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Methodology for Radiological Risk Assessment of Deep Borehole Disposal Operations

Spent Fuel and Waste Disposition

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Contents

List of Figures

List of Tables

Acronyms

ALARA	As low as reasonably achievable
CFR	Code of Federal Regulations
DBD	Deep borehole disposal
DBFT	Deep Borehole Field Test
ESD	Event sequence diagram
EZ	Emplacement zone
FMEA	Failure Modes and Effects Analysis
GROA	Geologic repository operations area
HAZOP	Hazard and Operability Analysis
HRA	Human Reliability Analysis
HVAC	Heating, ventilation and air conditioning
ITS	Important to safety
LWT	Legal weight truck
MLD	Master logic diagram
MT	Metric ton
PCSA	Preclosure safety analysis
PFD	Process flow diagram
PRA	Probabilistic risk assessment
SSC	Systems, structures and components
TAD	Transport, aging and disposal (canister)
TBD	To-be-determined
TEDE	Total effective dose equivalent
WP	Waste package

Methodology for Radiological Risk Assessment of Deep Borehole Disposal Operations

1. Purpose and Scope

The primary purpose of the preclosure radiological safety assessment (that this document supports) is to identify risk factors for disposal operations, to aid in design for the deep borehole field test (DBFT) engineering demonstration. As was the case for an earlier study (SNL 2016) the assessment will consider actual deep borehole disposal (DBD) operations, to develop conclusions that can be applied to the DBFT demonstration (which will be performed without using any form of nuclear waste). The safety assessment seeks to improve the conceptual design for DBD and the DBFT demonstration, by considering risks associated with the equipment and the activities that would be used for waste emplacement. The DBFT demonstration can then include features of the equipment and processes that are found to be important to safety. It is expected that by describing and analyzing disposal operations in more detail, from waste package receipt to borehole closure, that additional active and passive safety functions and operational controls can be identified and incorporated in the design.

This report proposes a methodology for the preclosure radiological safety assessment, consistent with the approach required by 10 CFR 63, and based on probabilistic risk assessment (PRA) concepts applied to the preclosure safety analysis (PCSA) for a Yucca Mountain repository (BSC 2008a,b). The approach is also consistent with the requirements at 10 CFR 60.

Performance standards and requirements on PCSA for DBD were summarized by Freeze et al. (2016). Key items to be included in a PCSA (10 CFR 63.112) are:

- A description of the design, both surface and subsurface, of the geologic repository operations area (GROA) including design requirements and criteria specified in the preclosure performance objectives, and the design bases.
- Identification and analysis of naturally occurring and human-induced hazards at the GROA, including potential initiating event sequences.
- The technical basis for including or excluding naturally occurring and human-induced hazards in the safety analysis.
- Analysis of systems, structures and components (SSCs) to identify those that are important to safety.

The conceptual design described by SNL (2016) will be analyzed, with changes expected to improve radiological safety. Detailed description of the concept of operations was given in the earlier report, and just a summary is provided in Section 2. The assessment will treat requirements specified in the preclosure performance objectives, in the manner summarized in Tables 1 and 2. Methodology considerations leading to selection of fault tree/event tree analysis are discussed in Section 3. An approach to identifying hazards, identifying initiating event sequences, and analyzing event probabilities, is described in Section 3, but actual implementation is planned for follow-on companion reports. Identification of SSCs important to safety, will also be addressed in that follow-on work. Additional assumptions in addition to the description in Section 2, that will be made in order to proceed with the assessment, are documented in Section 4. The DBD concept is presently non-site specific (i.e., generic) which requires assumptions on how it can be implemented (Section 4). Such assumptions also include which naturally occurring and human-induced hazards will be included in the assessment.

Table 1. Regulatory requirements pertaining to PCSA.

Hazard or Performance Objective	Regulatory Reference	Requirement	Treatment in This Study
On-Site Worker Dose	10 CFR 60.111(a) 10 CFR 63.111(a)(1) 10 CFR 20.1201(a)	The GROA must be designed so that, for normal operations and Category 1 event sequences through permanent closure, the aggregate radiation exposures and the aggregate radiation levels in both restricted and unrestricted areas, and the aggregate releases of radioactive materials to unrestricted areas, will limit doses to: • The more limiting of (i) an annual dose* ≤ 5 rem/yr, or (ii) the sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue other than the lens of the eye ≤ 50 rem/yr, and • Lens dose equivalent ≤ 15 rem/yr, and • Shallow-dose equivalent to the skin ≤ 50 rem/yr.	Qualitative, judgment-based ALARA treatment for normal and off-normal operations.
Off-Site Dose to Members of the Public	10 CFR 63.111(a)(2) 10 CFR 63.202 10 CFR 63.204 40 CFR 191.2 40 CFR 191.3(a) 40 CFR 197.4	Aggregated annual dose to an individual during normal operations including storage, and Category 1 event sequences, is limited to ≤ 15 mrem/yr.	• Off-site dose (caused by release of radioactive material) is not considered credible for normal and off-normal DBD operations (unless one or more waste packages is breached downhole, for which recovery operations could result in releases, but which is beyond the scope of this assessment). • Storage of waste on-site is not planned for DBD (see Section 4).
	10 CFR 60.111(a) 40 CFR 191.03(a)	Annual dose to any member of the public in the general environment limited to: • ≤ 25 mrem/yr to the whole body, and • ≤ 75 mrem/yr to the thyroid, and • ≤ 25 mrem/yr to any other critical organ.	
Pre-Closure Design Objectives	10 CFR 63.111(b)(2)	Taking into consideration a single Category 2 event sequence (i.e., at least one chance in 10,000 of occurring before permanent closure) off-site dose (on or beyond the site boundary) is as specified above for on-site worker dose.	Addressed by conceptual design activities described in this assessment.

Hazard or Performance Objective	Regulatory Reference	Requirement	Treatment in This Study
Preclosure Performance Objectives for the GROA	10 CFR 63.111 10 CFR 63.112 10 CFR 63.204	• Design of, and operations in the GROA must meet 10 CFR 20. • Preclosure safety analysis. A preclosure safety analysis of the GROA that meets the requirements specified at 63.112 must be performed. • Performance confirmation requirements from Part 63, Subpart F. • Waste retrievability requirements from 63.111(e)(1).	• Treatment of radiological hazards is limited to qualitative consideration of radiation exposure, as identified above. • PCSA requirements are addressed later in this report. • Performance confirmation is beyond the scope of this study. • Application of retrievability requirements to DBD and the DBFT is to-be-determined (SNL 2016, TBD-39).
Standards	40 CFR 191.03	Management and storage of spent nuclear fuel or high-level or transuranic radioactive wastes at all facilities regulated by the Commission or by Agreement States shall be conducted ... to provide reasonable assurance that the combined annual dose equivalent to any member of the public in the general environment resulting from: (1) discharges of radioactive material and direct radiation from such management and storage and (2) all operations covered by Part 190; shall not exceed 25 mrem to the whole body, 75 mrem to the thyroid, and 25 mrem to any other critical organ.	• The requirement stated to the left is that which would apply if the U.S. Nuclear Regulatory Commission regulated DBD. The applicability of regulatory requirements for DBD (and the DBFT) is to-be-determined (SNL 2016, TBD-01). • Off-site dose (caused by release of radioactive material) is not considered credible for normal and off-normal DBD operations, as identified above.

* TEDE = Total effective dose equivalent (the sum of the effective dose equivalent, for external exposures, and the committed effective dose equivalent, for internal exposures). ALARA = As low as reasonably achievable (10 CFR 20.1003).

Table 2. GROA design criteria from repository regulations.

