maximum credible pressure differential from events such as ventilation failure or a concussion from blasting operations. Doors located in the intake main isolation barrier are used during emergency conditions. During construction, isolation barrier locations change as construction is completed and the emplacement area is expanded.

B4 OTHER OPERATIONS

Other normal operations in the subsurface are:

- Ventilation
- Performance confirmation
- Waste package recovery
- Operational monitoring
- Security
- Maintenance.

B4.1 VENTILATION OPERATIONS

After the start of emplacement operations, the subsurface is ventilated during the preclosure period to cool the emplaced waste packages and to remove waste heat. Temperatures in access mains and turnouts are maintained below 32°C (90°F). In general, temperatures in emplacement drifts are maintained below 75°C (167°F) and below 50°C (122°F) when equipment is to operate in the drift (*Project Design Criteria Document* Ref. 2.2.38, Table 4.2-3). The great volume of air required to supply the emplacement drifts is more than sufficient to supply personnel with breathable air in the underground area, and to remove radon generated from the volcanic tuff.

Ventilation operations in the subsurface include the adjustment of the ventilation regulator for each emplacement drift. The regulator in the emplacement access door is opened, closed, or incrementally adjusted to control the flow rate and, thus, the temperature in the drift. The regulator is opened completely to cool the drift prior to equipment entering the drift for inspection or maintenance operations. The exhaust main side of the emplacement drift will not permit human access under normal operating conditions, (Ref. 2.2.63, Section 6.4 because of the high temperatures and the radiation hazard emanating from the open end of the emplacement drift.

B4.2 PERFORMANCE CONFIRMATION OPERATIONS

Performance confirmation activities are ongoing throughout the entire preclosure period within the subsurface as noted in the *Performance Confirmation Plan* (Ref. 2.2.12, Section 2.2.1). These activities monitor the performance of the natural and engineered barriers to ensure their condition and performance are as expected. Various tests and monitoring (Ref. 2.2.12, Section 1.4.2) require staff to occasionally access various points in the subsurface during the preclosure period, concurrent with emplacement activities.

In addition, performance confirmation activities include the use of equipment in proximity to waste packages within the subsurface during and after emplacement. Activities include periodic inspection of emplacement drifts and waste packages (Ref. 2.2.12, Table 1-1. The *Performance Confirmation Plan* (Ref. 2.2.12) indicates the use of a remotely operated vehicle (ROV), equipped with cameras and sensing devices, but the specific configuration of the device is not explicitly stated ((Ref. 2.2.12, Section 3.3.1.8).

B4.3 RECOVERY OF WASTE PACKAGES OPERATIONS

Another normal process of the Subsurface Operations is the recovery of waste packages. Waste package *recovery* is defined in this analysis as the removal of a one (or a limited number of waste packages) from an emplacement drift to the surface or into another emplacement drift as part of normal operations. *Recovery* is considered distinct from the term *retrieval.* In this analysis, *retrieval* is used as defined in 10 CFR 63.2 (Ref 2.3.1) as the act of permanently removing radioactive waste from the underground location at which the waste had been previously emplaced for disposal. Retrieval is not considered as part of PCSA or normal Subsurface Operations and therefore is not included in this analysis.

At any time between emplacement and closure of the repository, recovery of one or more waste packages may occur for the purposes of inspecting, testing, and repairing suspected damaged waste packages or to adjust the thermal loading of an emplacement drift. The specific nature of these operations is not specified and only a limited number of these recovery operations are expected. However, the overall process is the reverse of the emplacement process.

B4.4 OPERATIONAL MONITORING

Operational monitoring is conducted in the repository throughout the entire preclosure period. Most measurements are conducted remotely and do not directly involve personnel entering the subsurface to conduct tests. These remote measurements are taken for health and safety of workers (i.e., radon and dust).

B4.5 SECURITY

In addition to staffed entry points, security operations for the surface include visual monitoring at all portals and shafts/raises using remote television cameras. Visual monitoring is also performed at various locations underground. In general, security operations do not directly involve personnel entering the subsurface to conduct patrols or other related activities.

B4.6 MAINTENANCE

The maintenance, repair, and replacement of subsurface systems and components will also occur over the preclosure period. Upgrades of any subsurface SSC are also part of the normal operations. These operations require both remotely operated vehicles and personnel to enter the subsurface to repair or replace equipment and instruments at various times during the preclosure period. Operations by personnel include the use of hand-held manual and electrically-driven tools.

B5 CLOSURE-RELATED OPERATIONS

As part of the closure process, various activities will be conducted to prepare the subsurface for postclosure in addition to the emplacement of drip shields. These activities will involve the placement of backfill and seals in various openings, excluding emplacement drifts, such as (1) the sealing of boreholes, (2) the backfilling of ramps and shafts, and (3) the closing of shafts(Ref. 2.2.59.Other activities involve the removal of non-committed material from access mains and ramps in the subsurface. Non-committed materials are those materials which will be removed from the subsurface prior to closure. All material in the emplacement drifts is considered committed material, and therefore will remain in place at closure. The non-committed material includes isolation barriers (e.g., the access door bulkheads and the associated ventilation controls and equipment), electrical and communication equipment, running and third rails and other materials. Concurrent with the removal of these materials, activities may involve the placement of postclosure instrumentation and monitoring equipment (if any).

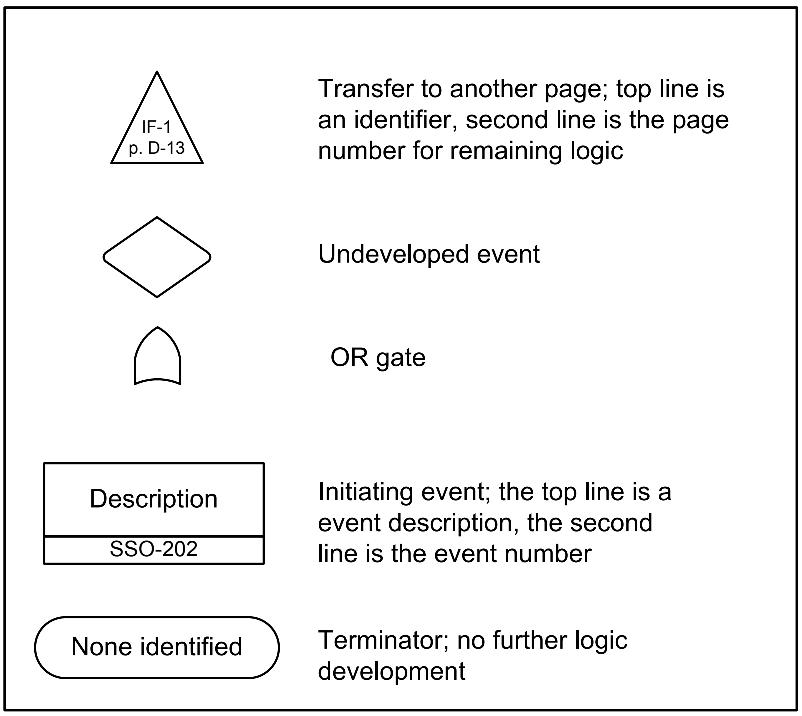
ATTACHMENT C
[NOT USED]

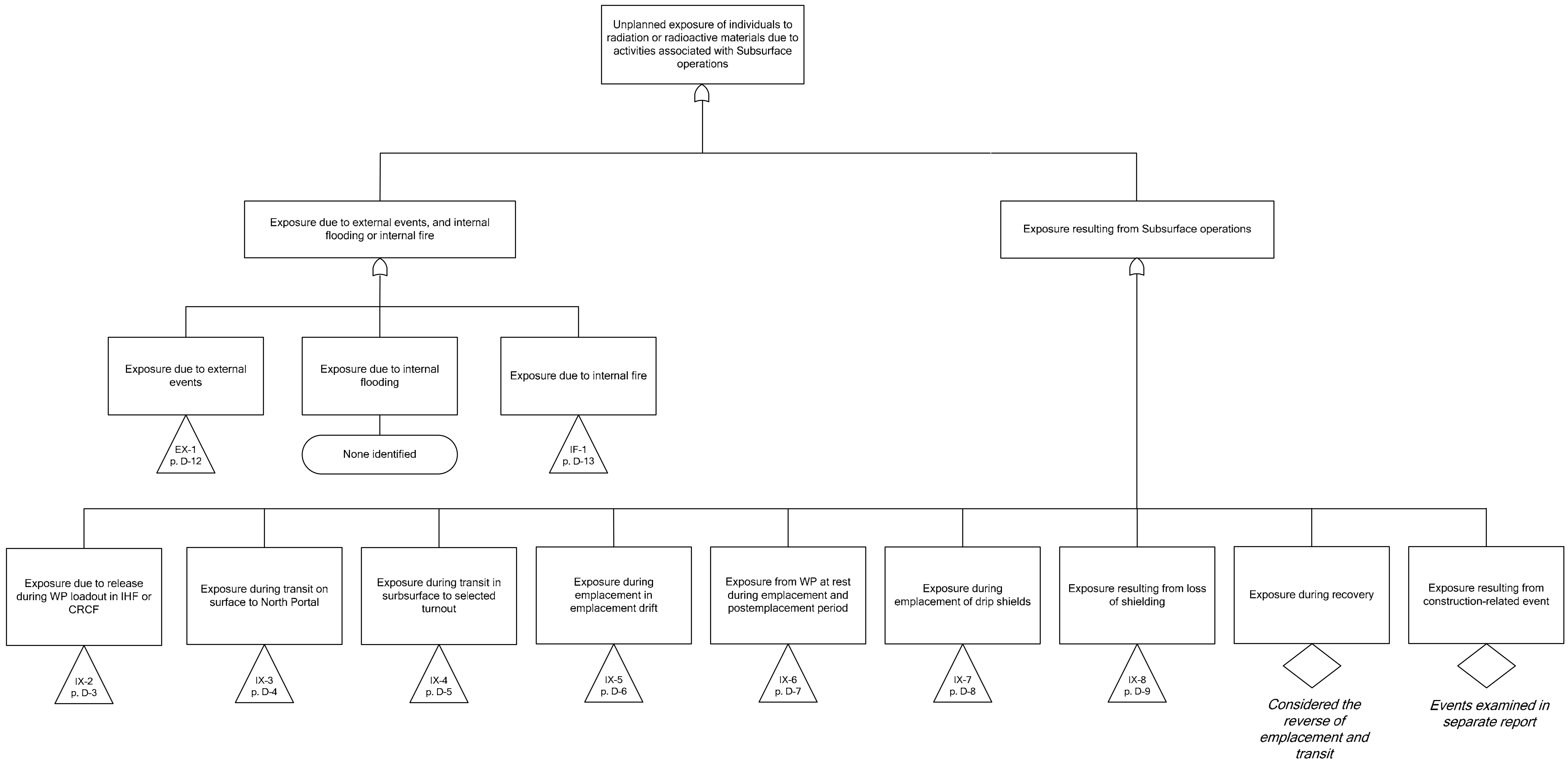
ATTACHMENT D
SUBSURFACE OPERATIONS MASTER LOGIC DIAGRAM

The MLD for the Subsurface Operations is presented in Figures D-1 through D-12. An exhaustive list of contributors (examples) is not shown on the MLD, rather, the diagram is limited to presenting only one example of each initiating event to provide clarity. However, the range of potential contributors will be considered in subsequent quantitative analyses (i.e., *Subsurface Operations Reliability and Event Sequence Categorization Analysis*, Ref. 2.4.1).

The legend for these figures is as follows:

Legend

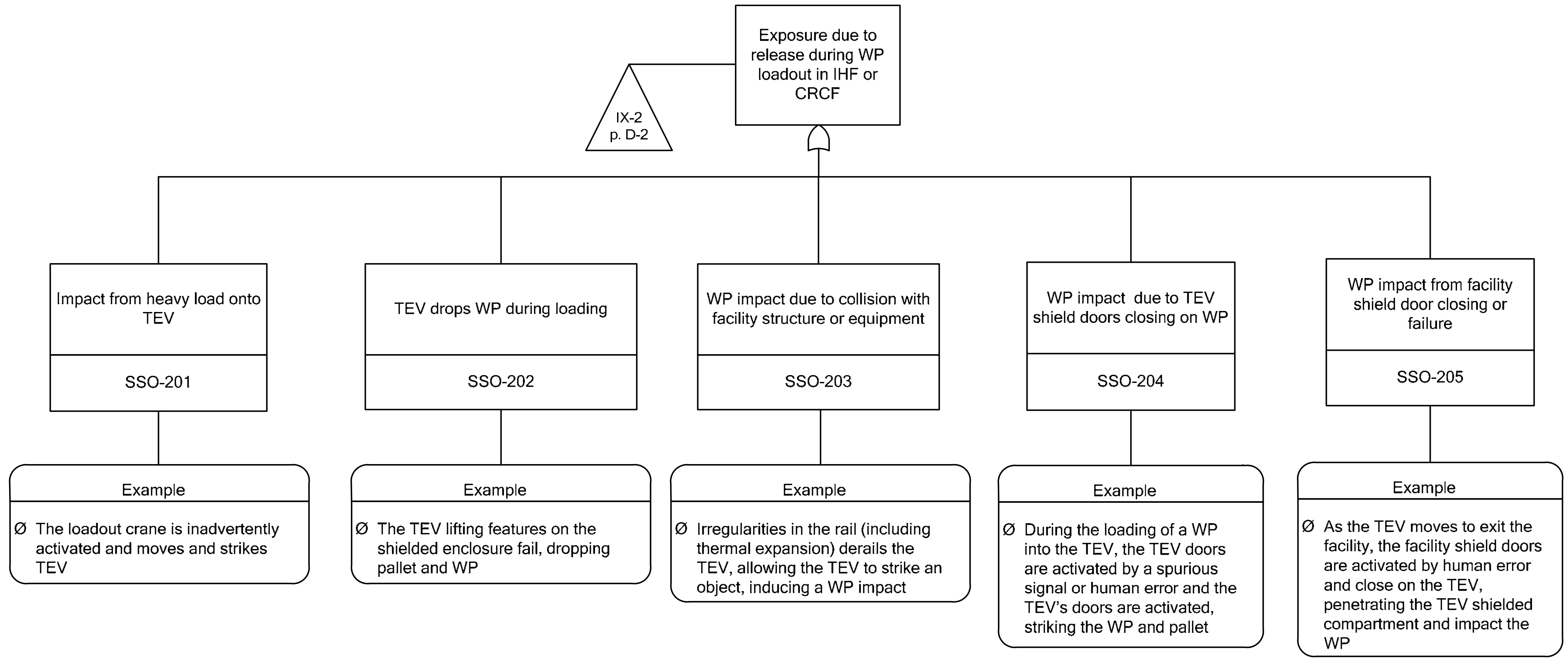




NOTES: Subsurface operations, in this context, are defined as all operations from the TEV lifting and loading the WP within a handling facility on the surface, the transit of the WP on the surface to the portal, and the transit through the subsurface to the emplacement drift, as well as all operations within the emplacement drift.
CRCF = Canister Receipt and Closure Facility; IHF = Initial Handling Facility; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

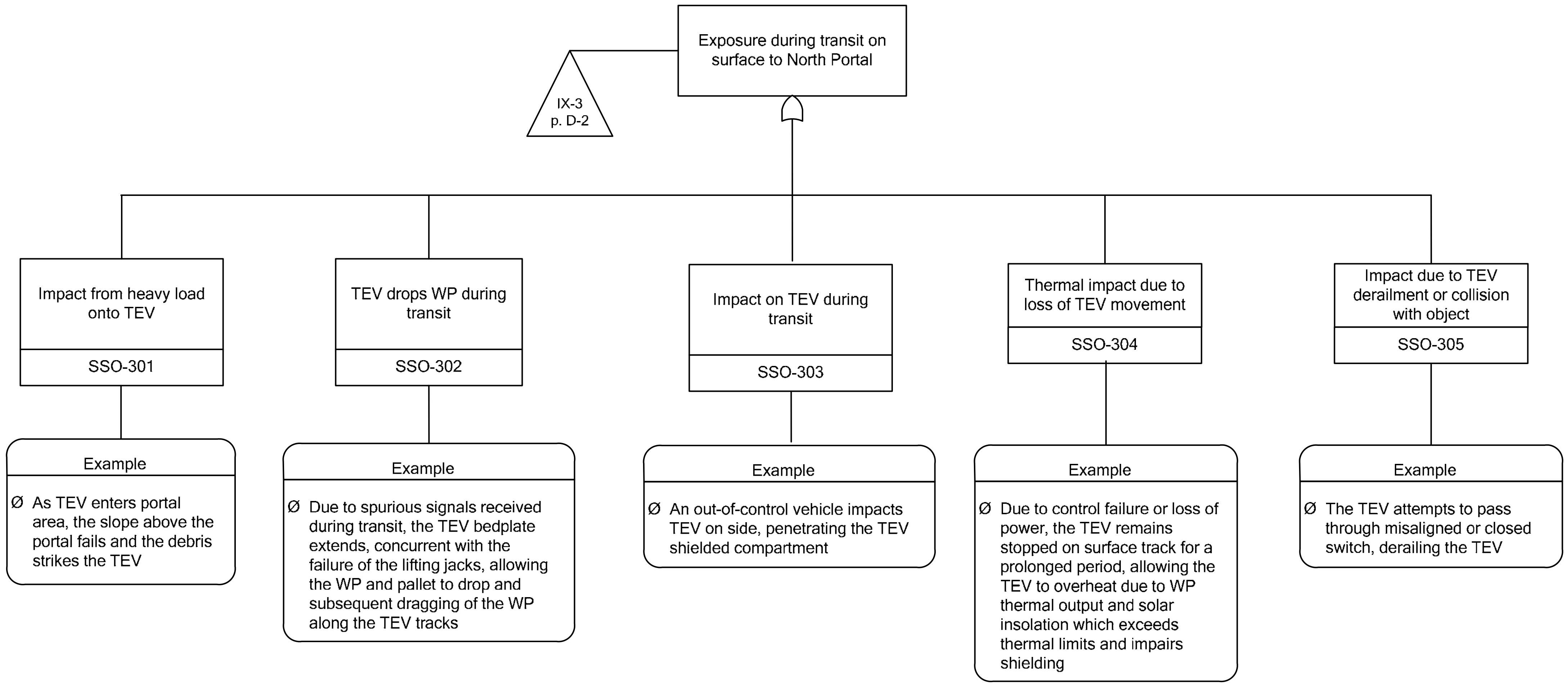
Figure D-1. Unplanned Exposure of Individuals to Radiation or Radioactive Materials due to Activities Associated with Subsurface Operations