Design Criteria	Treatment in This Study
10 CFR 60.131 – General design criteria for the geologic repository operations area.	
(a) Radiological protection. The GROA shall be designed to maintain radiation doses, levels, and concentrations of radioactive material in air in restricted areas within the limits specified in part 20 of this chapter. Design shall include: (1) Means to limit concentrations of radioactive material in air; (2) Means to limit the time required to perform work in the vicinity of radioactive materials, including, as appropriate, designing equipment for ease of repair and replacement and providing adequate space for ease of operation; (3) Suitable shielding; (4) Means to monitor and control the dispersal of radioactive contamination; (5) Means to control access to high radiation areas or airborne radioactivity areas; and (6) A radiation alarm system to warn of significant increases in radiation levels, concentrations of radioactive material in air, and of increased radioactivity released in effluents. The alarm system shall be designed with provisions for calibration and for testing its operability.	• Qualitative, judgment-based ALARA treatment for normal and off-normal operations. • Review will identify, where appropriate, design features and procedural steps to limit worker exposure. • Shielding is included in the conceptual design, and may be supplemented (SNL 2016; TBD-37). • Access control and monitoring of radiation in work areas, and monitoring for radioactive contamination, with alarms, are assumed (see Section 4). • Measures to control dispersal of radioactive contamination, should it occur, will be considered.
60.131 (b) Protection against design basis events. The structures, systems, and components important to safety shall be designed so that they will perform their necessary safety functions, assuming occurrence of design basis events.	• Design basis earthquake ground motion will be assumed (see Section 4) and incorporated in the safety assessment. • Extreme weather (wind, lightning) will be assumed; procedural controls and design features will be considered for mitigation.
60.131 (c) Protection against dynamic effects of equipment failure and similar events. The structures, systems, and components important to safety shall be designed to withstand dynamic effects such as missile impacts, that could result from equipment failure, and similar events and conditions that could lead to loss of their safety functions.	Any use of equipment with stored energy sufficient to cause damage that could potentially lead to radiological consequences (aside from local fire), will be identified and evaluated.

Design Criteria	Treatment in This Study
60.131 (d) Protection against fires and explosions. (1) The structures, systems, and components important to safety shall be designed to perform their safety functions during and after credible fires or explosions in the geologic repository operations area. (2) To the extent practicable, the GROA shall be designed to incorporate the use of noncombustible and heat resistant materials. (3) The GROA shall be designed to include explosion and fire detection alarm systems and appropriate suppression systems with sufficient capacity and capability to reduce the adverse effects of fires and explosions on structures, systems, and components important to safety. (4) The GROA shall be designed to include means to protect systems, structures, and components important to safety against the adverse effects of either the operation or failure of the fire suppression systems.	• The potential for explosions will be evaluated. • Casks will be designed to maintain shielding functions in the event of credible fires in the GROA. • Materials used in the GROA will be noncombustible except as identified and evaluated in this study. • Explosion and/or fire alarms will be included in the conceptual design. • Fire suppression systems will be included, and evaluated for impact in the event of operation or failure to operate.
60.131 (e) Emergency capability. (1) The structures, systems, and components important to safety shall be designed to maintain control of radioactive waste and radioactive effluents, and permit prompt termination of operations and evacuation of personnel during an emergency. (2) The GROA shall be designed to include onsite facilities and services that ensure a safe and timely response to emergency conditions and that facilitate the use of available offsite services (such as fire, police, medical, and ambulance service) that may aid in recovery from emergencies.	Responses to emergencies will be evaluated, including types of credible events (fire, weather, accident), and measures to ensure that operations can be safely terminated and personnel evacuated.

Design Criteria	Treatment in This Study
60.131 (f) Utility services. (1) Each utility service system that is important to safety shall be designed so that essential safety functions can be performed, assuming occurrence of the design basis events. (2) The utility services important to safety shall include redundant systems to the extent necessary to maintain, with adequate capacity, the ability to perform their safety functions. (3) Provisions shall be made so that, if there is a loss of the primary electric power source or circuit, reliable and timely emergency power can be provided to instruments, utility service systems, and operating systems, including alarm systems, important to safety.	• Safety functions of utility systems such as electrical power will be identified and evaluated, including the need for redundant systems. • Recovery from loss of electrical power will be described and any associated safety equipment identified.
60.131 (g) Inspection, testing, and maintenance. The structures, systems, and components important to safety shall be designed to permit periodic inspection, testing, and maintenance, as necessary, to ensure their continued functioning and readiness.	Means to inspect and maintain all equipment, especially that which functions in radiation areas, will be specified.
60.131 (h) Criticality control. All systems for processing, transporting, handling, storage, retrieval, emplacement, and isolation of radioactive waste shall be designed to ensure that nuclear criticality is not possible unless at least two unlikely, independent, and concurrent or sequential changes have occurred in the conditions essential to nuclear criticality safety. Each system must be designed for criticality safety assuming occurrence of design basis events. The calculated effective multiplication factor (k_{eff}) must be sufficiently below unity to show at least a 5 percent margin, after allowance for the bias in the method of calculation and the uncertainty in the experiments used to validate the method of calculation.	Waste types considered in this analysis do not include fissile materials in sufficient quantities for criticality to be credible (SNL 2016; TBD-23).
60.131 (i) Instrumentation and control systems. The design shall include provisions for instrumentation and control systems to monitor and control the behavior of systems important to safety, assuming occurrence of design basis events.	The system for handling, transferring and emplacing waste packages in a deep borehole will include functional safety (interlock) components. The need for interlocks will be developed in the fault tree analysis (where human error is explicitly considered).
60.131 (j) Compliance with mining regulations. To the extent that DOE is not subject to the Federal Mine Safety and Health Act of 1977, as to the construction and operation of the GROA, the design of the GROA shall nevertheless include provisions for worker protection necessary to provide reasonable assurance that all structures, systems,	Mining regulations do not apply to deep borehole operations.

Design Criteria	Treatment in This Study
and components important to safety can perform their intended functions. Any deviation from relevant design requirements in 30 CFR, chapter I, subchapters D, E, and N will give rise to a rebuttable presumption that this requirement has not been met.	
60.131 (k) Shaft conveyances used in radioactive waste handling. (1) Hoists important to safety shall be designed to preclude cage free fall. (2) Hoists important to safety shall be designed with a reliable cage location system. (3) Loading and unloading systems for hoists important to safety shall be designed with a reliable system of interlocks that will fail safely upon malfunction. (4) Hoists important to safety shall be designed to include two independent indicators to indicate when waste packages are in place and ready for transfer.	• Shaft conveyances will not be used in DBD operations. • Standard wireline hoists will be used, with tool configurations to provide indications (SNL 2016; TBD-21). • Inherent safety features of the DBD emplacement system will limit radiological consequences in the event of hoist failure (analysis of dropped packages in SNL 2016).
10 CFR 60.132 – Additional design criteria for surface facilities in the geologic repository operations area.	
60.132 (a) Facilities for receipt and retrieval of waste. Surface facilities in the GROA shall be designed to allow safe handling and storage of wastes at the geologic repository operations area, whether these wastes are on the surface before emplacement or as a result of retrieval from the underground facility.	This requirement is directly addressed in the conceptual design.
60.132 (b) Surface facility ventilation. Surface facility ventilation systems supporting waste transfer, inspection, decontamination, processing, or packaging shall be designed to provide protection against radiation exposures and offsite releases as provided in 60.111(a).	Surface facilities of types requiring ventilation are not included in the conceptual design.

Design Criteria	Treatment in This Study
60.132 (c) Radiation control and monitoring: (1) Effluent control. The surface facilities shall be designed to control the release of radioactive materials in effluents during Category 1 design basis events so as to meet the performance objectives of 60.111(a). (2) Effluent monitoring. The effluent monitoring systems shall be designed to measure the amount and concentration of radionuclides in any effluent with sufficient precision to determine whether releases conform to the design requirement for effluent control. The monitoring systems shall be designed to include alarms that can be periodically tested.	Effluents (other than internal combustion exhaust) will not be generated by DBD normal operations, and Category 1 events (that do not include release of radioactive material).
60.132 (d) Waste treatment. Radioactive waste treatment facilities shall be designed to process any radioactive wastes generated at the GROA into a form suitable to permit safe disposal at the GROA or to permit safe transportation and conversion to a form suitable for disposal at an alternative site in accordance with any regulations that are applicable.	Radioactive waste will not be generated by DBD normal operations or Category 1 events.
60.132 (e) Consideration of decommissioning. The surface facility shall be designed to facilitate decontamination or dismantlement to the same extent as would be required, under other parts of this chapter, with respect to equivalent activities licensed thereunder.	Consideration of final decommissioning of disposal boreholes, and surface operations, is part of the DBD concept.
10 CFR 60.133 – Additional design criteria for the underground facility [only parts most relevant to DBD are listed].	
(a) General criteria for the underground facility. (1) The orientation, geometry, layout, and depth of the underground facility, and the design of any engineered barriers that are part of the underground facility shall contribute to the containment and isolation of radionuclides. (2) The underground facility shall be designed so that the effects of credible disruptive events during the period of operations, such as flooding, fires and explosions, will not spread through the facility.	• Borehole verticality and dogleg severity are addressed in the conceptual design (SNL 2016; TBD-10 and -11). • Consequences of radioactive material release in the borehole (waste package breach) are addressed.
(c) Retrieval of waste. The underground facility shall be designed to permit retrieval of waste in accordance with the performance objectives of 60.111.	Retrieval requirements for borehole disposal are to-be-determined (SNL 2016; TBD-39).