NOTE: CRCF = Canister Receipt and Closure Facility; IHF = Initial Handling Facility; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

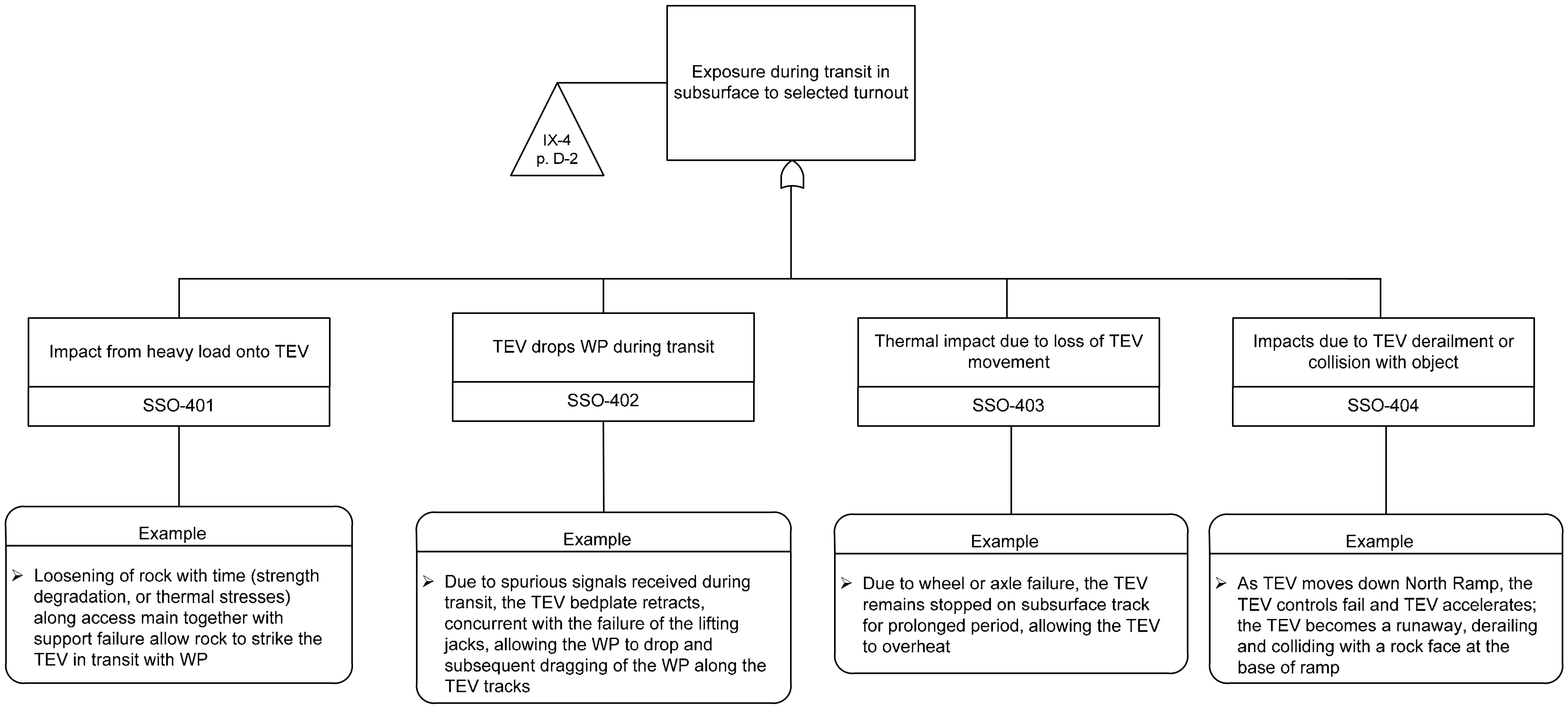
Figure D-2. Exposure due to Release during WP Loadout in the IHF or CRCF



NOTES: TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

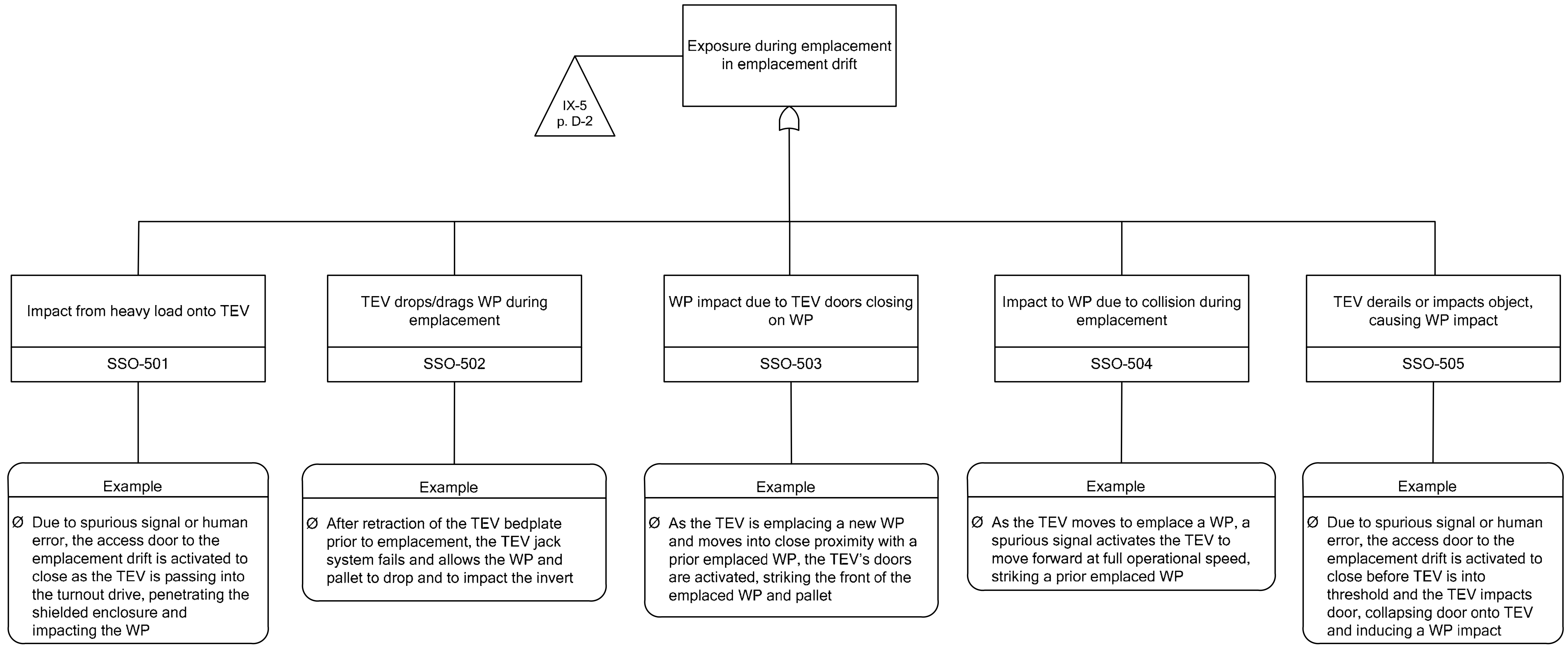
Figure D-3 Exposure during Transit on Surface to North Portal



NOTE: TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

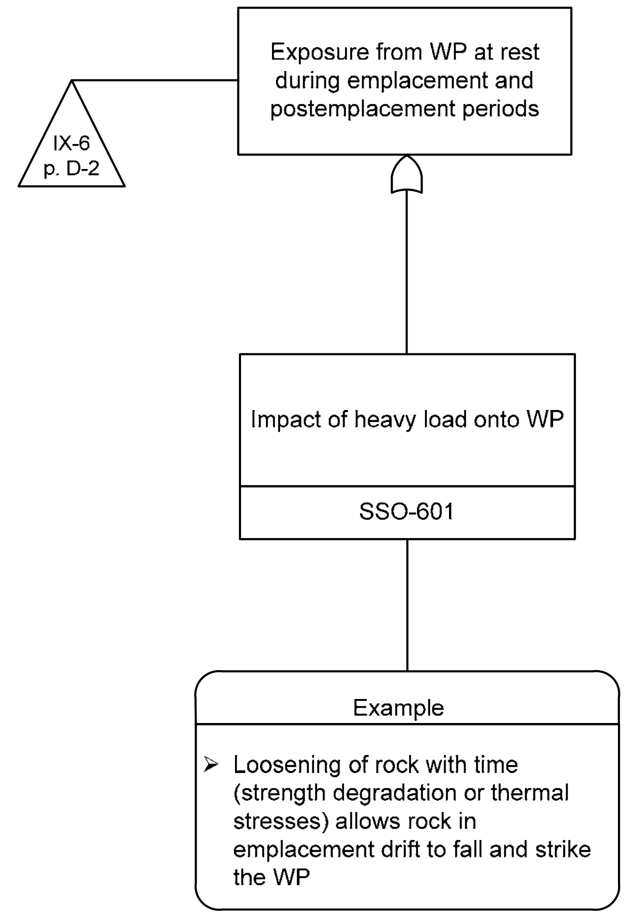
Figure D-4. Exposure during Transit in Subsurface to Selected Turnout



NOTE: TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

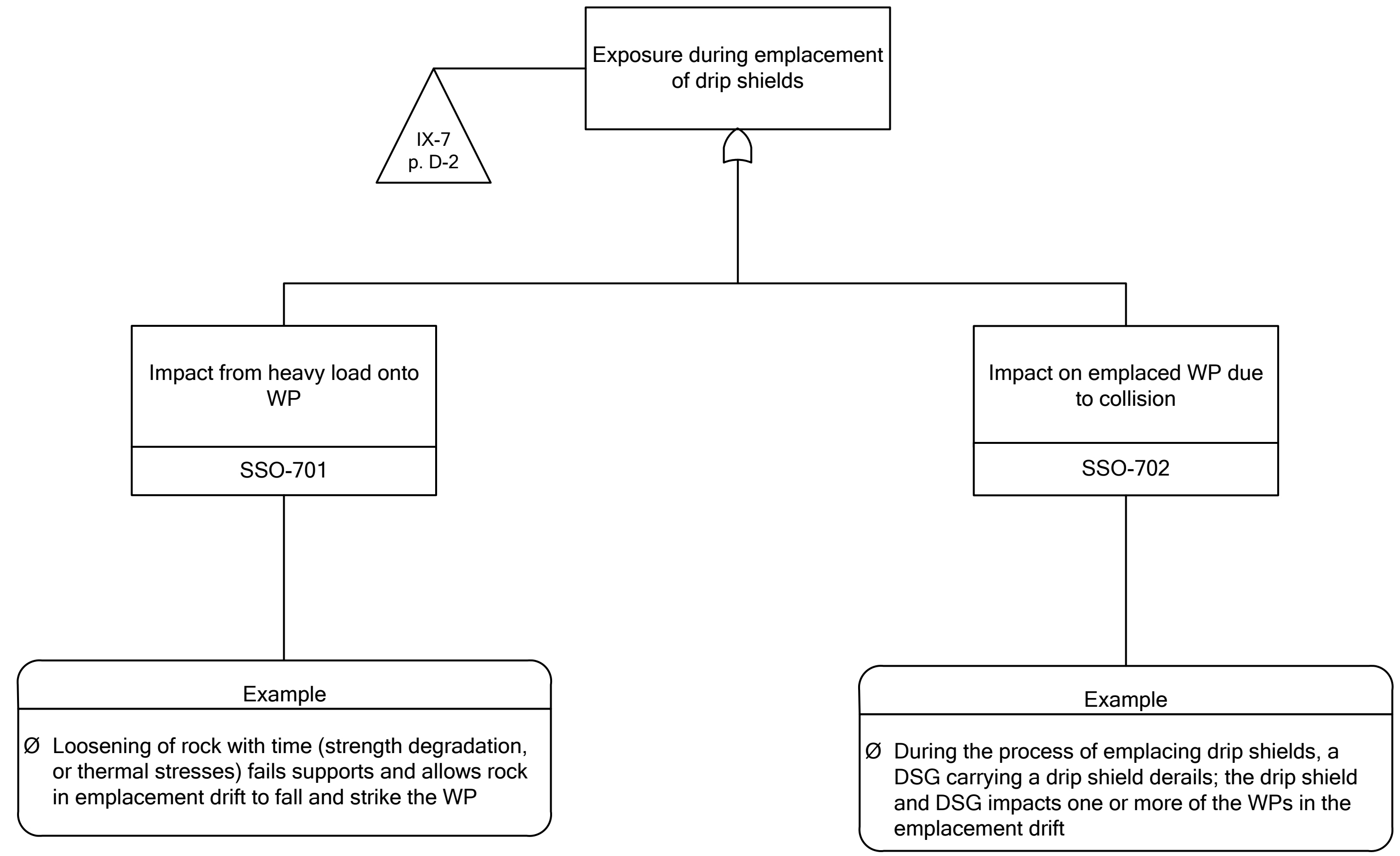
Figure D-5. Exposure during Emplacement in Emplacement Drift



NOTE: WP = waste package.

Source: Original

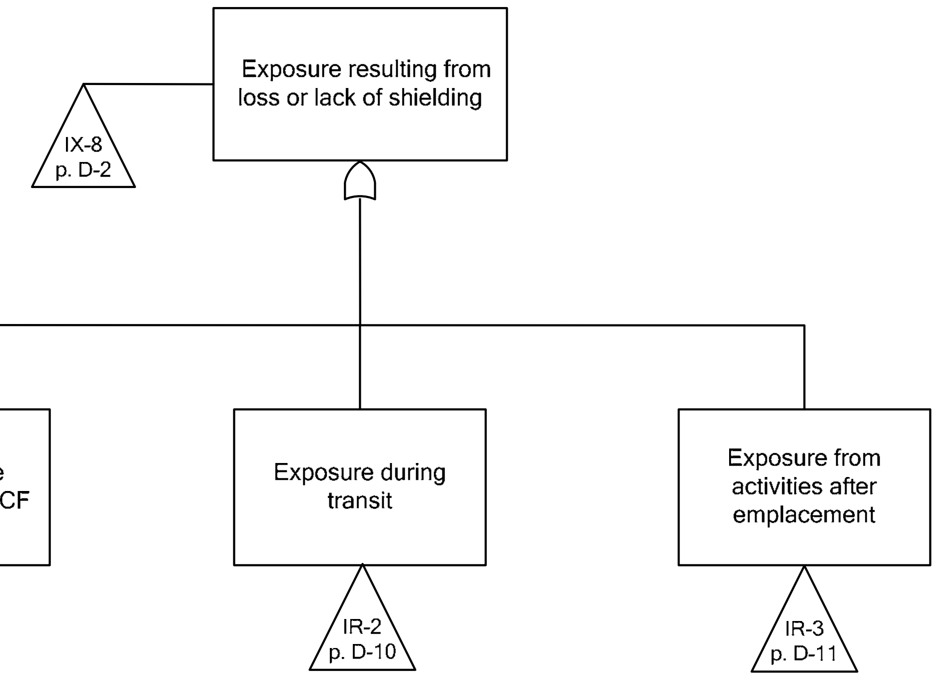
Figure D-6. Exposure from WP at Rest during Emplacement and Post-Emplacement Periods



NOTE: DSG = drip shield emplacement gantry; WP = waste package.

Source: Original

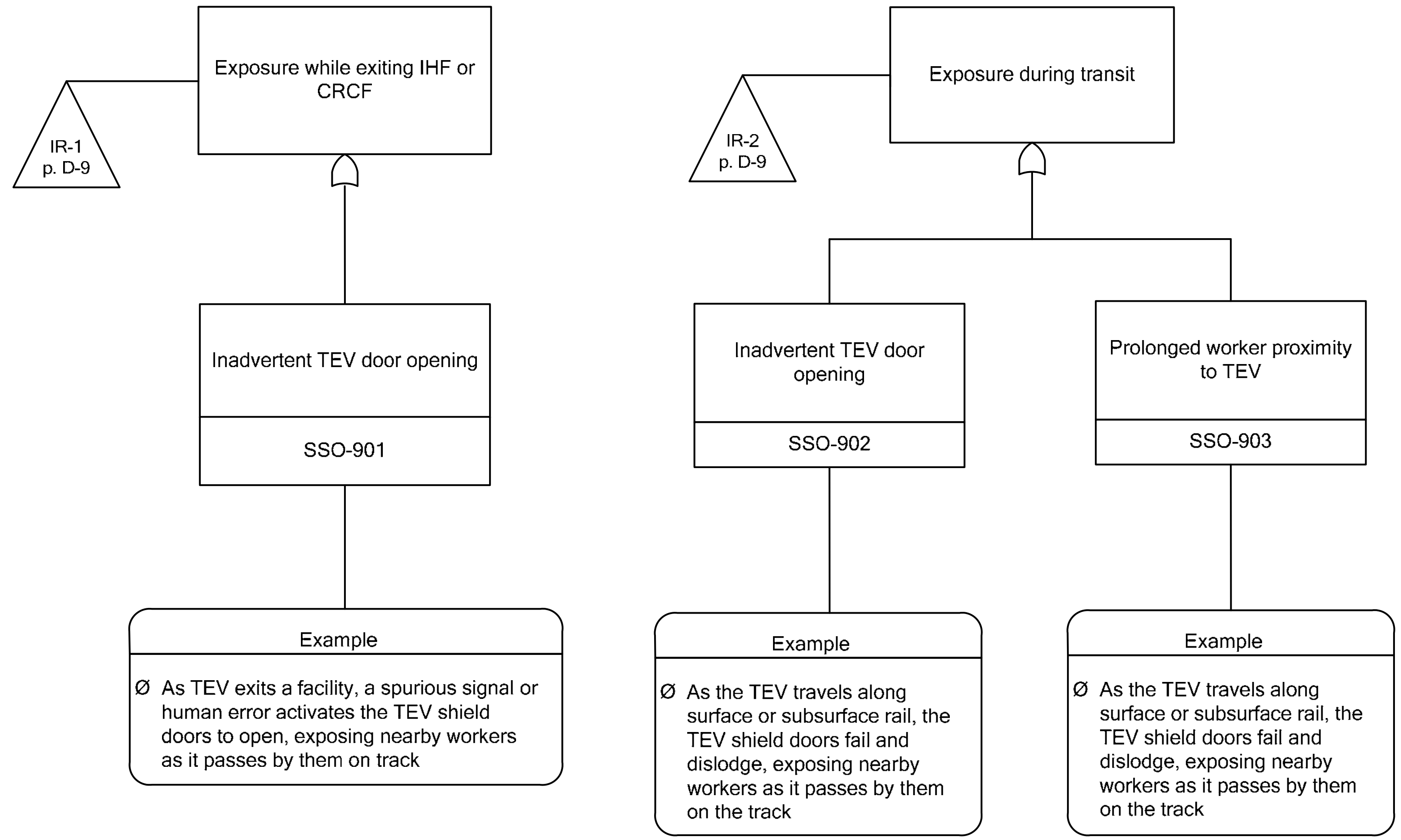
Figure D-7. Exposure during Emplacement of Drip Shields



NOTE: CRCF = Canister Receipt and Closure Facility; IHF = Initial Handling Facility; WP = waste package.

Source: Original

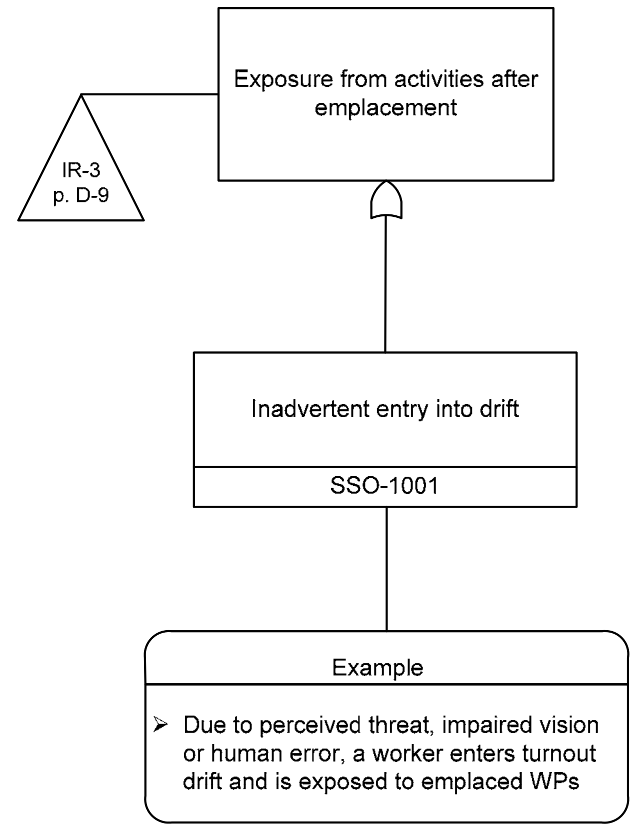
Figure D-8. Exposure Resulting from Loss or Lack of Shielding



NOTE: CRCF = Canister Receipt and Closure Facility; IHF = Initial Handling Facility; TEV = transport and emplacement vehicle.

Source: Original

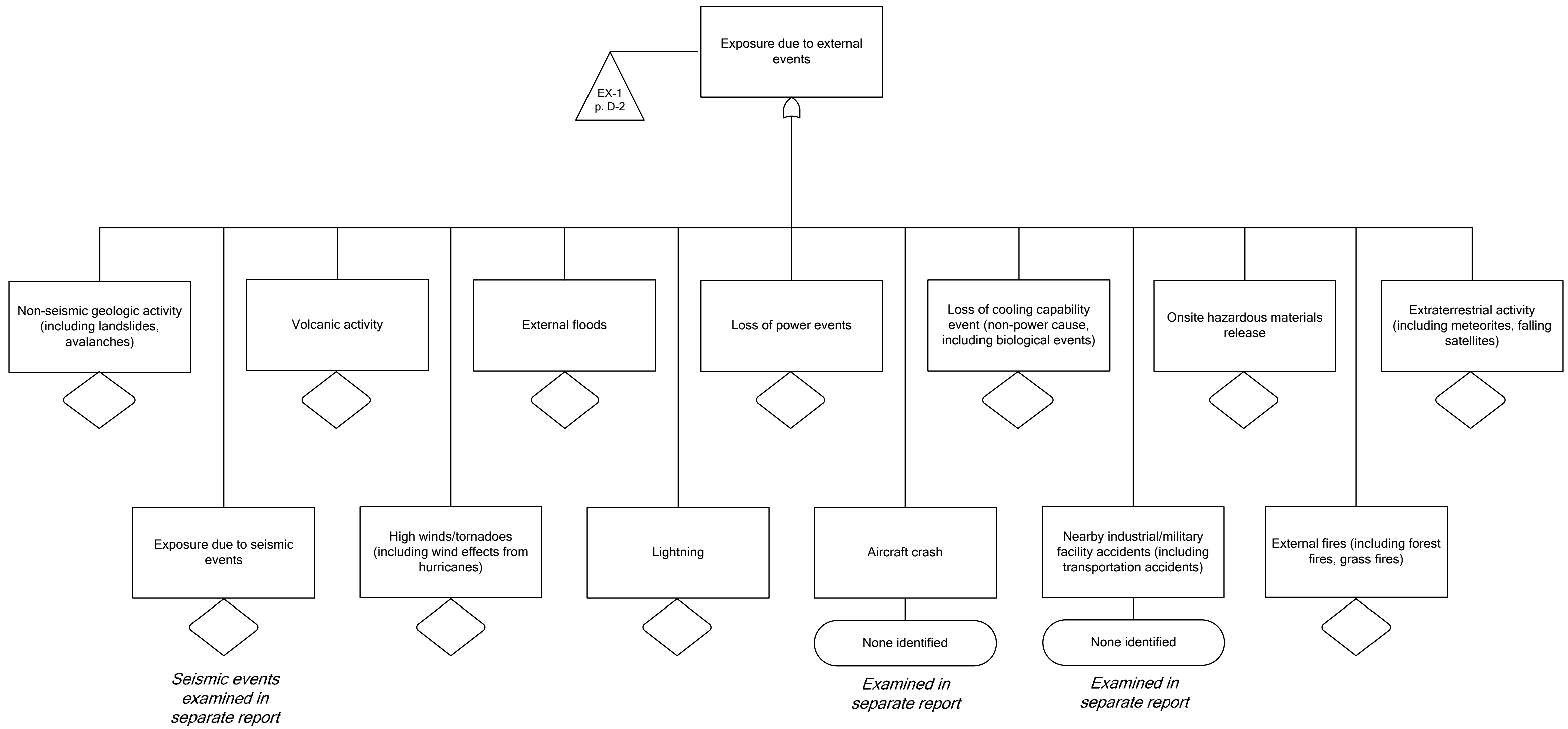
Figure D-9. Exposure while Exiting IHF or CRCF, and Exposure during Transit



NOTE: WP = waste package.

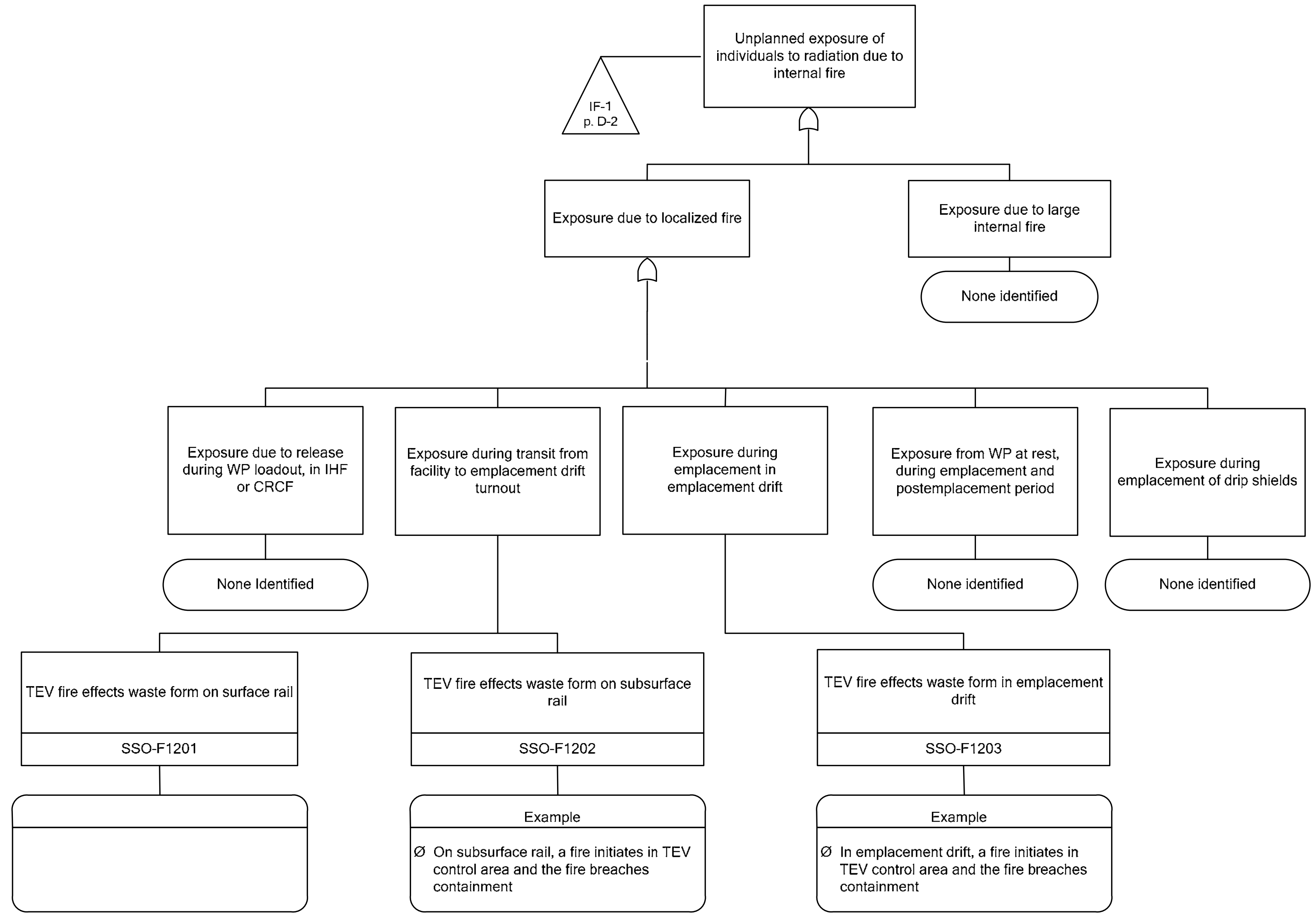
Source: Original

Figure D-10. Exposure from Activities after Emplacement



Source: Original

Figure D-11. Exposure due to External Events



NOTE: CRCF = Canister Receipt and Closure Facility; IHF = Initial Handling Facility; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Figure D-12. Unplanned Exposure due to Internal Fire

ATTACHMENT E
SUBSURFACE OPERATIONS HAZARD AND OPERABILITY EVALUATION

E1 GENERAL

A hazard and operability evaluation for the Subsurface Operations is provided in this attachment. The HAZOP evaluation was conducted in accordance with the process described in Section 4.3.1.3. The HAZOP evaluations were conducted in a series of meetings that lasted from 4 to 8 hours for each facility. A list of attendees and biographies of the team members is also provided in this attachment. The HAZOP evaluation meeting for Subsurface Operations was conducted at a meeting that lasted approximately eight hours on April 5, 2007.

E2 LIST OF SUBJECT MATTER EXPERT ATTENDEES AND BIOGRAPHIES

Table E-1 contains the HAZOP meeting dates and the names of subject matter experts who attended the meetings.

Table E-1. HAZOP Meeting Dates and List of Attendees

HAZOP Evaluation Meetings		
Name	**Telephone Number**	**Organization**
Meeting Date: March 26, 2007		
Erin Collins	702-821-7913	SAIC
Robert Garrett	702-821-8239	B&A
Norm Graves	702-821-7012	BSC
Phuoc Le	702-821-7468	SAIC
Kelvin Montague	702-821-7847	B&A
Doug Orvis	702-821-7914	BSC
Clarence Smith	702-821-7126	BSC
Meeting Date: March 27, 2007		
Erin Collins	702-821-7913	SAIC
Robert Garrett	702-821-8239	B&A
Phuoc Le	702-821-7468	SAIC
Doug Orvis	702-821-7914	BSC
Kelvin Montague	702-821-7847	B&A
Clarence Smith	702-821-7126	BSC

Table E-1. HAZOP Meeting Dates and List of Attendees (Continued)

HAZOP Evaluation Meetings		
Name	**Telephone Number**	**Organization**
Meeting Date: March 28, 2007		
Erin Collins	702-821-7913	SAIC
Norm Graves	702-821-7012	BSC
Daryl Keppler	505-272-7102	ARES
Phuoc Le	702-821-7468	SAIC
Kelvin Montague	702-821-7847	B&A
Doug Orvis	702-821-7914	BSC
Mary Presley	505-272-7102	ARES
Guy Ragan	702-821-7637	BSC
Daniel Reny	505-272-7102	ARES
Meeting Date: March 29, 2007		
Erin Collins	702-821-7913	SAIC
Norm Graves	702-821-7012	BSC
Daryl Keppler	505-272-7102	ARES
Phuoc Le	702-821-7468	SAIC
Suzanne Loyd	702-821-7350	SAIC
Jeff Marr	505-272-7102	ARES
Kelvin Montague	702-821-7847	B&A
Doug Orvis	702-821-7914	BSC
Mary Presley	505-272-7102	ARES
Guy Ragan	702-821-7637	BSC
Daniel Reny	505-272-7102	ARES
Clarence Smith	702-821-7126	BSC
Meeting Date: April 2, 2007		
Erin Collins	702-821-7913	SAIC
Norm Graves	702-821-7012	BSC
Daryl Keppler	505-272-7102	ARES
Phuoc Le	702-821-7468	SAIC
Kelvin Montague	702-821-7847	B&A
Doug Orvis	702-821-7914	BSC
Mary Presley	505-272-7102	ARES
Guy Ragan	702-821-7637	BSC
Clarence Smith	702-821-7126	BSC

Table E-1. HAZOP Meeting Dates and List of Attendees (Continued)

HAZOP Evaluation Meetings		
Name	**Telephone Number**	**Organization**
Meeting Date: April 3, 2007		
Paul Amico	702-821-7911	SAIC
Erin Collins	702-821-7913	SAIC
Robert Garrett	702-821-8239	B&A
Norm Graves	702-821-7012	BSC
Daryl Keppler	505-272-7102	ARES
Phuoc Le	702-821-7468	SAIC
Kelvin Montague	702-821-7847	B&A
Doug Orvis	702-821-7914	BSC
Mary Presley	505-272-7102	ARES
Guy Ragan	702-821-7637	BSC
Clarence Smith	702-821-7126	BSC
Meeting Date: April 4, 2007		
Paul Amico	702-821-7911	SAIC
Erin Collins	702-821-7913	SAIC
Norm Graves	702-821-7012	BSC
Daryl Keppler	505-272-7102	ARES
Phuoc Le	702-821-7468	SAIC
Kelvin Montague	702-821-7847	B&A
Doug Orvis	702-821-7914	BSC
Mary Presley	505-272-7102	ARES
Guy Ragan	702-821-7637	BSC
Clarence Smith	702-821-7126	BSC
Meeting Date: April 5, 2007		
Paul Amico	702-821-7911	SAIC
Erin Collins	702-821-7913	SAIC
Norm Graves	702-821-7012	BSC
Daryl Keppler	505-272-7102	ARES
Phuoc Le	702-821-7468	SAIC
Ernest Lindner	702-821-7713	BSC
Suzanne Loyd	702-821-7350	SAIC
Doug Orvis	702-821-7914	BSC
Mary Presley	505-272-7102	ARES
Clarence Smith	702-821-7126	BSC

Table E-1. HAZOP Meeting Dates and List of Attendees (Continued)

HAZOP Evaluation Meetings		
Name	**Telephone Number**	**Organization**
Meeting Date: April 6, 2007		
Paul Amico	702-821-7911	SAIC
Norm Graves	702-821-7012	BSC
Daryl Keppler	505-272-7102	ARES
Phuoc Le	702-821-7468	SAIC
Dale Pendry	702-821-8380	BSC
Mary Presley	505-272-7102	ARES

NOTE: ARES = Applied Research & Engineering Sciences (ARES) Corporation;
B&A = Beckman and Associates, Inc.; BSC = Bechtel SAIC Company, LLC;
SAIC = Science Applications International (SAIC) Corporation.

Source: Original

Biographies of subject matter experts attending the HAZOP evaluation meetings:

Paul J. Amico: Mr. Amico is a nuclear engineer with 30 years of experience in risk, safety, regulation, and operation of nuclear power plants, nuclear material production reactors, nuclear weapons research, production, and storage facilities, nuclear fuel cycle facilities, chemical demilitarization facilities, and industrial chemical plants.