Design Criteria	Treatment in This Study
(h) Engineered barriers. Engineered barriers shall be designed to assist the geologic setting in meeting the performance objectives for the period following permanent closure.	Engineered barriers consisting of borehole plugs and seals are included in the conceptual design, but specifics are to-be-determined (SNL 2016; TBD-46).
(i) Thermal loads. The underground facility shall be designed so that the performance objectives will be met taking into account the predicted thermal and thermomechanical response of the host rock, and surrounding strata, groundwater system.	Thermal analysis supports the conceptual design (SNL 2015, 2016), and the downhole structures and waste packaging will function within specified temperature limits.
10 CFR 60.134 – Design of seals for shafts and boreholes.	
(a) *General design criterion*. Seals for shafts and boreholes shall be designed so that following permanent closure they do not become pathways that compromise the geologic repository's ability to meet the performance objectives or the period following permanent closure.	Borehole plugs and seals are included in the conceptual design, but specifics are to-be-determined (SNL 2016; TBD-46).
(b) *Selection of materials and placement methods*. Materials and placement methods for seals shall be selected to reduce, to the extent practicable: (1) The potential for creating a preferential pathway for groundwater to contact the waste packages or (2) For radionuclide migration through existing pathways.	These criteria have been used for conceptual design of borehole plugs and seals (e.g., see Arnold et al. 2011).
10 CFR 60.135 – Criteria for the waste package and its components (only parts most relevant to DBD are listed).	
• (a) High-level-waste package design in general • (1) Packages for HLW shall be designed so that the in situ chemical, physical, and nuclear properties of the waste package and its interactions with the emplacement environment do not compromise the function of the waste packages or the performance of the underground facility or the geologic setting. • (2) The design shall include but not be limited to consideration of the following factors: solubility, oxidation/reduction reactions, corrosion, hydriding, gas generation, thermal effects, mechanical strength, mechanical stress, radiolysis, radiation damage, radionuclide retardation, leaching, fire and explosion hazards, thermal loads, and synergistic interactions.	• Waste packages will be designed to provide containment in the borehole environment, with margin for unexpected conditions. Requirements include weight of stacked packages, hydrostatic pressure, downhole temperature, and containment longevity to corrosion (including radiolysis). Specifics of design features are to-be-determined (SNL 2016; TBD-12, -13, -14, -15, -17, -18, -19, -27, -32, -40, 41, and -48). • Gas generation by corroding ferrous materials is addressed in the conceptual design but aspects such as final material selection for DBD are to-be-determined (SNL 2016; TBD-43). • Fire and explosion hazards in the borehole environment are not credible.
10 CFR 60.136 – Preclosure controlled area.	
(a) A preclosure controlled area must be established for the GROA.	A controlled area boundary is assumed (see Section 4) but is not critical to the analysis because it is generic (non-site specific), and because release and dispersal of radioactive material are not credible.

Design Criteria	Treatment in This Study
(b) The GROA shall be designed so that, for Category 2 design basis events, no individual located on or beyond any point on the boundary of the preclosure controlled area will receive the more limiting of a total effective dose equivalent of 0.05 Sv (5 rem), or the sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue (other than the lens of the eye) of 0.5 Sv (50 rem). The eye dose equivalent shall not exceed 0.15 Sv (15 rem), and the shallow dose equivalent to skin shall not exceed 0.5 Sv (50 rem). The minimum distance from the surface facilities in the GROA to the boundary of the preclosure controlled area must be at least 100 meters.	This requirement is important to DBD only if the design basis Category 2 event causes waste package breach at the surface, and release of radioactive material. That outcome is judged to be not credible because of the extreme robustness of DBD waste packages, based on the finite element analysis provided in this report.
(c) The preclosure controlled area may be traversed by a highway, railroad, or waterway, so long as appropriate and effective arrangements are made to control traffic and to protect public health and safety.	Protection of the public using highways, etc., is addressed by assumption (see Section 4) but is not critical to the analysis because it is generic (non-site specific).

The full extent of pre-closure safety analysis for deep geologic disposal of nuclear waste following 10CFR63.112 (and related parts, and a review plan such as NUREG-1804), is not practical or necessary for developing a generic conceptual design for the DBFT. This analysis is intended to identify risk mitigation measures for incorporation in the design, and to characterize but not necessarily quantify the various risks from disposal operations. This important distinction moderates the scope of events that must be considered, and the effort needed to quantify probabilities and analyze fragility for affected systems, structures and components (SSCs). This analysis does develop a preliminary list of SSCs that would be relied on to assure safe operations and could therefore be categorized as important to safety (ITS).

A companion report (*Hazard Analysis for Radiological Risk Assessment of Deep Borehole disposal Operations*, SFWD-SFWST-2017-000109) will analyze deep borehole disposal operations stepwise, to identify hazards and event sequences. Both reports will be contributions to the broader scope of *Pre-Closure Safety Analysis for Deep Borehole Disposal* (SFWD-SFWST-2017-000010).

2. Overview of DBD Concept of Operations

The following information is excerpted from SNL (2016), the current source for conceptual design of DBD packaging and emplacement systems (the description is written in the indicative rather than subjunctive mood, for clarity).

Waste forms to be considered for disposal are granular high-level waste (HLW) materials, including those in sealed capsules. Packages will be heavy-walled metal vessels having fill ports with redundant closures, designed to resist the external fluid pressure at the bottom of a 5-km disposal borehole. Suitable materials, connections, closures, impact limiters, and fabrication services are available from vendors to the oil-and-gas industry. The heavy construction of waste packages (WPs) will give them significant resistance to damage from accidental drops during surface handling (Appendix A). Packages will be filled with waste and sealed before transport to the borehole disposal site. They will weigh up to approximately 2.1 MT depending on the borehole size (up to 17-inch diameter) and the waste form contained.

Borehole drilling and construction will be based on currently available technology. The goal will be to achieve total depth with the maximum diameter that can be completed with reasonable certainty in the emplacement zone (EZ) at depths up to approximately 5 km. The final stage in borehole construction will be to hang a guidance casing of constant diameter, over the full length of the borehole, in two pieces. The lower piece will permanently line the EZ, while the upper piece (tieback) will be removable for final plugging/sealing. Wireline emplacement will be used for WPs based on consideration of safety and cost (SNL 2016). Wireline emplacement is made more attractive by the availability of modern wireline cable and equipment, and the use of impact limiters at the bottom of every waste package.

The disposal system will include surface equipment to receive one WP at a time in a truck-transportation cask, transfer the WP to a double-ended transfer cask, position the transfer cask over a disposal borehole, and lower the WP on a wireline, emplacing it at depth. The concept was developed (SNL 2016) assuming availability of the NAC LWT® Type B transportation cask (or equivalent). The purpose-built transfer cask must be double-ended (operable openings at both ends) in order to lower packages into the borehole. The transfer cask, wellhead (the top of the borehole), and associated components are required to serve together as part of the pressure envelope for well control, i.e., to contain an unlikely pressure "kick" during operations, as a safety measure. To this end, the concept meets the engineering challenge of removing a shield plug at the bottom of the transfer cask and then attaching the open cask to the wellhead, using remotely operated equipment.

The operational sequence will begin with placing the transportation cask containing a WP into a cradle at ground level. The transfer cask will be placed in another cradle, with the cradles arranged end-to-end. A sliding plate shield between them will allow for removal or replacement of shield plugs from the cask ends, and for pulling or pushing a waste package from one cask to the other.

At this stage of WP handling and emplacement operations, a special suite of wireline logs will be run to qualify the borehole (e.g., an acoustic casing-caliper, radiation detector, and a gauge ring with a junk basket).

The transfer cask containing the WP, with the lower shield plug installed, will be hoisted into a vertical position over the borehole and lowered onto the top surface of a shielded enclosure around the wellhead. The top of the enclosure will consist of a shield plate, with a large (e.g., 3 m diameter) circular plate insert or "carousel" that turns to locate the cask over tool stations below, or directly over the wellhead (see SNL 2016, Section 3 for illustrations).

Below the carousel, the shielded "pit" will contain: 1) the wellhead (with remotely operated valves, fittings for fluid control, annular blowout preventer, and a flange for attaching the transfer cask); 2) remotely operated equipment to remove or replace the lower shield plug from the transfer cask; 3) a remotely operated actuator to make/unmake the wellhead flange connection; and 4) a sump for collecting spilled borehole fluid and draining wash down water. Once the transfer cask is fixed to the wellhead flange, the cask and associated hardware will be part of the pressure envelope for well control, so that any unexpected pressure transients encountered during emplacement operations would not necessarily require actuation of a blowout preventer. Details of the shield plate, carousel, pit, transfer cask attachment, the wireline interface at the top of the transfer cask, and provisions to access the borehole for plugging, sealing, and WP fishing, are provided by SNL (2016).

The WP will be supported by side latches in the transfer cask at all times when it is mounted on the carousel or attached to the wellhead, before a secure wireline connection has been established, as a backup so that a single component failure or human error cannot cause a WP to drop into the wellhead or borehole.

The wireline system will include a headframe (approximately 20 m tall) with sheaves, wireline cable, winch, a cable head, and a downhole tool string that includes an electromechanical release and logging tools for location, tool weight, and other downhole monitoring functions. The release mechanism will be designed with the capability to re-latch a WP in case retrieval is required.

For emplacement, the WP will be supported by the wireline, the borehole valve opened, and the side latches released so the package can be lowered into the borehole. The electromechanical release will be actuated once the WP is landed on the bottom. Each WP will have an impact limiter attached at the bottom to prevent damage if the package is accidentally dropped in the borehole. A latch and fishing neck will be attached at the top. Wireline retrieval of individual WPs can be done by reversing the steps and hoisting the WP back into the transfer cask.

The WP descent rate during wireline emplacement will be about 0.15 m/sec for the first kilometer, to control load transients that could break the wireline, then 0.6 m/sec thereafter (SNL 2016, Section 2.9.3). After releasing the WP, the wireline and tool string will be hoisted out of the borehole with an ascent rate of approximately 1 m/sec. Once the tool string is back in the transfer cask, the wellhead valve will be closed, and the transfer cask and tool string will be moved to a wash-down area for cleaning, inspection, and preparation for the next use.

Waste packages will be emplaced individually and stacked one on top of the other. They will be designed to provide containment throughout the emplacement phase and plugging/sealing of the borehole, to avoid radioactive contamination of borehole fluid during operations.

The reference disposal concept calls for 10-m cement plugs within the guidance casing, spaced about 200 m apart in the EZ (SNL 2016, Section 3.1). Cement plug installation is therefore part of emplacement operations, and will be done using wireline tools and coiled-tubing. A squeeze cement method with casing perforations is recommended (SNL 2016, Option 2) for bonding the guidance casing to the host rock, to stabilize the guidance casing and support the weight of stacked WPs. Once all WPs are emplaced, a drilling or workover rig would be moved in for final plugging/sealing of the borehole.

This study will assess radiological risk for all activities associated with WP receipt, handling, emplacement, and setting of cement plugs. Final plugging/sealing activities under normal conditions will not involve radioactive materials or the potential for radiation exposures, and are therefore beyond the scope of this study.

3. Risk Analysis Methodology

Selection of Fault Tree/Event Tree Analysis

Quantitative PRA is regarded among the most suitable methods for developing full understanding of process risks and appropriate measures to prevent or mitigate them (Milstein 2001). The fault tree/event tree implementation of PRA is also considered to be one of the best methods for analyzing multiple-failure sequences. Other documented methodologies that are comparable to PRA include:

- Hazard and Operability Analysis (HAZOP)
- Failure Modes and Effects Analysis (FMEA)
- Human Reliability Analysis (HRA)

HAZOP and FMEA are more structured than other alternatives. HAZOP is well suited for identification of failure modes and initiating events, while FMEA is typically used for system-level treatment that begins with failure modes. HAZOP focuses on "process upset conditions," while FMEA focuses on "failure of equipment and components" (Milstein 2001). The structure built into these methodologies is challenging to implement for conceptual design, given limited detail (without explicit specifications, engineering drawings, procedures, etc.).

The fault tree/event tree PRA approach can be implemented at a more general level while still providing useful design insights (e.g., SNL 2016, Appendix A). Both inductive and deductive approaches can be used (a deductive approach is described below for this study). For the present study, unlike the previous DBFT design selection study (SNL 2016), radiological consequences need to be considered rather than cost. Other hazards are also considered to determine if they affect radiological risk, including flammable materials, toxic materials, potential hazardous process conditions, and external hazards. The analysis will rely on engineering judgment to determine whether an initiating event, or subsequent events in a sequence, will lead to consequences of concern (Milstein 2001).

Where compartmentalization of systems (into subsystems) is used to simplify the analysis of risk, the effect of a particular hazard should be followed by consideration of the resulting effects on or contributions from other subsystems (Ma et al. 1992). For example, off-normal events during emplacement of waste packages could potentially degrade processes used to retrieve them. In addition, each hazard should be correlated to other hazards to evaluate the likelihood, and if appropriate, the consequences of joint occurrence (see Section 3.2). Finally, the interfaces between subsystems require clearly defined boundaries and similar levels of descriptive detail ("level of resolution") so that inconsistencies can be recognized (Vesely et al. 1981).

Recommended Methodology (Internal Initiating Events)

The methodology for examination of DBD concept performance should be modeled on 10 CFR 63, because that rule (and 10 CFR 60) is a modern approach deemed appropriate by the U.S. Nuclear Regulatory Commission (NRC) for licensing nuclear waste disposal facilities. These regulations do not actually prescribe a methodology, but they specify event probability levels of significance, which requires a PRA approach. The only real-world application of these regulations for preclosure operational safety is found in the Yucca Mountain Safety Analysis Report (SAR; DOE 2008), and the complementary Safety Evaluation Report (NRC 2015).

Simplifications to the approach used for the Yucca Mountain license application are warranted for this assessment because:

- The present assessment is generic (non-site specific) so certain information is not available and must be assumed, such as site characteristics that control dispersal of released radioactive material.
- The purpose of the present assessment is to evaluate the current conceptual design (limited to system description that is mostly qualitative).
- The waste inventory is not significantly fissile.
- Operations will be outdoor with no enclosed structures or confinement systems.
- Radionuclide releases from cask drops, including those caused by external events (e.g., seismic, extreme weather) will not result in loss of containment (see Section 4 and Appendix A).
- The potential for dropping a WP outside of a protective cask, is limited.

The recommended approach follows that used for the Receipt Facility described for the Yucca Mountain repository (BSC 2008a). It involves construction of the following products:

- Process flow diagram (PFD) – Describes the SSCs associated with normal operations. A preliminary PFD for DBD operations is shown in Figure 1. The nodal arrangement suggests a way to compartmentalize the lifts, transfers, and other operations for simplification and to find common elements.
- Master logic diagram (MLD) – Top-down structure showing what initiating events, or groups of similar initiating events, could contribute to radiological consequences. A preliminary MLD for DBD operations is shown in Figure 2 (on multiple pages), and descriptions for the MLD levels are provided in Table 3.
- HAZOP evaluation - Performed specifically to check that a full range of potentially important initiating events has been identified in the MLD. HAZOP evaluation generally addresses deviations at a lower level of detail than the MLD, but the higher level of the MLD is more appropriate for the PRA approach. Example HAZOP parameters and

deviations are presented in Table 4. Results of HAZOP analysis for DBD are presented by Peretz and Hardin (2017).

- Event sequence diagrams (ESDs) – Associate initiating events singly or in groups, with the response characteristics of the system that could allow radiological consequences, or mitigate them. A preliminary set of ESDs for DBD operations is shown in Figure 3 (on multiple pages). The ESD is a shorthand representation that will be used to summarize and inform the event trees developed for this study. ESDs show contributing initiating events, aggregated into a single event category, and the system response. Each pivotal event in the system response can be quantified using probabilities developed by analysis such as reliability or fragility.

Four end states of system response are possible for DBD operations, consistent with the approach of BSC (2008a) but without facility ventilation (HVAC confinement) or the possibility of criticality:

- OK (normal operations)
- Degraded shielding, direct exposure – Applies to event sequences where 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.
- Loss of shielding, direct exposure – 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.
- Radionuclide release (unfiltered) – Indicates a release of radioactive material from its confinement, through an unfiltered path, to the environment.

The present study is intended to provide insights that improve the conceptual design for DBD, and not to estimate radiological exposure or dose for comparison to regulatory limits (Table 1). Accordingly, consequence analysis will be abstracted in a way that assigns relative levels of possible exposure or dose without quantification (e.g., as dose categories A, B, etc.).

Initiating events will include internal events that are initiated within the WP receipt/handling/ emplacement system, and external events (seismic, extreme weather, external fire). Selection of internal and external events is addressed further in Section 4. Initiating events identified on the MLD will be correlated to evaluate the likelihood, and if appropriate, the potential consequences of joint occurrence.