Erin P. Collins: Ms. Collins is a risk analyst with over 20 years of experience in safety, reliability and risk analysis for the Army chemical weapons destruction program, National Aeronautics and Space Administration, Federal Aviation Administration, nuclear power plants, and the chemical process industry. Her specialties are equipment reliability database development and human reliability analysis. She has participated in two prior HAZOP evaluation s as part of the Army and chemical process work.

Robert J. Garrett: Mr. Garrett is a safety analyst with over 17 years of experience in risk analysis and hazards analysis at DOE non-reactor nuclear facilities. He has participated in several HAZOP evaluations for facilities at the Savannah River Site and the Yucca Mountain Project. For this study, Mr. Garrett served as a representative in the Intra-Site Operations areas for the HAZOP evaluation sessions.

Norman L. Graves: Mr. Graves is an engineer with over 40 years of experience in the nuclear industry including operations, construction, risk analysis, and waste disposal. For this study, Mr. Graves served as the preclosure safety analysis lead for the HAZOP evaluation sessions.

Daryl C. Keppler: Mr. Keppler is an Electrical Engineer with over 35 years experience in all phases of weapon and space system development, deployment, and disposal. For 5 years Mr. Keppler served as the technical advisor to the Chairman of the Nuclear Weapons System Safety Group and was the United States Air Force's certification authority for all software programs developed for ground launched missile systems. Mr. Keppler participated in numerous safety assessments for the Department of Defense, the DOE, and the National Aeronautics and Space Administration. Mr. Keppler served as a participant/observer during the HAZOP evaluation sessions.

Phuoc T. Le: Mr. Phuoc Le is an engineer with over 27 years of experience in risk analysis for nuclear power plants, chemical processing and petroleum refining industry. Mr. Le has led many HAZOP evaluations ranging from nuclear to chemical processing and food industries. For this study, Mr. Le served as co-leader of the HAZOP evaluation sessions.

Ernest N. Lindner Ph.D. (Mining): Dr. Lindner is a member of Preclosure Safety Analysis Department with over 3 years direct experience on evaluating repository hazards, and has over 30 years experience in civil and geotechnical engineering. Dr. Lindner has a Ph.D. in Mining with a major of geomechanics, together with a Master of Science (specializing in soil and rock mechanics), and a Bachelor of Engineering in Civil Engineering. Dr. Lindner also has a Professional Engineering License, and his experience includes work on nuclear facilities and other nuclear waste programs together with commercial engineering experience on subsurface projects. He is designated as the lead analyst for Subsurface Operations.

Suzanne M. Loyd: Ms. Loyd is a risk analyst with over 7 years of experience in risk analysis for chemical weapons demilitarization. Ms. Loyd has participated in HAZOP evaluations for various processes, including incineration and hazardous materials handling. For this study, Ms. Loyd served as a participant for Subsurface-related HAZOP evaluation sessions.

Jeffrey W. Marr: Mr. Marr is a senior safety analyst with over 20 years of experience in the reliability and safety analysis fields providing services to the DOE and the Department of Defense. Mr. Marr has participated in several hazard studies and hazard analyses in the support and development of Safety Analysis Reports and Documented Safety Analyses. For this study, Mr. Marr served as a participant for the purpose of using the HAZOP evaluation results for development of the CRCF Master Logic Diagram, Event Sequence Diagrams, and event trees.

Kelvin J. Montague: Mr. Montague is an engineer with over 16 years of experience in safety analysis. Mr. Montague has led numerous HAZOP evaluations in nuclear industries. For this study, Mr. Montague served as co-leader of the HAZOP evaluation sessions and lead analyst for Intra-Site Operations.

Douglas D. Orvis, Ph.D. (Nuclear): Dr. Orvis is a registered professional engineer (California, Nuclear No. 0925) with over 35 years of experience in nuclear engineering, regulation, and risk analysis of nuclear power plants, alternative concepts for interim storage of spent nuclear fuel, and aerospace applications. He has performed numerous qualitative and quantitative safety assessments, to include participation in HAZOP evaluation sessions. He has participated in the development of human reliability analysis techniques (e.g., SHARP, Systematic Human Action Reliability Procedure) and conducted measurements of, and analyzed data for, nuclear power plant control room operators during simulated accidents. He has performed event tree and fault tree analyses of hazardous systems for both internal events and seismic initiators. Dr. Orvis is a former supervisor of the BSC Preclosure Safety Analysis group.

Dale L. Pendry: Currently the YMP Nuclear Operations Manager, Mr. Pendry's credentials include a civil engineering degree and a Senior Reactor Operator license. Mr. Pendry was a U.S. Navy nuclear submarine officer and has 25 years of experience encompassing nuclear operations, maintenance, licensing, engineering, chemistry, radiological controls, and waste disposal. He has managed commercial nuclear and DOE's National Nuclear Security Administration facilities, including experimental facilities tasked with nuclear stockpile stewardship. Mr. Pendry was an operations representative for this study.

Mary R. Presley: Ms. Presley is an engineer with 3 years of experience in risk analysis for nuclear power plants, specializing in human reliability. Ms. Presley graduated in 2006 from the Massachusetts Institute of Technology with her M.S. in nuclear engineering.

Guy E. Ragan Ph.D. (Nuclear): Dr. Ragan is an engineer with over 17 years of experience related to nuclear technology. For this study, Dr. Ragan served as lead preclosure safety analyst for the events associated with the IHF.

Daniel A. Reny: Mr. Reny is a nuclear safety analyst with over 27 years of experience in risk analysis for nuclear power plants and DOE nuclear facilities. Mr. Reny has participated in several HAZOP studies on nuclear facilities. For this study, Mr. Reny served as a representative for the CRCF for the HAZOP evaluation sessions.

Clarence L. Smith: Mr. Smith has approximately 45 years of extensive management and supervisory experience within the engineering field and nuclear facilities that includes 27 years of nuclear operational and maintenance experience. Mr. Smith has participated in the decommissioning and decontamination of various nuclear reactors at the Hanford site in Richland, Washington. He has served as liaison in the design development of various processing facilities to coordinate and ensure that operability and maintainability features such as reliability, maintainability, accountability and inspectability are incorporated. Mr. Smith has negotiated and managed contract work that included safeguards in the erection of support facilities

Table E-2. Subsurface HAZOP Evaluation Results - Node 1

Facility/Operation: Subsurface					**Process**: Waste Package Loadout		
Node 1: Load TEV with Waste Package and TEV exits facility					**Process/Equipment**: TEV, Waste Package		
Guidewords: No, More, Less, Reverse, Other Than, As Well As, Part Of					**Consequence Categories**: Radioactive Release, Lack of Shielding, Criticality		
Node Item Number	**Parameter**	**Deviation Considered**	**Postulated Cause**	**Consequence**	**Potential Prevention/Mitigation Design of Operational Feature**	**Note**	**MLD Identifier**
1.1	Lift (WP)	(More) Lifted load too heavy	No cause identified	No safety consequence		Starting point: TEV lowered, doors open with WP positioned within the TEV envelope	---
1.2	Lift (WP)	(Less) Load is less than it's supposed to be	No cause identified	No safety consequence			---
1.3	Lift (WP)	(Other Than) Asymmetrical lift	Screw jack failure	No safety consequence			---
1.4	Lift (WP)	(Other Than) Drop	Mechanical failure	Potential radioactive release	Design of TEV, pallet and WP	Verify maximum drop of 1ft	SSO-202
1.5	Lift (WP)	(Less) Not lifted high enough	Mechanical failure	No safety consequence		Track not aligned for base plate movement	---
1.6	Retract (Base Plate)	(No) Does not retract	Mechanical failure	No safety consequence	PLC interlock: if base plate does not retract then TEV should not move. PLC interlock also does not allow TEV to move unless both front and rear shield doors are closed	Precursor to potential direct exposure if system continues in motion Shine from rear shield door open and lack of base plate	---
1.7	Shielding (Shield Door Closed)	(Less or No) Door not completely closed	Mechanical failure	No safety consequence	PLC interlock also does not allow TEV to move unless both front and rear shield doors are closed	Precursor to potential direct exposure if system continues in motion Shine from rear shield door open	SSO-901
1.8	Facility Door Open	(Less or No) Door not completely opened	Human failure or mechanical failure	Potential release of radioactive material due to collision	1 - TEV design 2 - Facility design 3 - Procedures and training	Facility door independently controlled by operator [a]	SSO-203
1.9	Facility Door Open	(Other Than) Facility door improperly opened (see Retract and TEV Shield door precursors)	Human failure	Potential direct exposure	Procedures and training	Verify radiation detectors inform operators that door should not be opened	Not part of Subsurface Operations
1.10	Facility Door Close	(Other Than) Inadvertent closure of facility door while TEV in doorway	Human failure or mechanical failure	Potential release of radioactive material due to collision	Procedures and training TEV design	Validate with PEFA	SSO-205
1.11	Movement	(Other Than) Derailment	Obstructions on rail or mechanical failure	Potential radioactive release direct exposure	1 - Training and procedures 2 - TEV design 3 - Rail design	Validate with PEFA TEV shielding can potentially be deformed due to roll over	SSO-203
1.12	Movement	(No) TEV stuck in doorway	Mechanical failure	No safety consequence		Increase exposure time to Facility door close	---

NOTE: [a] Facility door may collapse upon TEV due to impact.
Guidewords not used in this node: Reverse, As Well As, and Part Of.
ft = feet; PEFA = passive equipment failure analysis; PLC = programmable logic controller; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Table E-3. Subsurface HAZOP Evaluation Results - Node 2

Facility/Operation: Subsurface				**Process**: TEV on Surface Rail			
Node 2: TEV travels from Facility to North Portal				**Process/Equipment**: TEV, Waste Package, Rail			
Guidewords: No, More, Less, Reverse, Other Than, As Well As, Part Of				**Consequence Categories**: Radioactive Release, Lack of Shielding, Criticality			
Node Item Number	**Parameter**	**Deviation Considered**	**Postulated Cause**	**Consequence**	**Potential Prevention/Mitigation Design of Operational Feature**	**Note**	**MLD Identifier**
2.1	Movement	(Other Than) Concurrent movement of two or more TEVs	Human failure	Potential collision leading to radioactive release	1 - Procedures and training 2 - Rail power source design 3 - TEV design	Current operational design precludes this type of movement	SSO-305
2.2	Movement	(Other Than) TEV crossings not closed	Human failure	Potential collision leading to radioactive release	1 - Procedures and training	Verify with PEFA An operational criterion precludes movement of other vehicles, personnel or equipment in path of TEV	SSO-305
2.3	Movement	(Other Than) Personnel in close proximity to TEV	Human failure	Direct exposure	1 - Procedures and training	Verify barriers/indicators preventing personnel from approaching TEV	SSO-903
2.4	Speed	(More) TEV moves at greater than 1.7 mph	Mechanical failure	No safety consequence	1 - Motor burn-up at about 2 mph	Precursor to derailment	---
2.5	Speed	(Less) TEV moves slower than 1.7 mph	Mechanical failure	No safety consequence			---
2.6	Speed	(No) TEV does not move	Human failure, mechanical failure or loss of power	Potential overheating leading to radioactive release	1 - Procedures and training 2 - Design of TEV	Verify thermal effects of insolation coupled with heat of waste (determine duration to overheat) In case of loss of power, no active cooling	SSO-304
2.7	Direction	(Reverse) Back up instead of going forward	Mechanical failure	Potential collision or derailment leading to radioactive release	1 - Design of TEV 2 - Procedures and training	In order for a collision or derailment to happen, the TEV has to go through closed switch	SSO-305
2.8	Direction	(Other Than) Derailment	Mechanical failure of rail or obstruction of rail	Potential collision or rollover leading to radioactive release	1 - Design of TEV 2 - Procedure and training	Procedures include track inspection and visual confirmation of clear track	SSO-305
2.9	Vision	(Less or No)	Loss of light, loss of camera, environmental conditions	No safety consequence	1 - Procedures and training	If operator cannot see, they should stop the TEV	---
2.10	Rail Switch	(Reverse) Close instead of open	Human failure	Potential collision or rollover leading to radioactive release	1 - Design of TEV 2 - Procedures and training	Considered as cause for derailment	SSO-305
2.11	Shielding	(Less or No) Door open while in transit	Mechanical failure or abrupt stop and WP shift	Direct exposure	1 - Design of door	PLC initiates inappropriate door opening or mechanical failure of door	SSO-901

NOTE: Guidewords not used in this node: As Well As and Part Of.
PEFA = passive equipment failure analysis; PLC = programmable logic controller; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Table E-4. Subsurface HAZOP Evaluation Results - Node 3

Facility/Operation: Subsurface					**Process**: Subsurface Transit		
Node 3: Travel from North Portal to the door of assigned emplacement drift					**Process/Equipment**: TEV, Waste Package, Drift, Rail		
Guidewords: No, More, Less, Reverse, Other Than, As Well As, Part Of					**Consequence Categories**: Radioactive Release, Lack of Shielding, Criticality		
Node Item Number	**Parameter**	**Deviation Considered**	**Postulated Cause**	**Consequence**	**Potential Prevention/Mitigation Design of Operational Feature**	**Note**	**MLD Identifier**
3.1	Movement	(Other Than) Concurrent movement of two or more TEVs	Human failure	Potential collision leading to radioactive release	1 - Procedures and training 2 - Rail power source design 3 - TEV design		SSO-404
3.2	Movement	(Other Than) TEV crossings not closed	Human failure	Potential collision leading to radioactive release	1 - Procedures and raining	Verify with PEFA An operational criterion precludes movement of other vehicles, personnel or equipment in path of TEV	SSO-404
3.3	Movement	(Other Than) Personnel in close proximity to TEV	Human failure	Direct exposure	1 - Procedures and training	Verify barriers/indicators preventing personnel from approaching TEV	SSO-903
3.4	Speed	(More) TEV moves at greater than 1.7 mph	Mechanical failure	No safety consequence	1 - Motor burn up at about 2 mph	Precursor to derailment Uncontrolled descent down the ramp precluded by motor design unless all eight motors fail simultaneously	SSO-404
3.5	Speed	(More) TEV moves at greater than 1.7 mph	Loss of friction	Potential derailment or collision leading to radioactive release	1 - Procedures and training 2 - Design of TEV and rail		SSO-404
3.6	Speed	(Less) TEV moves slower than 1.7 mph	Mechanical failure	No safety consequence			---
3.7	Speed	(No) TEV does not move	Human failure, mechanical failure or loss of power	Potential overheating leading to radioactive release	1 - Procedures and training 2 - Design of TEV	Verify thermal effects of heat of waste (determine duration to overheating) In case of loss of power, no active cooling	SSO-403
3.8	Direction	(Reverse) Back up instead of going forward	Mechanical failure	Potential collision or derailment leading to radioactive release	1 - Design of TEV 2 - Procedures and raining	In order for a collision or derailment to happen, the TEV has to go through closed switch	SSO-404
3.9	Direction	(Other Than) Derailment	Mechanical failure of rail or obstruction of rail (including rockfall)	Potential collision or rollover leading to radioactive release	1 - Design of TEV. 2 - Procedure and raining	Procedures include track inspection and visual confirmation of clear track	SSO-404
3.10	Vision	(Less or No)	Loss of light, loss of camera, environmental conditions (dust)	No Safety Consequence	1 - Procedures and training	If operator cannot see, they should stop the TEV	---
3.11	Rail Switch	(Reverse) Close instead of open	Human failure	Potential collision or rollover leading to radioactive release	1 - Design of TEV 2 - Procedures and training	Closed switch will derail TEV	SSO-404
3.12	Shielding	(Less or No) Door open while in transit	Mechanical failure or abrupt stop and WP shift	Direct exposure	1 - Design of door	PLC initiates inappropriate door opening or mechanical failure of door	SSO-902
3.13	Shielding	(Less or No) Damage of TEV shielded enclosure	Rockfall	Direct exposure	1 - Design of TEV 2 - Ground support system	Verify PEFA Ground support system prevents rock movement	SSO-401

NOTE: Guidewords not used in this node: As Well As and Part Of.
PEFA = passive equipment failure analysis; PLC = programmable logic controller; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Table E-5. Subsurface HAZOP Evaluation Results - Node 4