Initiating events that are associated with conditions introduced in SSCs before they reach the site (e.g., drops of casks) or during cask or canister manufacture, are not within scope of the analysis.

The probability for each independent initiating event will be quantified using a fault tree. Fault trees are structured as having a top, undesirable event that is made up of casual events and basic events (basic events can be equipment malfunctions, human errors, etc.). Fault trees use logic and basic event probabilities to determine the top, undesirable event probability. Fault trees are also advantageous as they can identify probable significant events that may lead to a system failure.

The consequence of each failed end state (with contributing initiating events) is represented by the system response side of the ESDs. Fragility analyses such as that in Appendix A can be used where appropriate to quantify radiological consequences, and to inform pivotal logic events that may be defined between initiation and final consequence. Pivotal events in system response are identified only in the preliminary ESDs for failed states F, G, J and D2 (Figure 3, sheets 1, 2, 5 and 7 respectively). These all correspond to the state of WP containment integrity, in the case of cask damage and loss of containment.

Safety Functions of Support Equipment

We note that the treatment given to failed states and initiating events in this preliminary description of the risk assessment methodology, has not explicitly included the reliability of some key components of the system for WP receipt/handling/emplacement, such as the crane, headframe, hoist, generator, and wireline equipment (Section 2, and SNL 2016). The reliability and consequences of failure for such components is assumed (Section 4). For example, mechanical breakdown or malfunction of the crane, generator, or wireline equipment is not included in the MLD (Figure 2). Thus, backup or mitigating capabilities for these components are assumed, so that resulting cask drops and collisions, and falling or toppling objects, do not result in consequences that need to be considered explicitly in the analysis. Assumptions on reliability of supporting equipment may be carried forward as design criteria, or they may be incorporated explicitly in the risk assessment if design is unlikely to provide the assumed level of reliability.

Fragility Analysis

The level of detail in system response modeling depends on fragility analysis. For example, the analysis in Appendix A addresses the likelihood of WP breach in the event of a drop, whether or not cask containment (and by inference, cask shielding integrity) is maintained. Beyond this study of consequence types, fragility analysis is not the focus of this assessment because of the generic, conceptual nature. Rather, this study is expected to assign design criteria to SSCs and to identify those SSCs likely to be important to safety in a DBD PCSA.

Method Summary (Internal Initiating Events)

Once the fault trees, top events, failed states, and system responses are assessed, the PRA is implemented as follows:

- I1. Identify failed end states (loss of shielding, etc.) and initiating events.
- I2. Construct fault trees for internal initiating events ("top events"):
  - Include human errors and functional safety system (e.g., interlock) failures.
  - Include prevention and mitigation measures.
  - Estimate basic event probabilities and quantify top event probabilities.
- I3. Assess system responses (worker exposures resulting from failed end states; see discussion on qualitative description of consequences).
- I4. Identify SSCs relied upon to limit consequences (potentially important to safety).
- I5. Construct event trees and sum probabilities for all outcomes.

SSCs that mitigate or prevent initiating events may be designated important to safety (ITS), for event sequences that are credible and result from Category 1 or 2 events as defined by regulation (Table 1). ITS designations are used for emphasis in design, licensing review, construction or procurement, and operation of SSCs. ITS designations are one of the important outcomes of

PCSA (BSC 2008b), but are of lesser importance for the present study (which is intended to generate insights for improvement of the design, and will not support licensing).

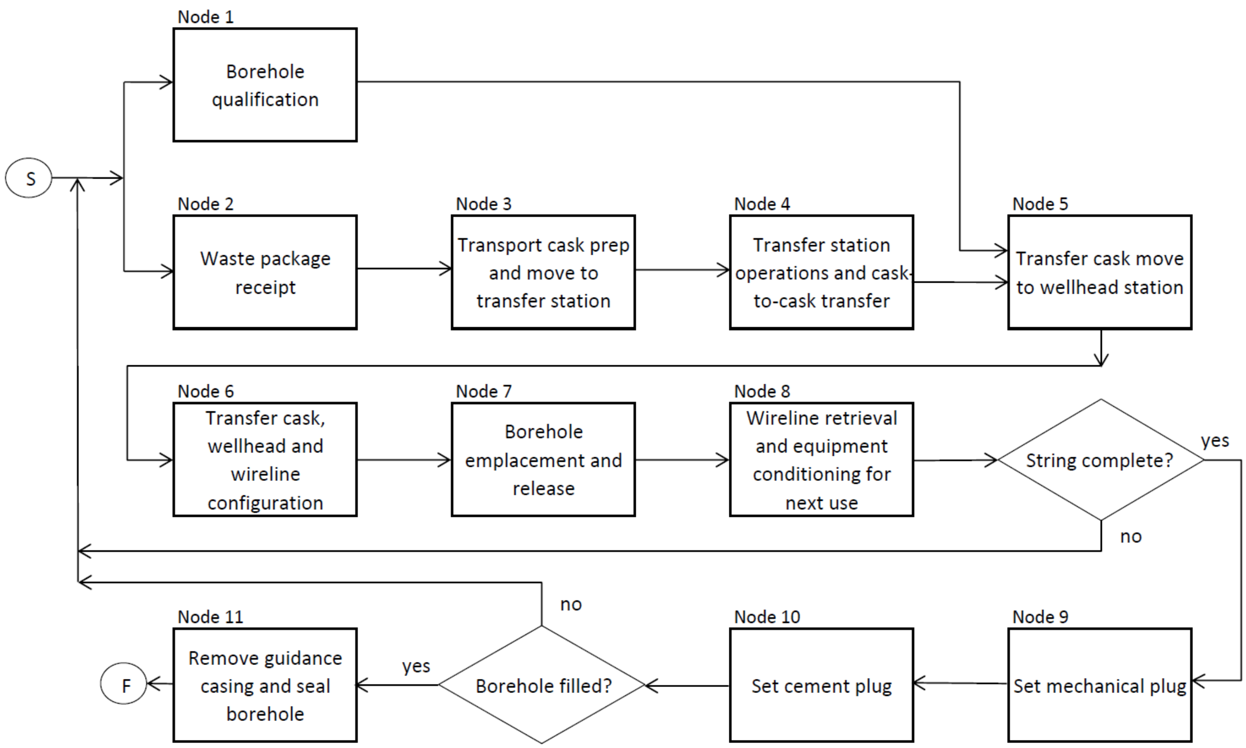


Figure 1. Preliminary process flow diagram (see Peretz and Hardin 2017 for changes).

Table 3. Master logic diagram level descriptions (based on BSC 2008a).

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. 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., seismic ground motion). 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 where the initiating events can occur.
Level 3	This level identifies the exposure pathways of concern for the operational areas identified in Level 2.
Level 4	This level identifies the specific operational activities to be evaluated.
Level 5	This level specifies the initiating event that can result in the failure in the specified operational activity (i.e., the actual deviations from successful operation that could lead to the exposure type). Level 5 is considered the appropriate grouping of initiating events for purposes of subsequent fault tree analysis.
Level 6	This level provides a short list of examples (one or two) to help elucidate the interpretation of the Level 5 initiating event group. 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.

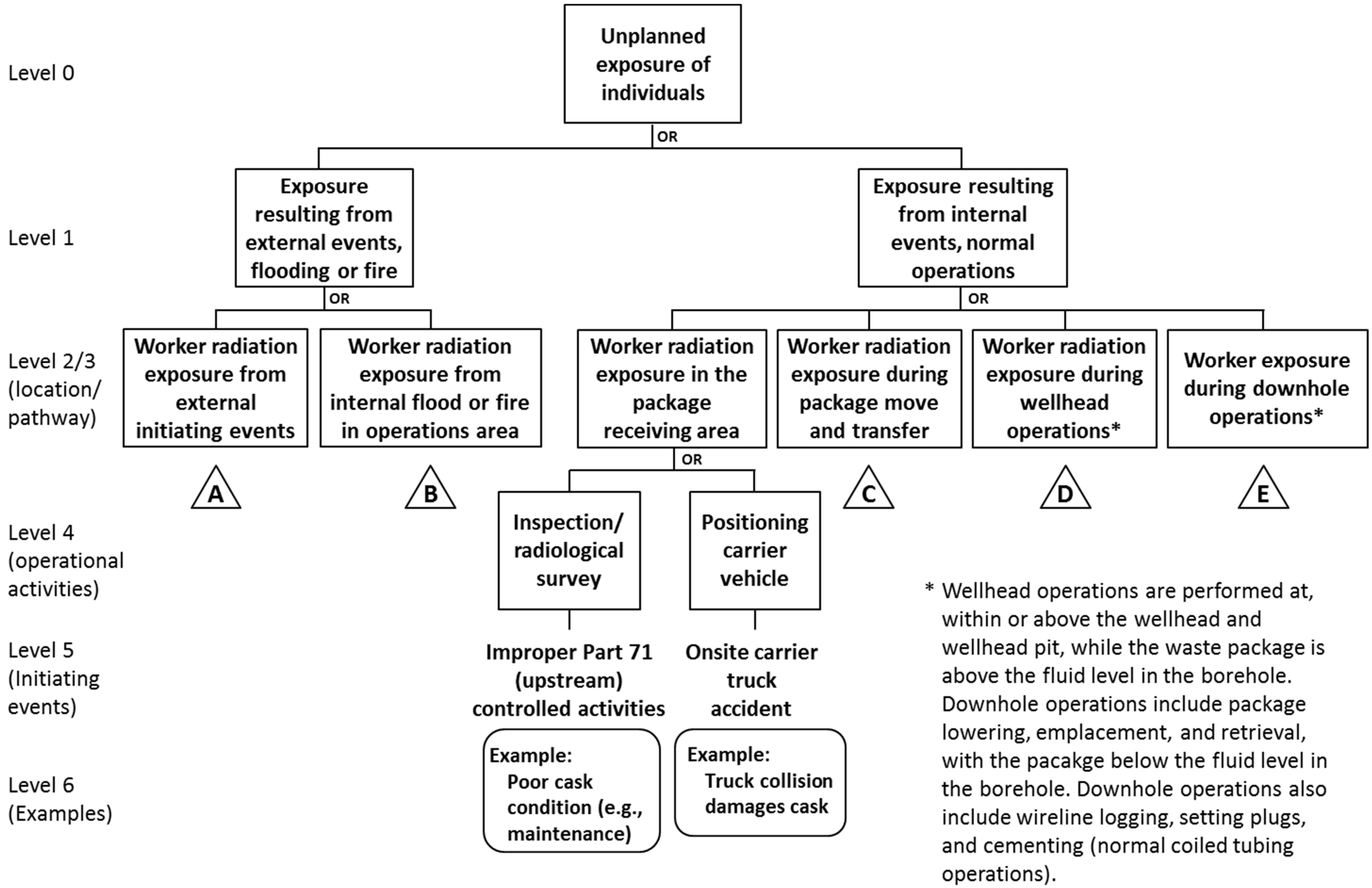


Figure 2. Preliminary master logic diagram for DBD operations (sheet 1 of 8).

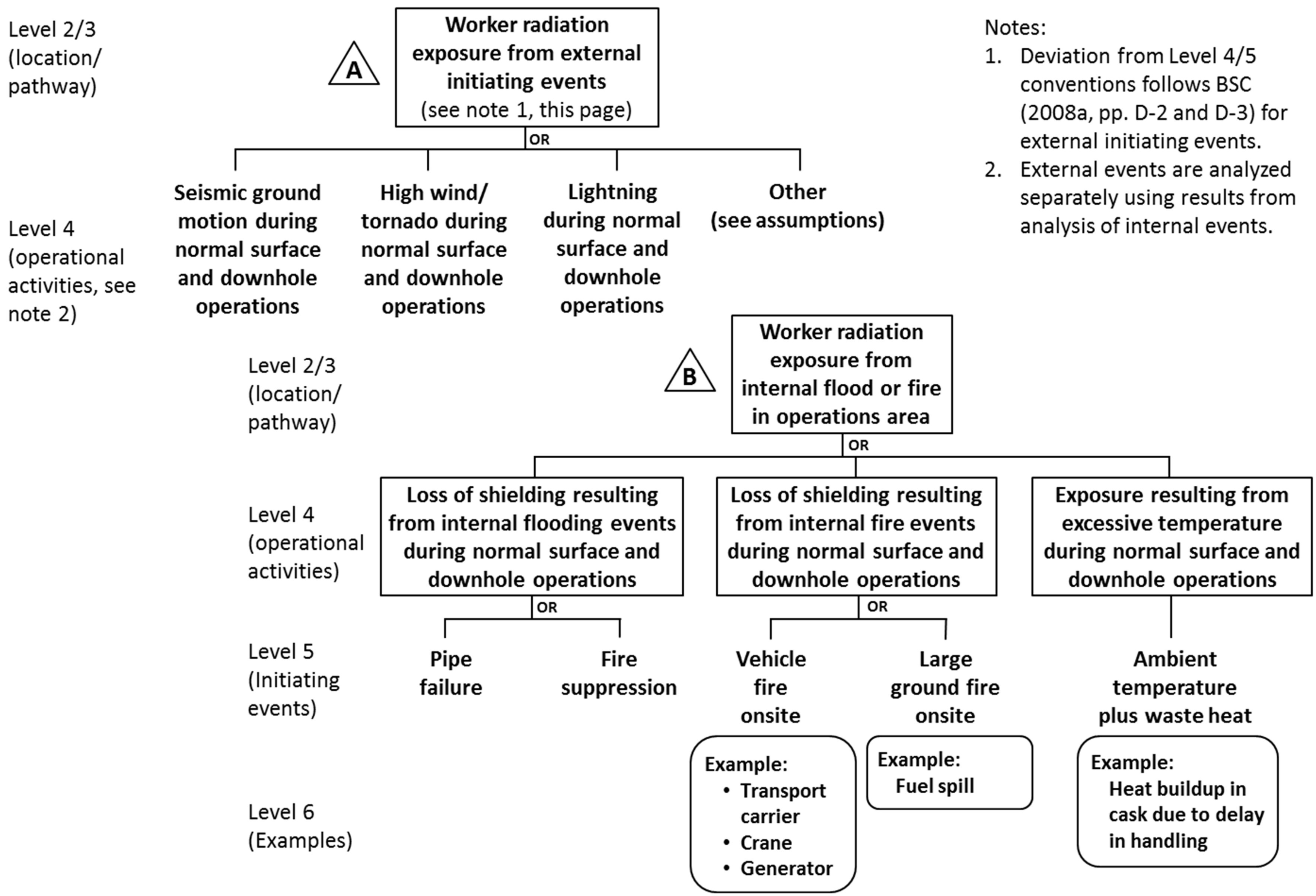


Figure 2. Preliminary master logic diagram for DBD operations, continued (sheet 2 of 8).