Facility/Operation: Subsurface				**Process**: Waste Package Emplacement Operations			
Node 4: Emplace Waste Package in drift				**Process/Equipment**: TEV, Waste Package, Rail			
Guidewords: No, More, Less, Reverse, Other Than, As Well As, Part Of				**Consequence Categories**: Radioactive Release, Lack of Shielding, Criticality			
Node Item Number	**Parameter**	**Deviation Considered**	**Postulated Cause**	**Consequence**	**Potential Prevention/Mitigation Design of Operational Feature**	**Note**	**MLD Identifier**
4.1	Shielding	(Less or No) Damage of TEV shielded enclosure	Rockfall	Direct exposure	1 - Design TEV 2 - Ground support system	Verify PEFA Ground support system prevents rock movement	SSO-501
4.2	Emplacement Access Door Open	(Less or No) Door not completely opened	Human failure or mechanical failure	Potential release of radioactive material due to collision	1 - TEV design 2 - Emplacement access door design 3 - Procedures and training	Emplacement access door independently controlled by operator	SSO-505
4.3	Movement (Into Drift)	(Other Than) Derailment	Obstructions on rail or mechanical failure	Potential radioactive release direct exposure	1 - Training and procedures 2 - TEV design 3 - Rail design	Validate with PEFA TEV shielding can potentially be deformed due to roll over	SSO-505
4.4	Movement (Into Drift)	(No) TEV stuck in doorway	Mechanical failure	No safety consequence		Increase exposure time to emplacement access door close	---
4.5	Emplacement Access Door Close	(Other Than) Inadvertent closure of emplacement access door while TEV in doorway	Human failure or mechanical failure	Potential release of radioactive material due to collision	1 - Procedures and training 2 - TEV design	Validate with PEFA	SSO-501
4.6	Position Calibration	(Other Than) Miscalibrates position	Mechanical failure	Potential release of radioactive material due to collision	1 -Procedures and training 2 - TEV design	TEV carries diverse positional sensors and cameras Result is collision with a WP	SSO-504
4.7	Shielding (Door Open)	(Less or No) Door not completely opened	Mechanical failure	Potential release of radioactive material due to collision of door with WP in drift	1 - TEV design		SSO-503
4.8	Extend (Bsae plate)	(No or Less) Does not extend	Mechanical failure	No safety consequence			---
4.9	Movement (to Emplacement Point)	(More) TEV moves too far	Mechanical failure	Potential release of radioactive material due to collision of TEV door with WP in drift or drift itself	1 - TEV design 2 - WP design 3 - Procedures and training	Operator observing emplacement and stop TEV if necessary	SSO-504
4.10	Movement (To Emplacement Point)	(Less) TEV moves too little	Mechanical failure	No safety consequence			---
4.11	Speed	(More) TEV moves too fast	Mechanical failure	No safety consequence		Precursor to damaging collision with WP	---
4.12	Direction	(Reverse) TEV goes backwards instead of forwards	Mechanical failure	Potential release of radioactive material due to collision with emplace access door	1 - TEV design 2 - WP design 3 - Procedures and training		SSO-504
4.13	Lower (WP)	(Other Than) Asymmetrical lowering	Screw jack failure	No safety consequence			---
4.14	Lower (WP)	(Other Than) Drop	Mechanical failure	Potential radioactive release	1 - Design of TEV and WP	Verify maximum drop of 1ft	SSO-502
4.15	Lower (WP)	(Less or No) Not lowered enough - WP partially unloaded	Mechanical failure	No safety consequence		Precursor to potential WP damage due to dragging while backing TEV out	---
4.16	Lower (WP)	(Less or No) Not lowered enough - WP not unloaded	Mechanical failure	No safety consequence		Precursor to bringing WP back out, however the TEV is inspected on the way out	---

Table E-5. Subsurface HAZOP Results – Node 4 (Continued)

Facility/Operation: Subsurface				**Process**: Waste Package Emplacement Operations			
Node 4: Emplace Waste Package in drift				**Process/Equipment**: TEV, Waste Package, Rail			
Guidewords: No, More, Less, Reverse, Other Than, As Well As, Part Of				**Consequence Categories**: Radioactive Release, Lack of Shielding, Criticality			
Node Item Number	**Parameter**	**Deviation Considered**	**Postulated Cause**	**Consequence**	**Potential Prevention/Mitigation Design of Operational Feature**	**Note**	**MLD Identifier**
4.17	Movement (to clear WP)	(Other Than) TEV drags WP, see precursor above.	Mechanical failure	Potential release of radioactive material	1 - TEV design 2 - WP design 3 - Procedures and training		SSO-502
4.18	Movement (to clear WP)	(More) TEV moves too far	Mechanical failure	No safety consequence			---
4.19	Movement (to clear WP)	(Less) TEV does not clear WP	Mechanical failure	Potential release of radioactive material due TEV door close on WP	1 - WP design 2 - Procedures and training		SSO-503
4.20	Speed (to clear WP)	(More) TEV moves too fast	Mechanical failure	No safety consequence			---
4.21	Direction (movement to clear WP)	(Reverse) TEV goes forwards instead of backwards	Mechanical failure	Potential release of radioactive material due to collision of TEV with WP	1 - TEV design 2 - WP design 3 - Procedures and training	Back shield door of TEV will push into emplaced WP, and push WP off the pallet	SSO-504
4.22	All (prepare to leave drift)	(Anything)	---	No safety consequence		No WP	---
4.23	Open emplacement access door	(Less or No) Emplacement Door does not completely open	Mechanical failure	No safety consequence			---
4.24	Direction (leaving drift)	(Reverse) TEV goes forwards instead of backwards	Mechanical failure	Potential release of radioactive material due to collision of TEV with WP	1 - TEV design 2 - WP design 3 - Procedures and training		SSO-504

NOTE: ft = feet; PEFA = passive equipment failure analysis; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Table E-6. Subsurface HAZOP Evaluation Results - Node 5

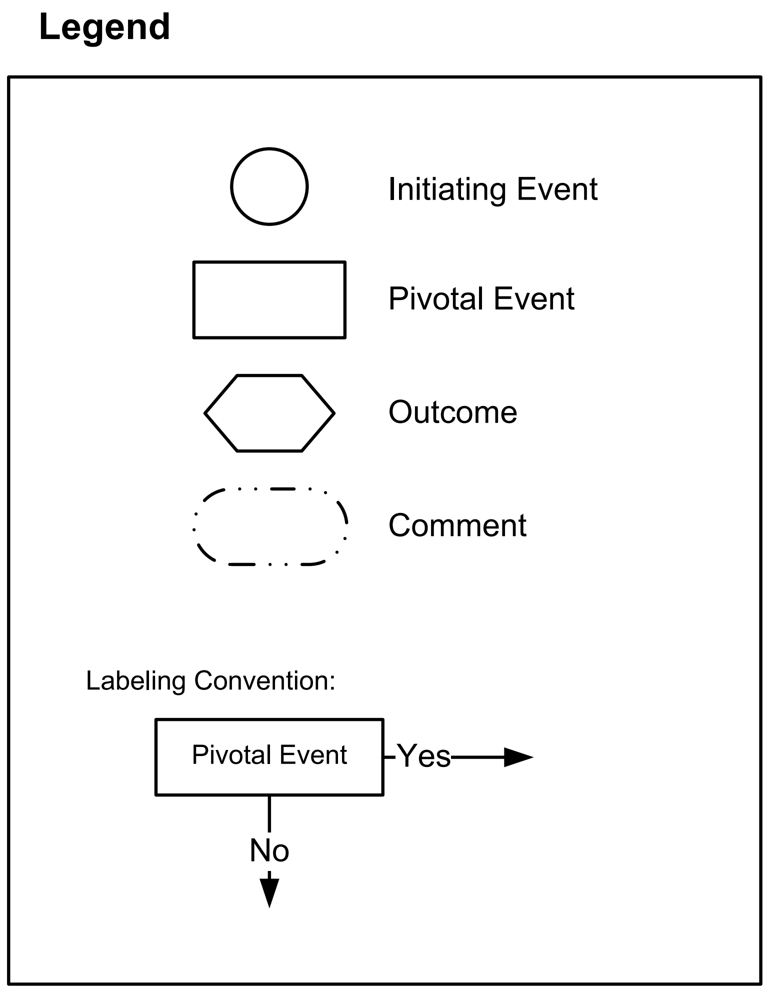
Facility/Operation: Subsurface				**Process**: Drip Shield Emplacement Operations			
Node 5: Emplace Drip shield in drift				**Process/Equipment**: DSG, Drip Shield, Waste Package			
Guidewords: No, More, Less, Reverse, Other Than, As Well As, Part of				**Consequence Categories**: Radioactive Release, Lack of Shielding, Criticality			
Node Item Number	**Parameter**	**Deviation Considered**	**Postulated Cause**	**Consequence**	**Potential Prevention/Mitigation Design of Operational Feature**	**Note**	**MLD Identifier**
5.1	Movement	(Other Than) Collapse	Mechanical failure or collision with an object causing derailment	No safety consequence	1 - Design of DSG	Verify drip shield cannot get into necessary orientation to contact the WP	SSO-702
5.2	Movement	(Other Than) Abrupt stop	Collision	No safety consequence	1 - Design of DSG	Verify drip shield cannot rotate enough to achieve necessary orientation to contact the WP	SSO-702

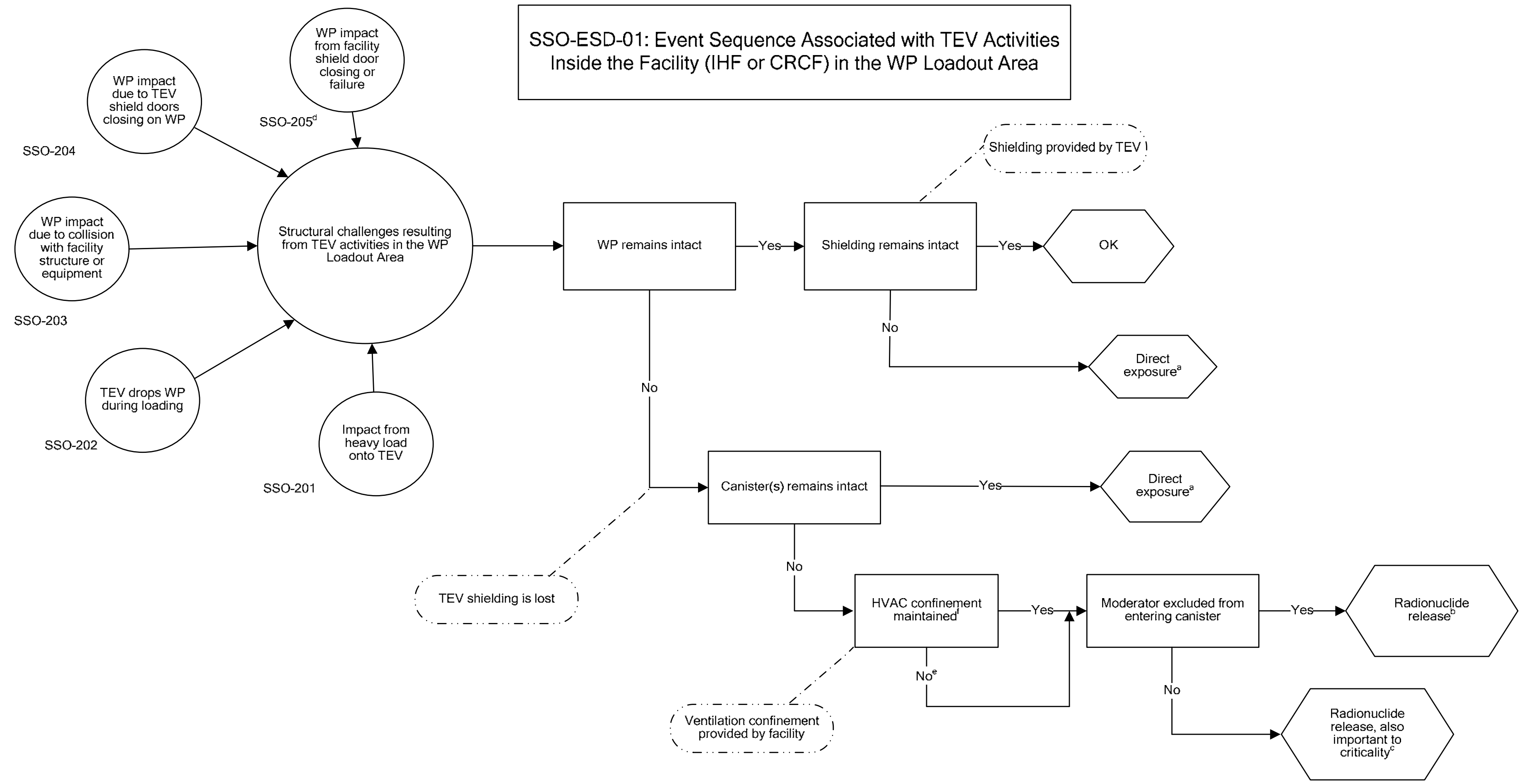
NOTE: Guidewords not used in this node: No, More, Less, Reverse, As Well As, and Part of.
DSG = drip shield emplacement gantry.

Source: Original

ATTACHMENT F
SUBSURFACE OPERATIONS EVENT SEQUENCE DIAGRAMS

Event Sequence Diagrams for the Subsurface Operations are presented in Figures F-1 through F-5.

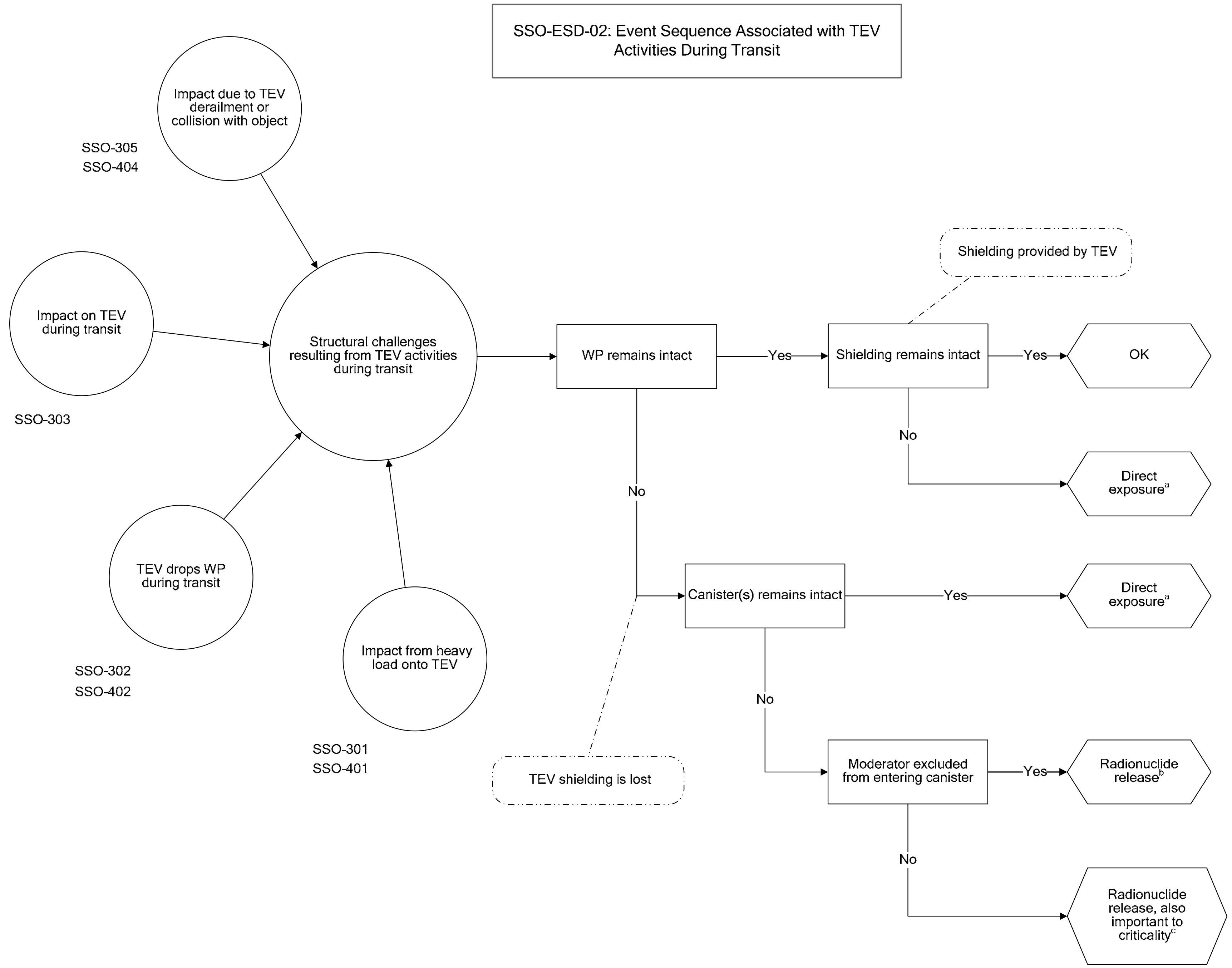




NOTE: [a] Direct exposure is that condition where individuals are directly exposed to the radiation beam streaming through areas where shielding has been compromised.
[b] Radionuclide release describes a condition where radioactive material has been released from the container creating an inhalation or ingestion hazard which is accompanied by the dose received from immersion in the plume, and direct exposure, described above.
[c] Radionuclide releases important to criticality describes a condition where the containment boundaries have been compromised, releasing radioactive material.
[d] A moderator is present and may enter the canister.
[e] SSO numbers next to the smaller circles are references to the Subsurface MLD.
[f] Pivotal events for which both the yes and no paths merge are provided to simplify communication of the event sequences. The end state frequency and consequences for each path may be different.
Potential for fire analyzed in fire ESDs.
Successful operation of the HVAC system would mitigate a radionuclide release.
ESD = event sequence diagram; MLD = master logic diagram; SSO = Subsurface Operations; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Figure F-1. SSO-ESD-01: Event Sequence Associated with TEV Activities inside the Facility (IHF or CRCF) in the WP Loadout Area



NOTE: [a] Direct exposure is that condition where individuals are directly exposed to the radiation beam streaming through areas where shielding has been compromised.

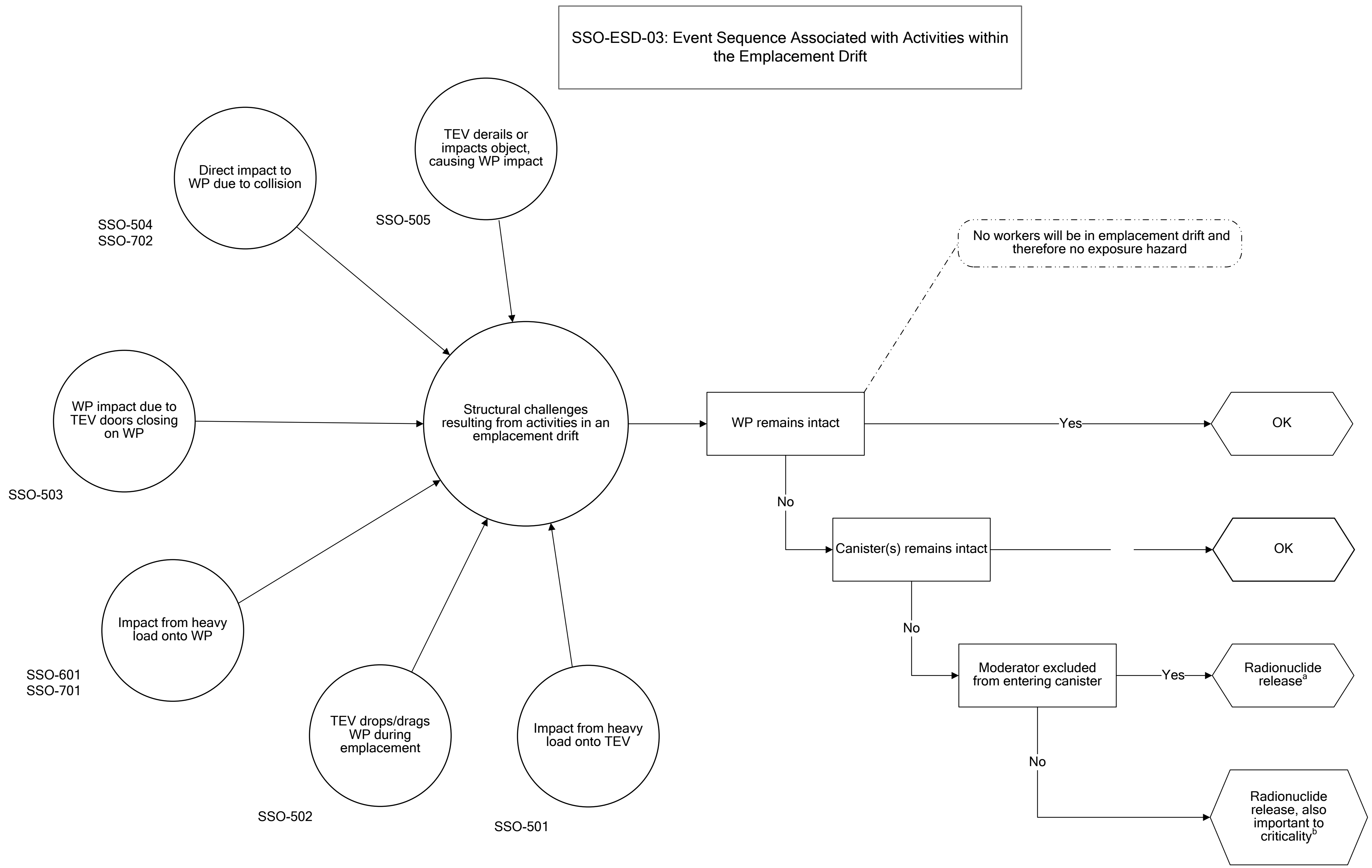
Radionuclide release describes a condition where radioactive material has been released from the container creating an inhalation or ingestion hazard which is accompanied by the dose received from immersion in the plume, and direct exposure, described above.

Radionuclide releases important to criticality describes a condition where the containment boundaries have been compromised, releasing radioactive material. A moderator is present and may enter the canister. Potential for fire analyzed in fire ESDs.

[b] ESD = event sequence diagram; MLD = master logic diagram; SSO = Subsurface Operations; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Figure F-2. SSO-ESD-02: Event Sequence Associated with TEV Activities during Transit



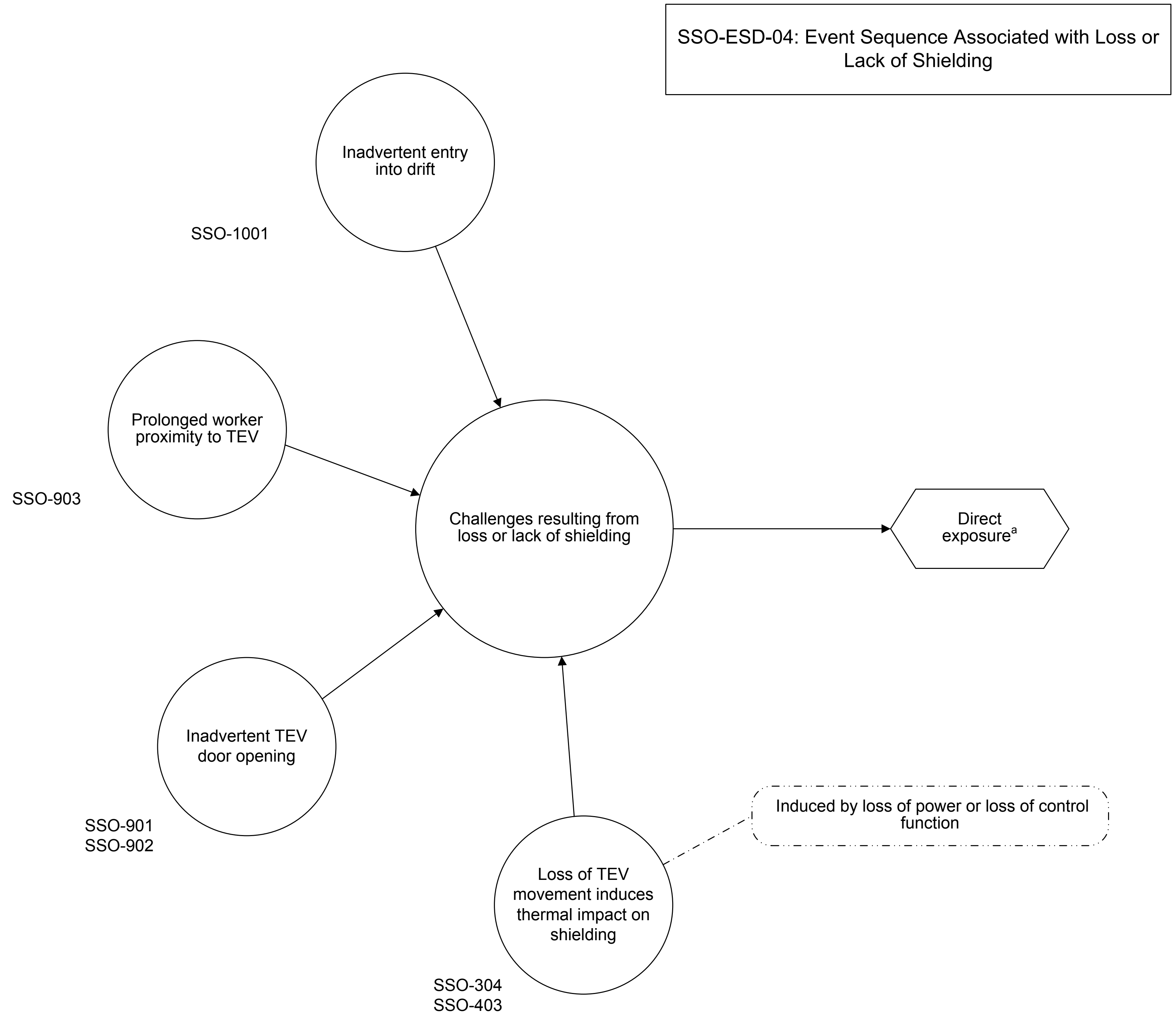
NOTE: [a] Radionuclide release describes a condition where radioactive material has been released from the container creating an inhalation or ingestion hazard which is accompanied by the dose received from immersion in the plume, and direct exposure, described above.

[b] Radionuclide releases important to criticality describes a condition where the containment boundaries have been compromised, releasing radioactive material. A moderator is present and may enter the canister. Potential for fire analyzed in fire ESDs.

ESD = event sequence diagram; MLD = master logic diagram; SSO = Subsurface Operations; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Figure F-3. SSO-ESD-03: Event Sequence Associated with Activities within the Emplacement Drift

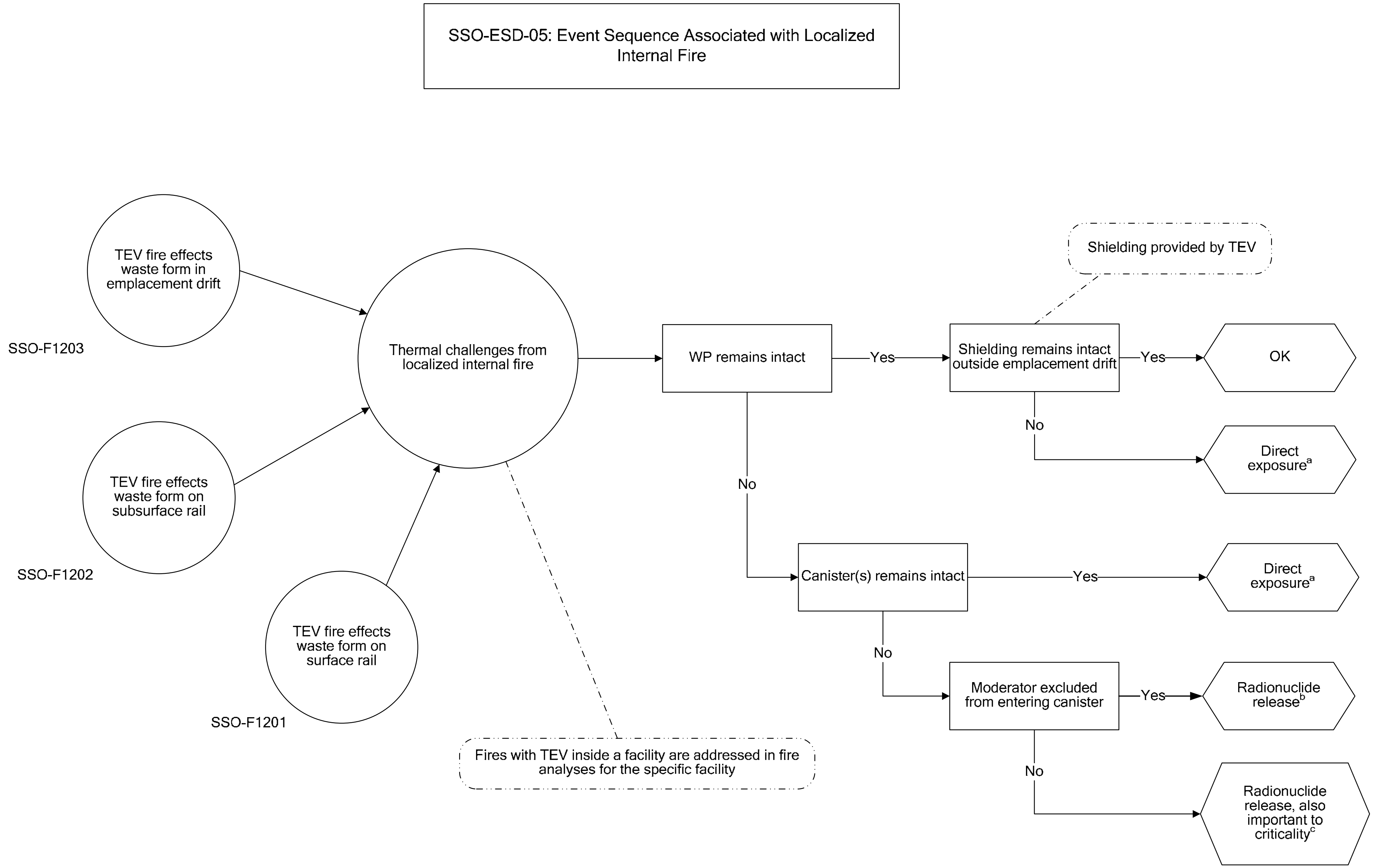


NOTE: [a] Direct exposure is that condition where individuals are directly exposed to the radiation beam streaming through areas where shielding has been compromised. Potential for fire analyzed in fire ESDs.

ESD = event sequence diagram; MLD = master logic diagram; SSO = Subsurface Operations; TEV = transport and emplacement vehicle.

Source: Original

Figure F-4. SSO-ESD-04: Event Sequence Associated with Loss or Lack of Shielding



NOTE: [a] Direct exposure is that condition where individuals are directly exposed to the radiation beam streaming through areas where shielding has been compromised.
Radionuclide release describes a condition where radioactive material has been released from the container creating an inhalation or ingestion hazard which is accompanied by the dose received from immersion in the plume, and direct exposure, described above.
[c] Radionuclide releases important to criticality describes a condition where the containment boundaries have been compromised, releasing radioactive material. A moderator is present and may enter the canister.

[b] MLD = master logic diagram; SSO = Subsurface Operations; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Figure F-5. SSO-ESD-05: Event Sequence Associated with Localized Internal Fire

ATTACHMENT G
SUBSURFACE OPERATIONS EVENT TREES

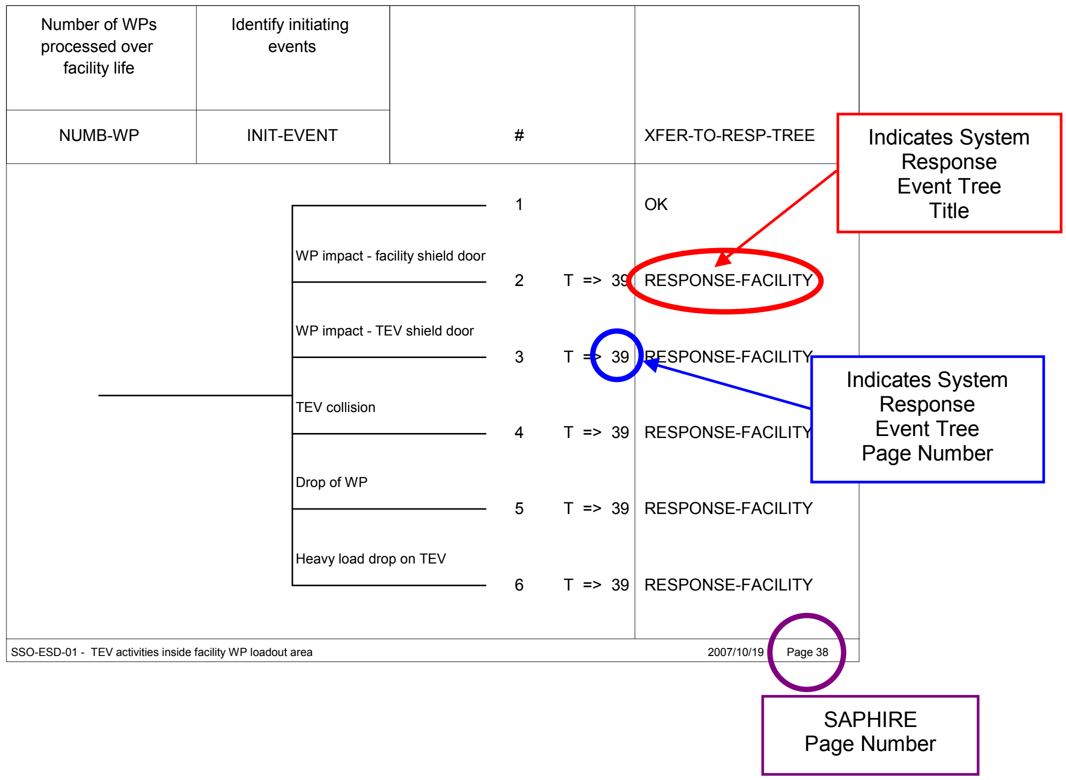
G1 GENERAL

This attachment presents event trees that are derived from the ESDs in Attachment F. Figure G-1 provides an example initiator event tree with navigation aids. Navigation from an initiator event tree to the corresponding system response event tree is assisted by the rightmost two columns on the initiator event trees. The numbers under the "#" symbol can be used by the analyst to reference a particular branch of an event tree, but it is not used elsewhere by SAPHIRE in this analysis. The title of the corresponding system response event tree is listed under the heading "XFER-TO-RESP-TREE". Refer to Table G-1 for the relationship between the ESDs, initiating event trees, and system response event trees.

The event trees are presented in Figures G-2 to G-10 according to the hierarchical ordering option in SAPHIRE. Note that there is no response tree for ESD-04 because the initiating event leads to the end state directly. There are no pivotal events.

This ordering places the system response event trees after the first of the corresponding initiator event trees. The initiator event trees are presented in order of ascending ESD number, with system response trees systematically intermingled. Each system response event tree is placed immediately after the first initiator event tree that transfers to that system response event tree. Event trees for which separate initiator and system response event trees are not needed, appear in ESD order, along with the initiator event trees.