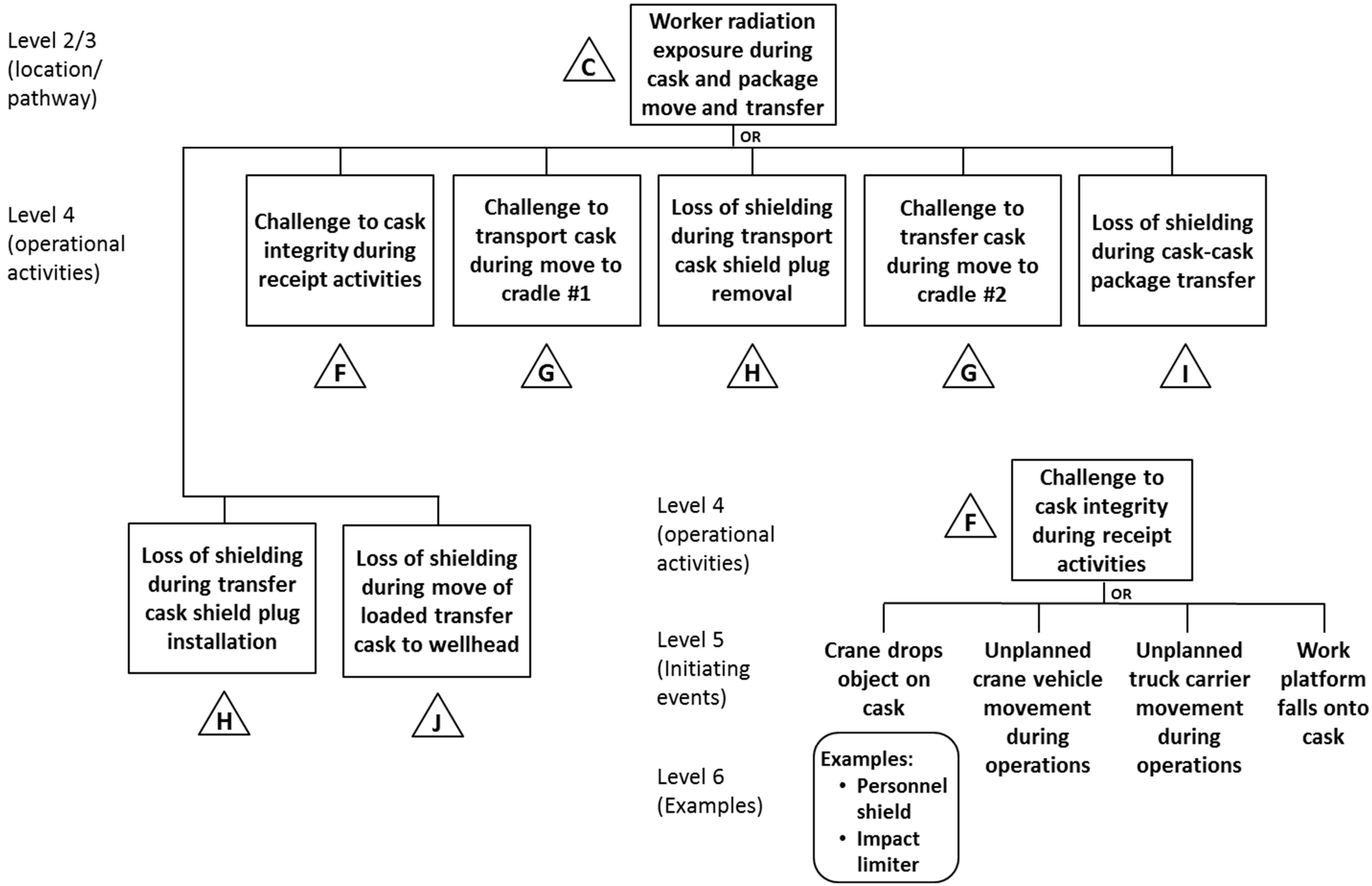


Figure 2. Preliminary master logic diagram for DBD operations, continued (sheet 3 of 8).

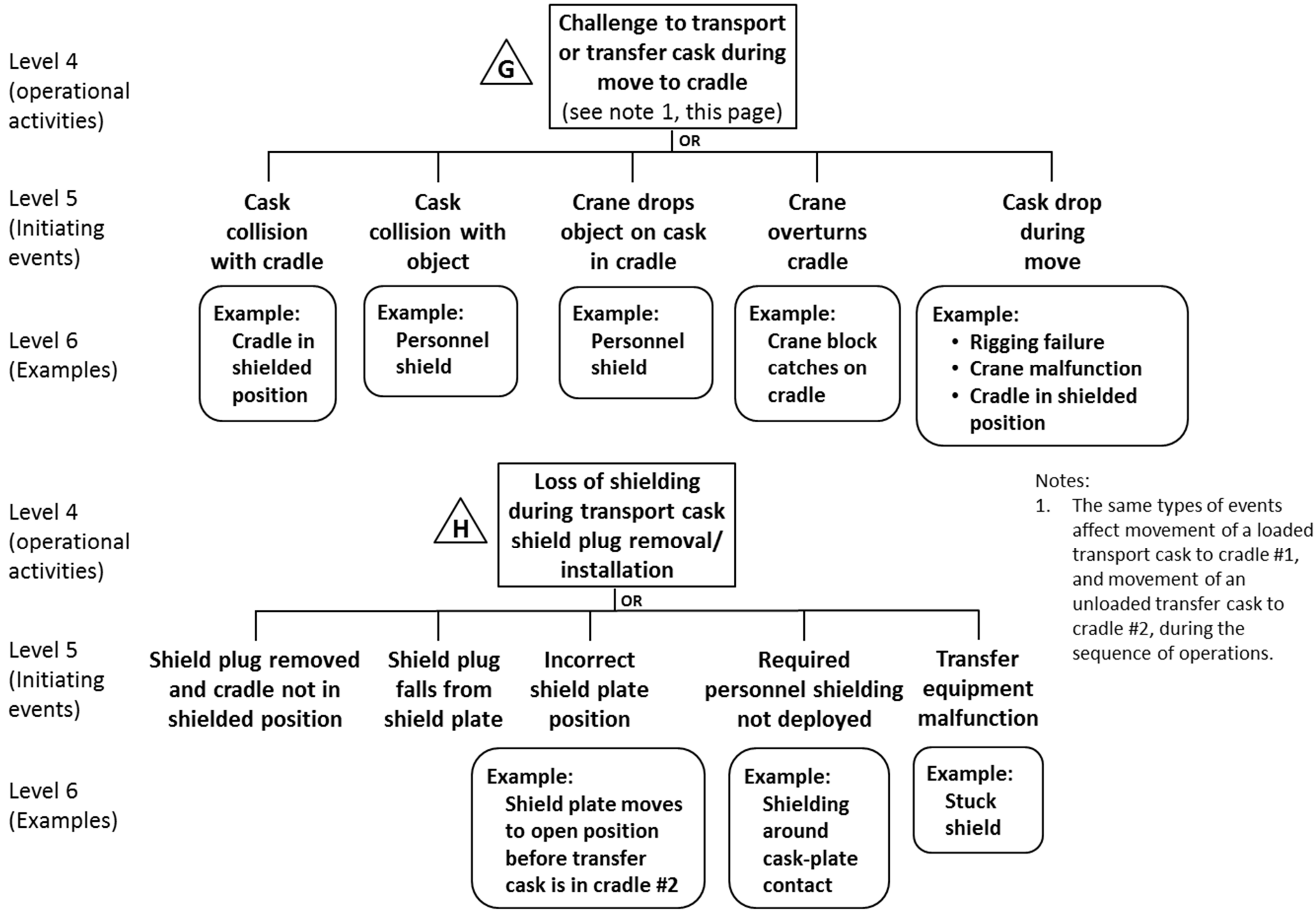


Figure 2. Preliminary master logic diagram for DBD operations, continued (sheet 4 of 8).

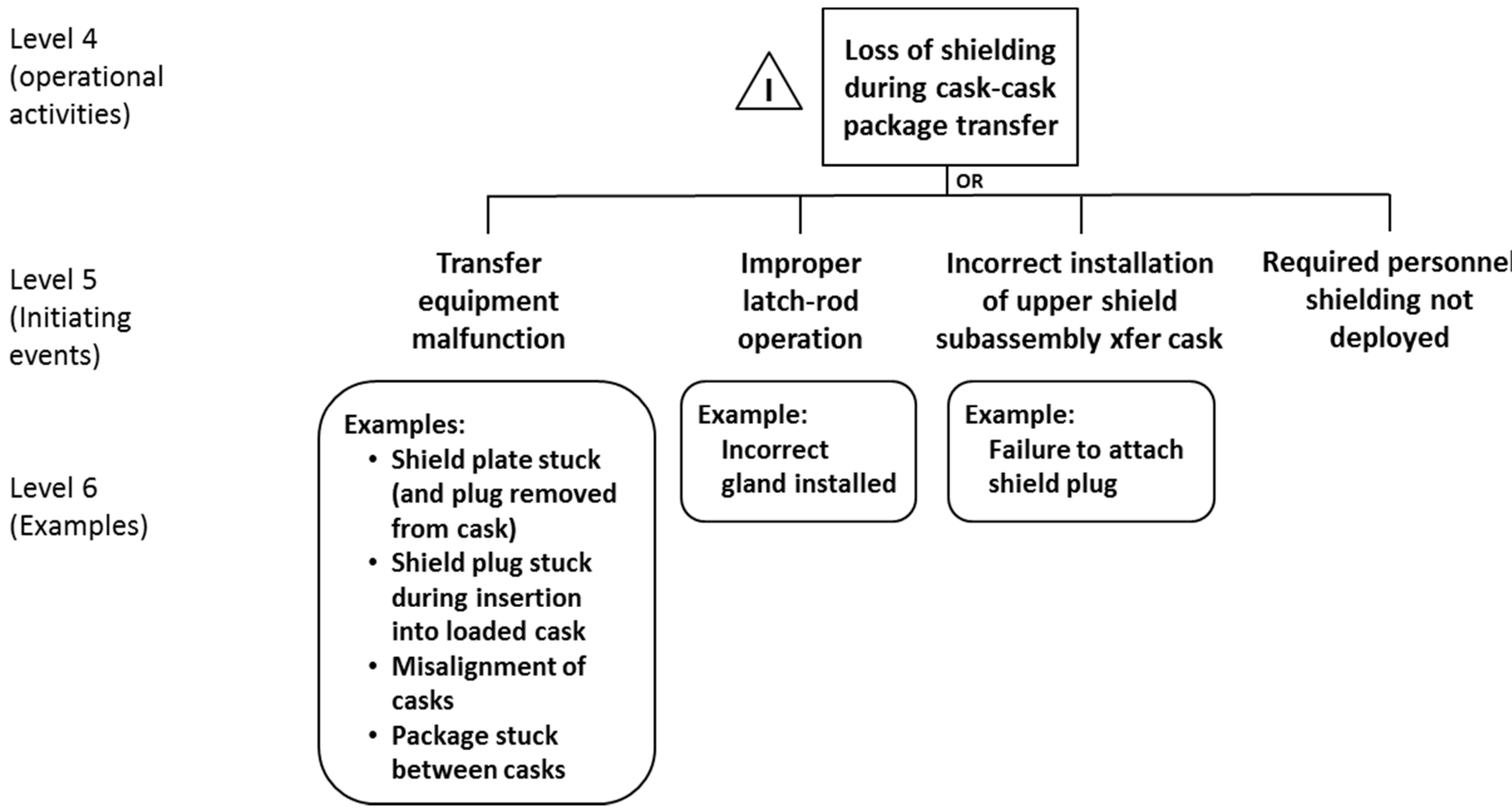


Figure 2. Preliminary master logic diagram for DBD operations, continued (sheet 5 of 8).