SAPHIRE



Source: Original

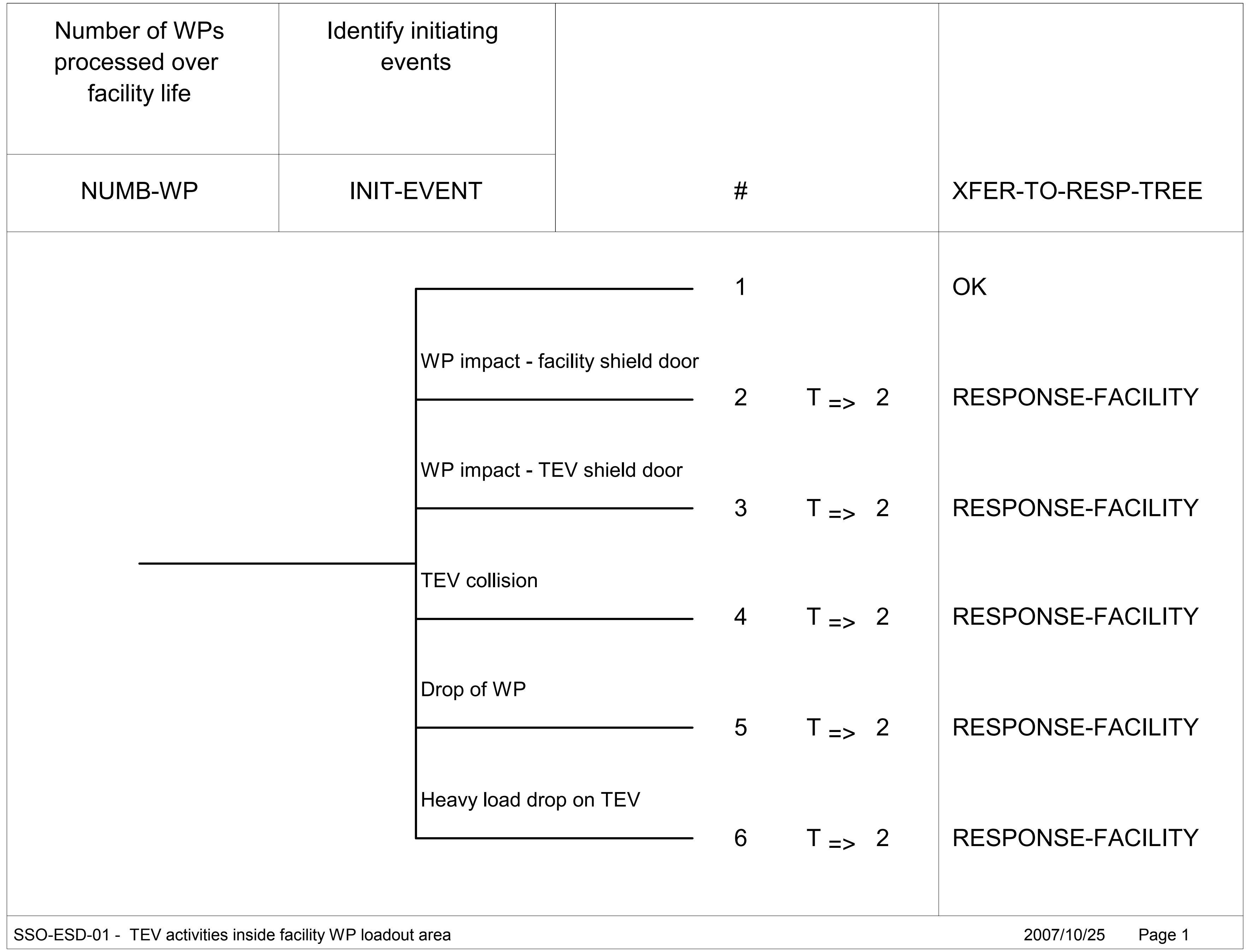
Figure G-1. Illustration on Navigation from an Initiator Event Tree to the Corresponding Response Event Tree

Table G-1. Relation of Event Sequence Diagrams to Event Trees

ESD#	ESD Title	IE Event Tree Name	IE Event Tree Location	Response Tree Name	Response Tree Location
SSO-ESD-01	Event Sequence Associated with TEV Activities inside the Facility (IHF or CRCF) in the WP Loadout Room	SSO-ET-01	Figure G-2	RESPONSE-FACILITY	Figure G-3
SSO-ESD-02	Event Sequence Associated with TEV Activities during Transit	SSO-ET-02	Figure G-4	RESPONSE-TRANSIT	Figure G-5
SSO-ESD-03	Event Sequence Associated with TEV Activities in an Emplacement Drift	SSO-ET-03	Figure G-6	RESPONSE-DRIFT	Figure G-7
SSO-ESD-04	Event Sequence Associated with Loss or Lack of Shielding	SSO-ET-04	Figure G-8	(None)	---
SSO-ESD-05	Event Sequence Associated with Localized Internal Fire	SSO-ET-05	Figure G-9	RESPONSE-TRANSIT	Figure G-10

NOTE: CRCF = Canister Receipt and Closure Facility; ESD = event sequence diagram; ET = event tree; IHF = Initial Handling Facility; SSO = Subsurface Operations; TEV = transport and emplacement vehicle; WP = waste package.

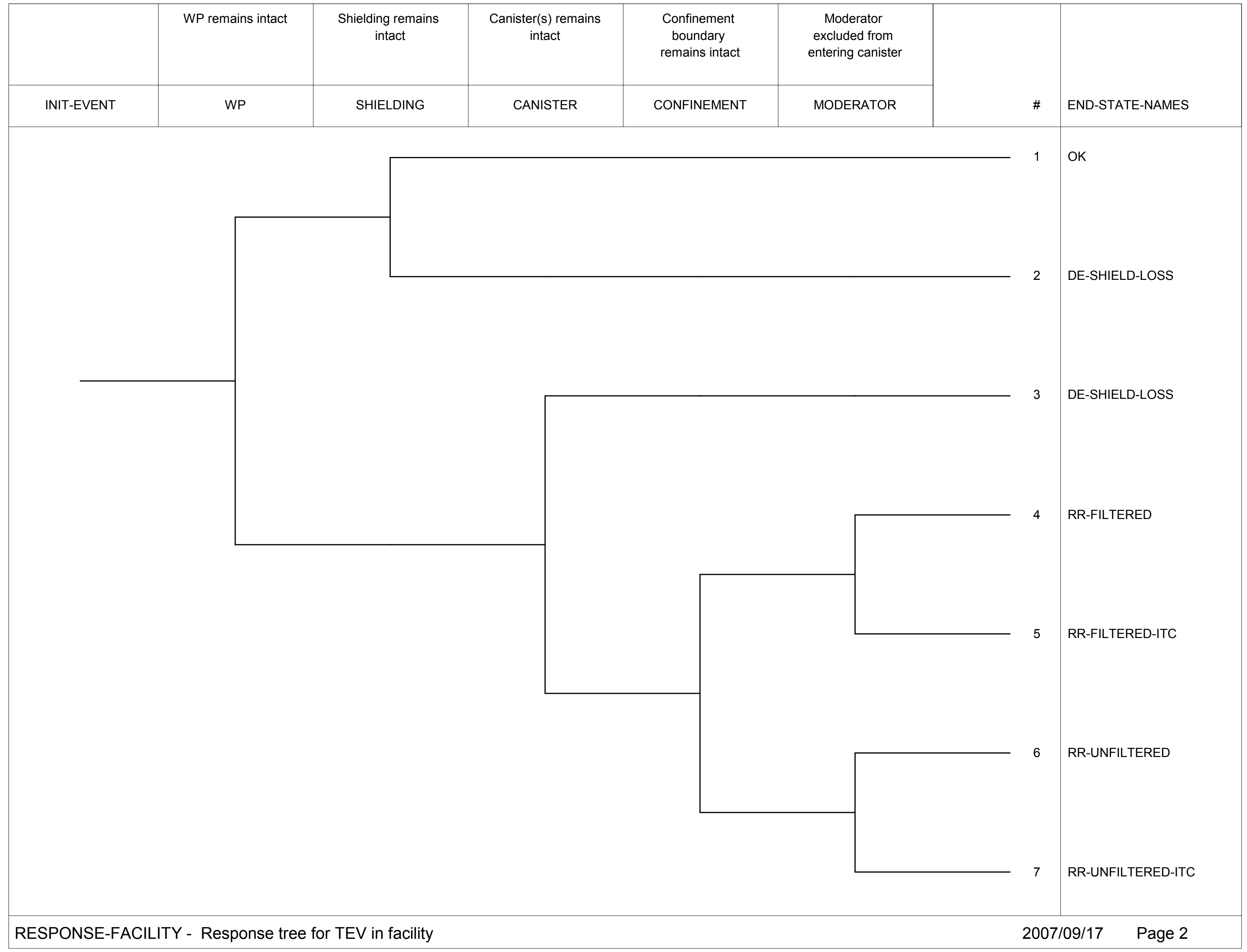
Source: Original



NOTE: ESD = event sequence diagram; INIT = initiating; NUMB = number; RESP = response; SSO = Subsurface Operations; T = transfer; TEV = transport and emplacement vehicle; WP = waste package; XFER = transfer.

Source: Original

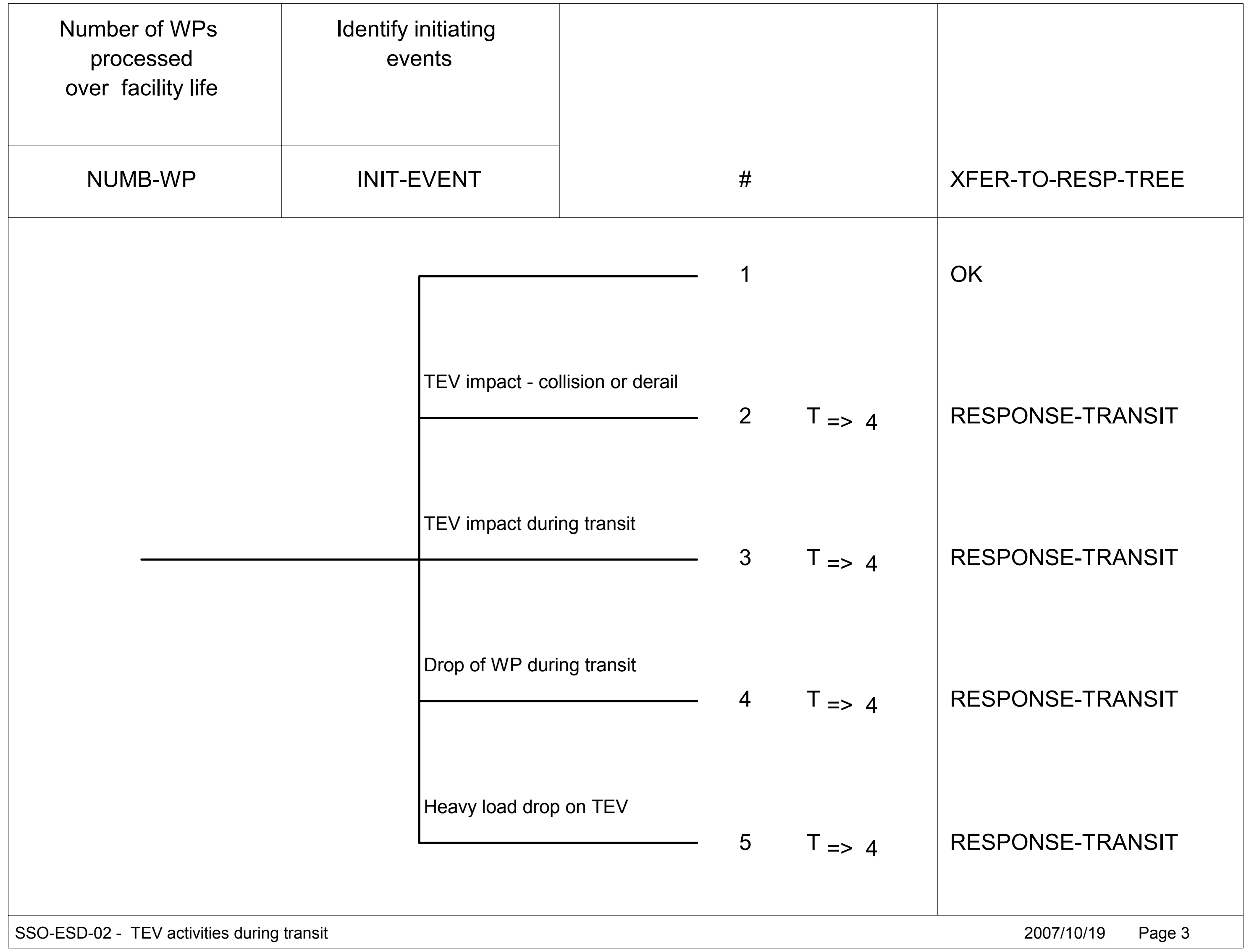
Figure G-2. Event Tree SSO-ET-01 – TEV Activities inside Facility (IHF or CRCF) in the Waste Package Loadout Room



NOTE: DE = direct exposure; INIT = initiating; ITC = important to criticality; RR = radionuclide release; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

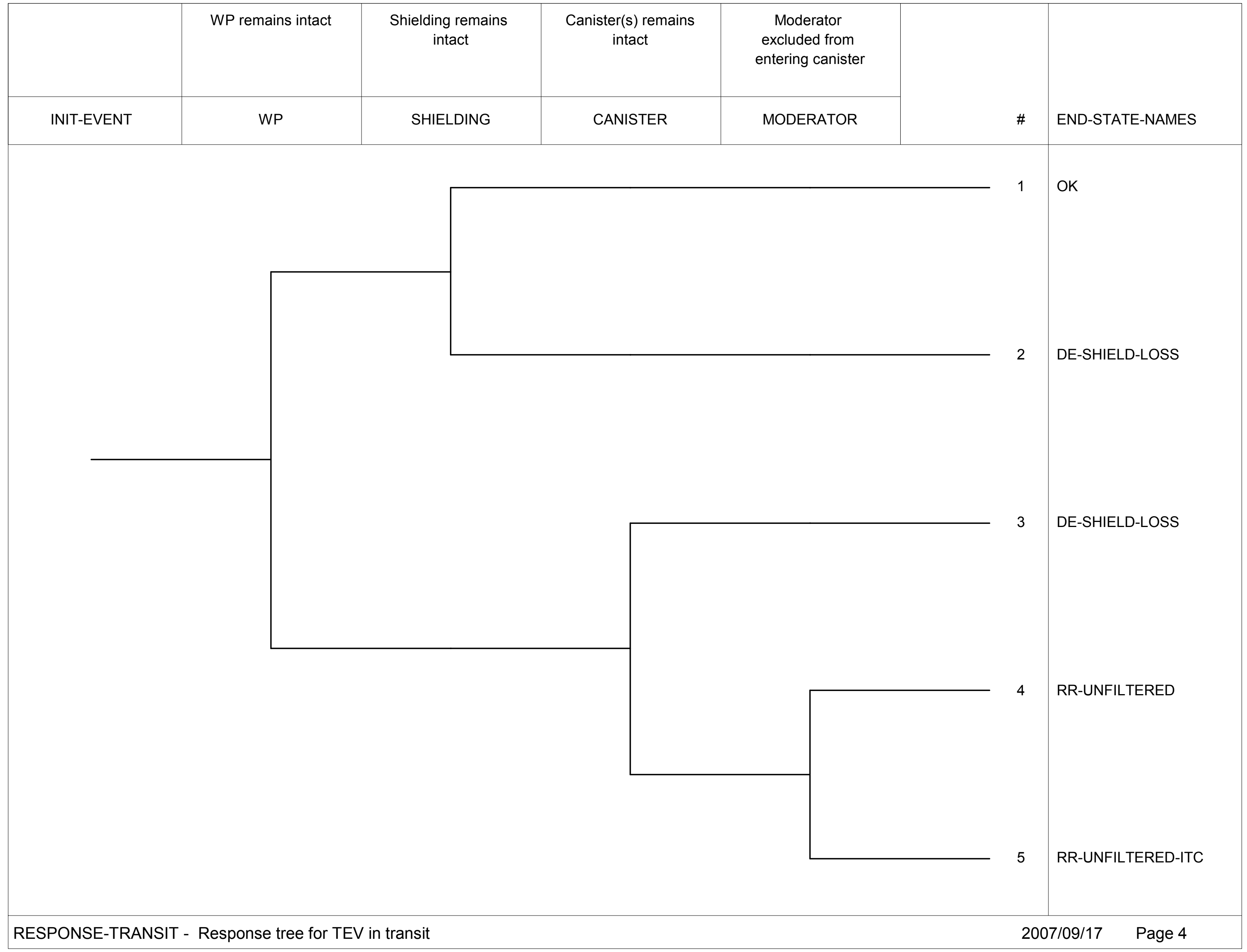
Figure G-3. RESPONSE-FACILITY – Response Tree for TEV in Facility



NOTE: ESD = event sequence diagram; INIT = initiating; NUMB = number; RESP = response; SSO = Subsurface Operations; T = transfer; TEV = transport and emplacement vehicle; WP = waste package; XFER = transfer.

Source: Original

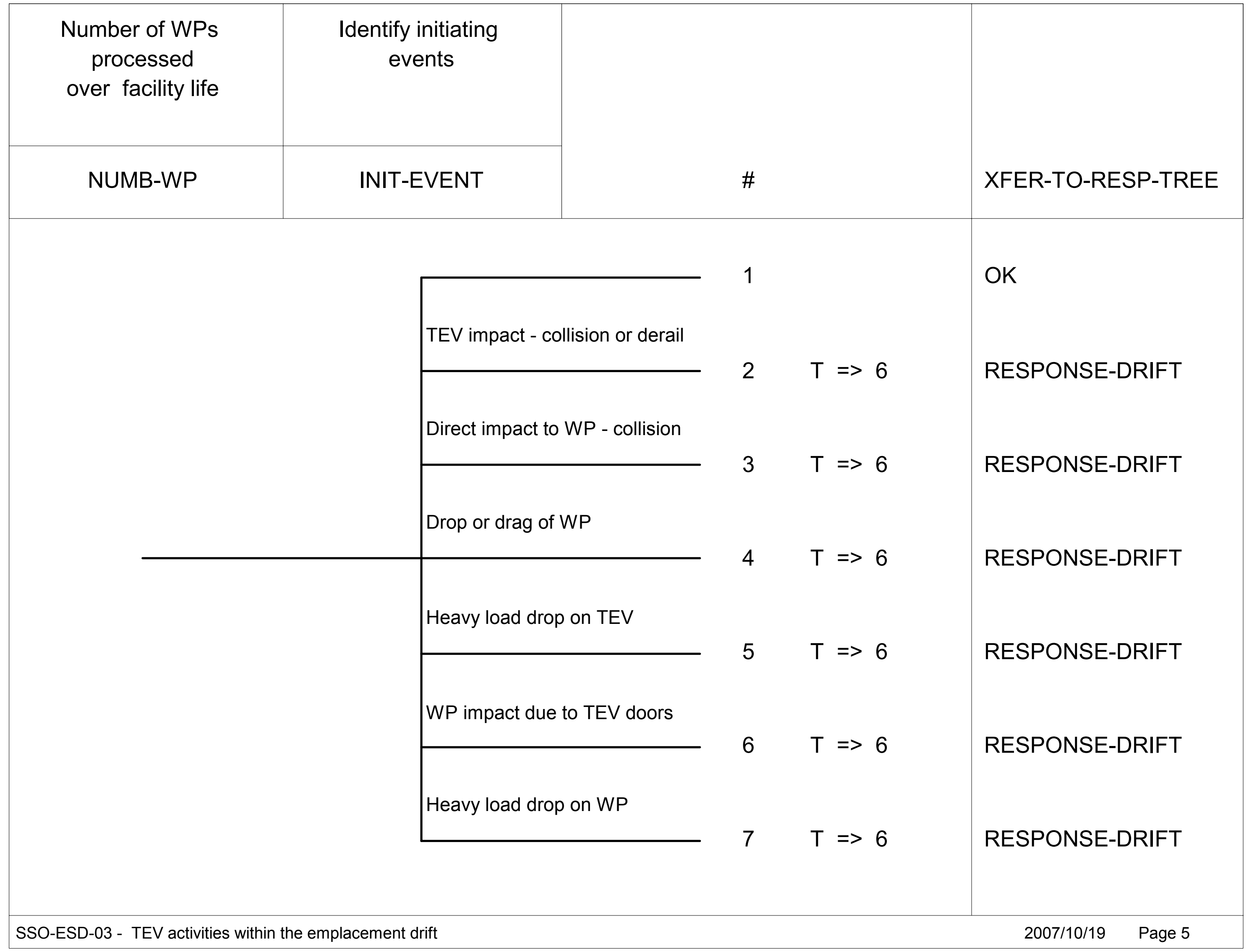
Figure G-4. Event Tree SSO-ET-02 – TEV Activities during Transit



NOTE: DE = direct exposure; INIT = initiating; ITC = important to criticality; RR = radionuclide release; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

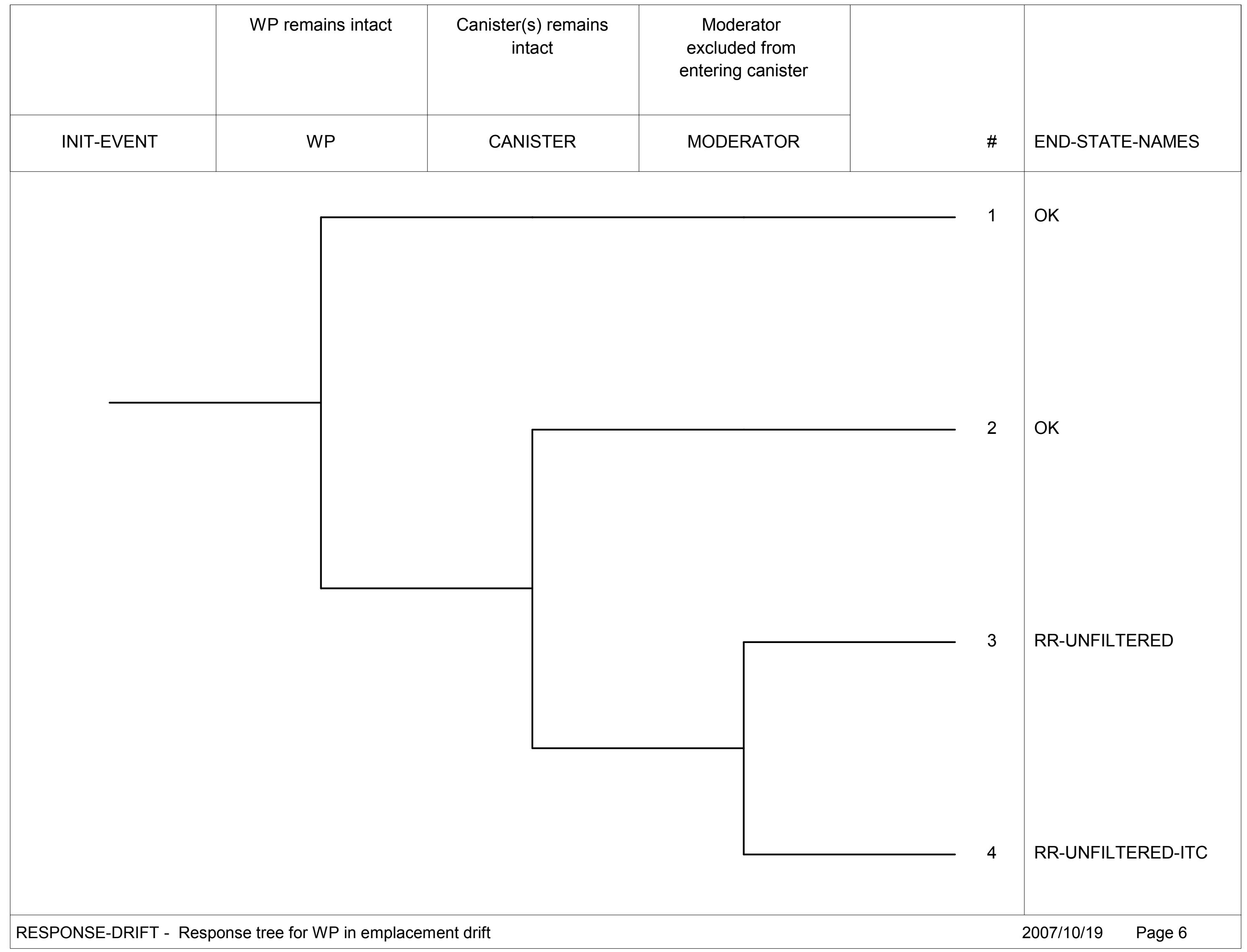
Figure G-5. RESPONSE-TRANSIT – Response Tree for TEV in Subsurface



NOTE: ESD = event sequence diagram; INIT = initiating; NUMB = number; RESP = response; SSO = Subsurface Operations; T = transfer; TEV = transport and emplacement vehicle; WP = waste package; XFER = transfer.

Source: Original

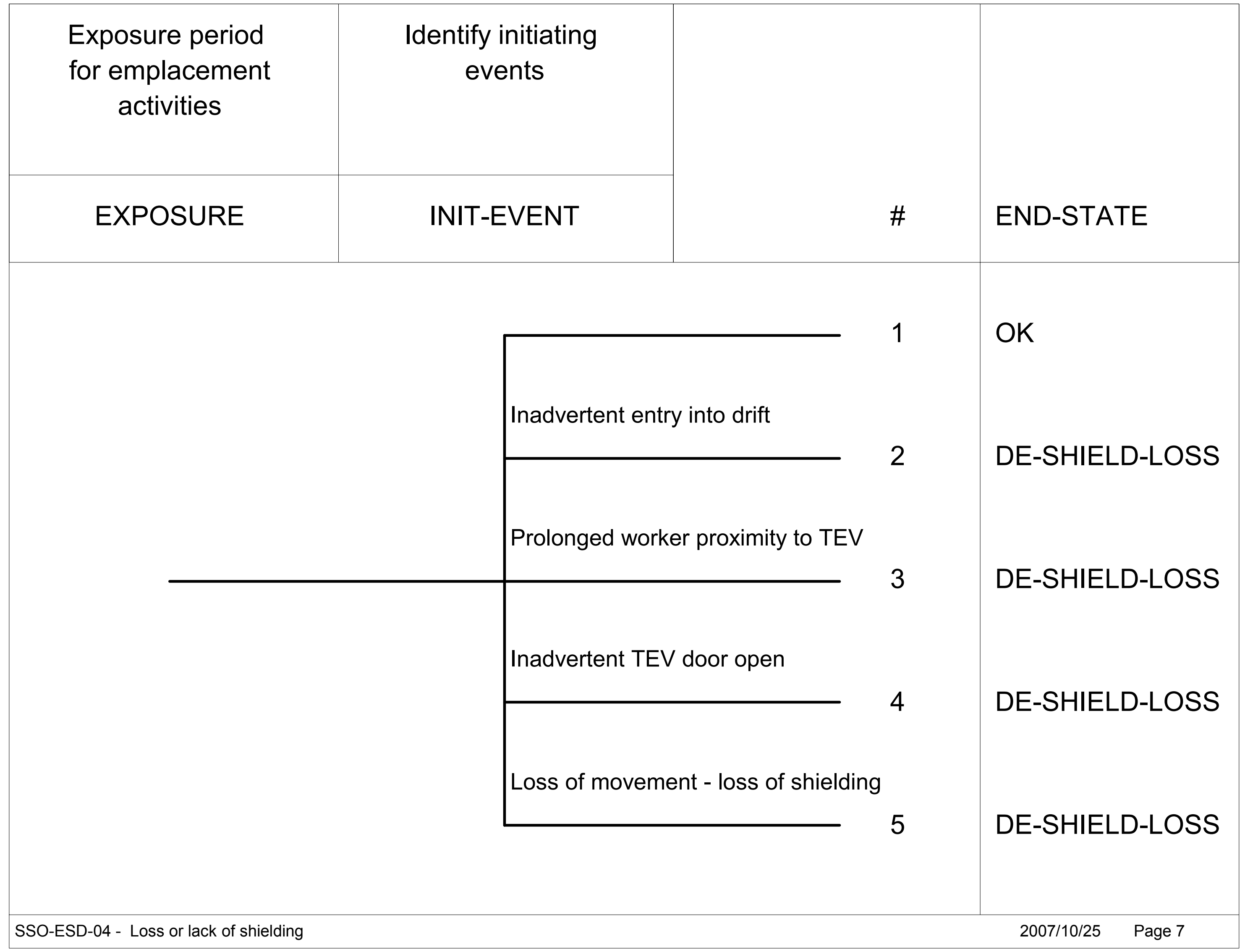
Figure G-6. Event Tree SSO-ET-03 – TEV Activities in an Emplacement Drift



NOTE: INIT = initiating; ITC = important to criticality; RR = radionuclide release; WP = waste package.

Source: Original

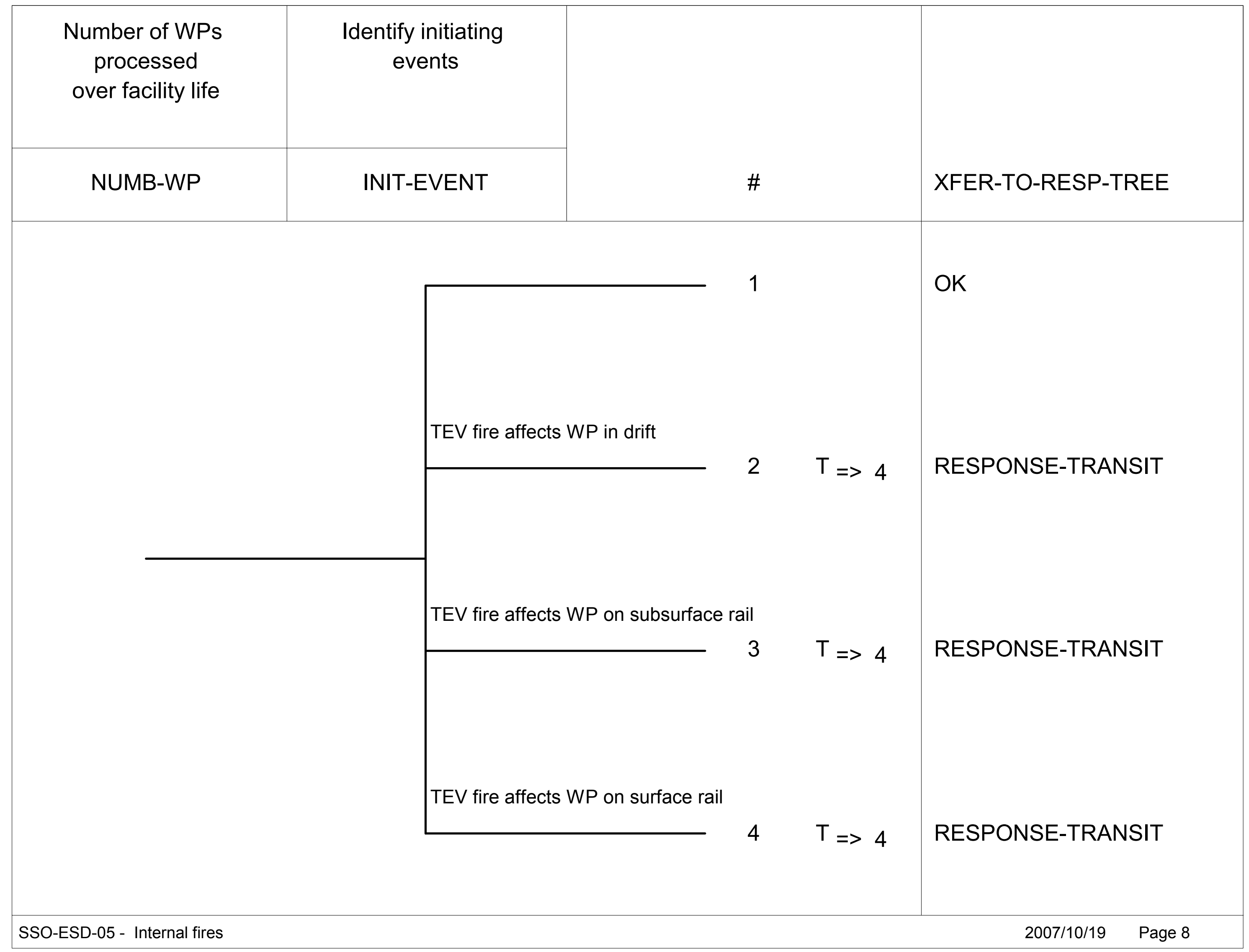
Figure G-7. RESPONSE DRIFT – Response Tree for Waste Package in Emplacement Drift



NOTE: ESD = event sequence diagram; INIT = initiating; SSO = Subsurface Operations; TEV = transport and emplacement vehicle.

Source: Original

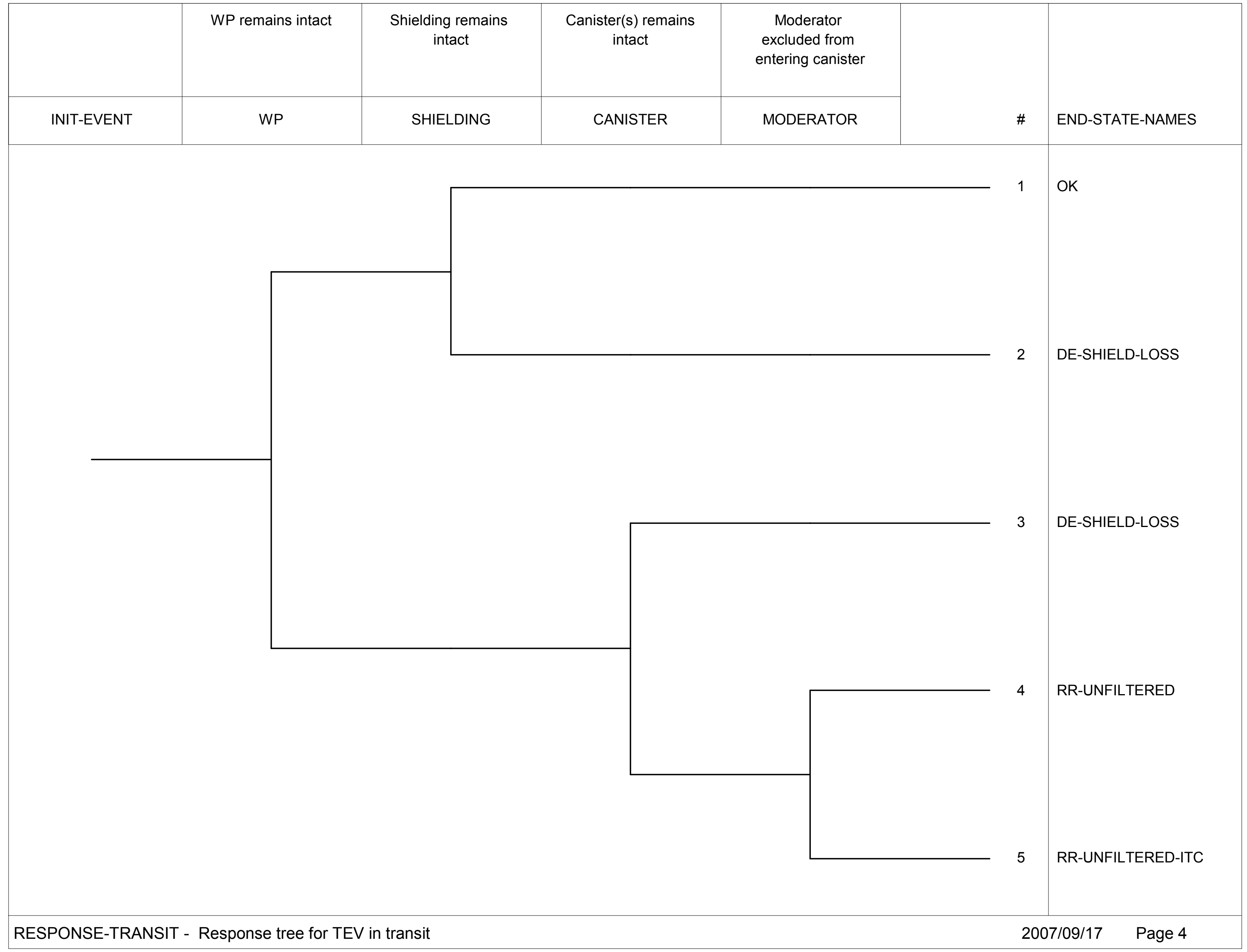
Figure G-8. Event Tree SSO-ET-04 – Loss or Lack of Shielding



NOTE: ESD = event sequence diagram; INIT = initiating; NUMB = number; RESP = response; SSO = Subsurface Operations; T = transfer; TEV = transport and emplacement vehicle; WP = waste package; XFER = transfer.

Source: Original

Figure G-9. Event Tree SSO-ET-05 – Localized Internal Fire



NOTE: DE = direct exposure; INIT = initiating; ITC = important to criticality; RR = radionuclide release; TEV = transport and emplacement vehicle; WP = waste package.

Source: Original

Figure G-10. RESPONSE-TRANSIT – Response Tree Used for Localized Fire