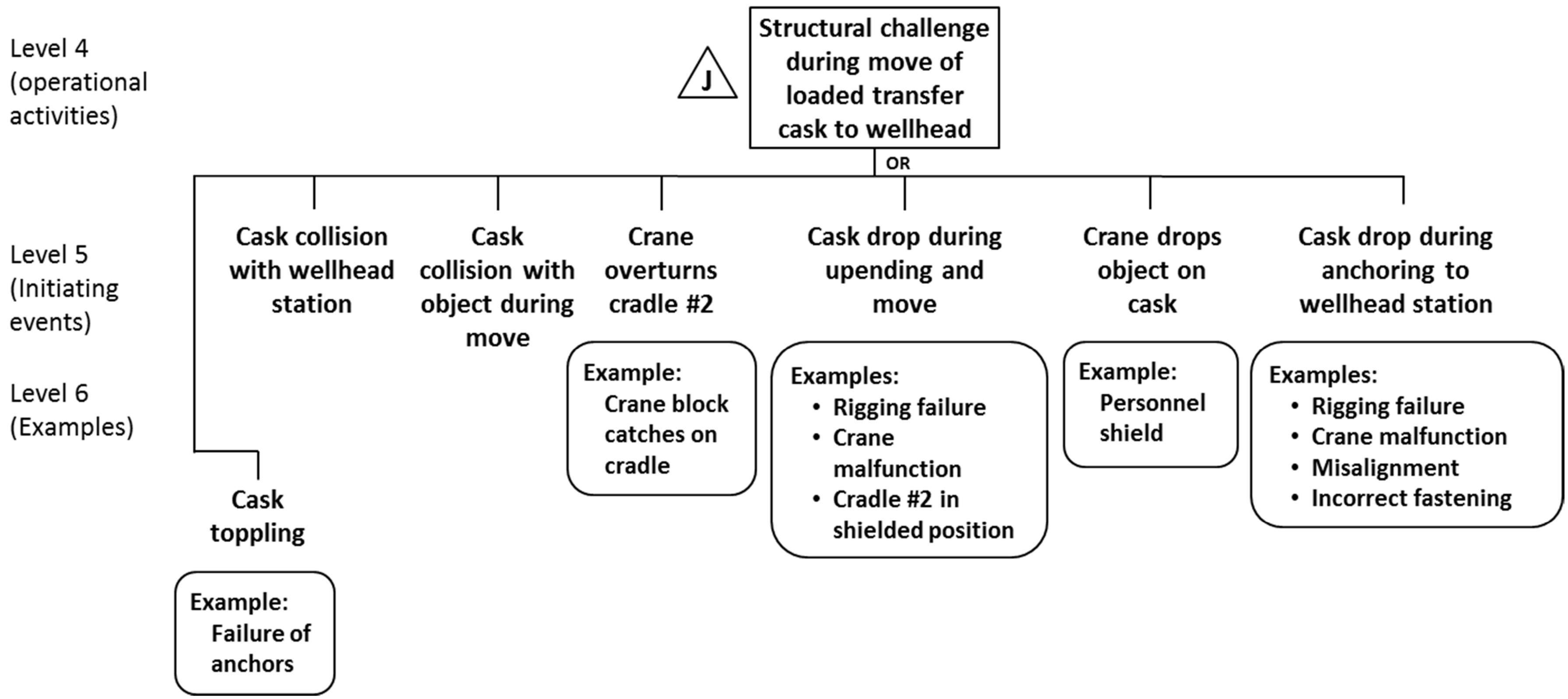


Figure 2. Preliminary master logic diagram for DBD operations, continued (sheet 6 of 8).

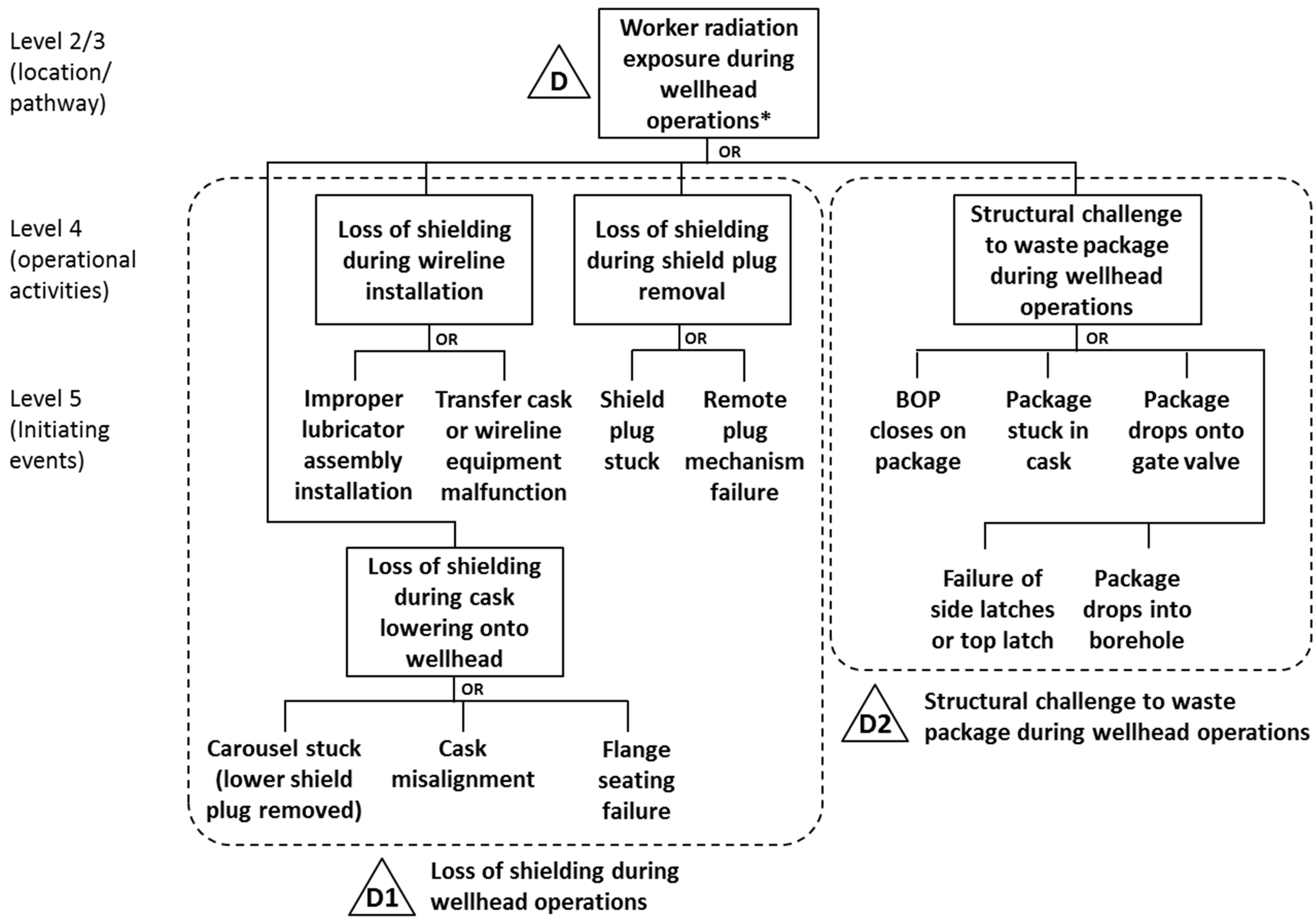


Figure 2. Preliminary master logic diagram for DBD operations, continued (sheet 7 of 8).

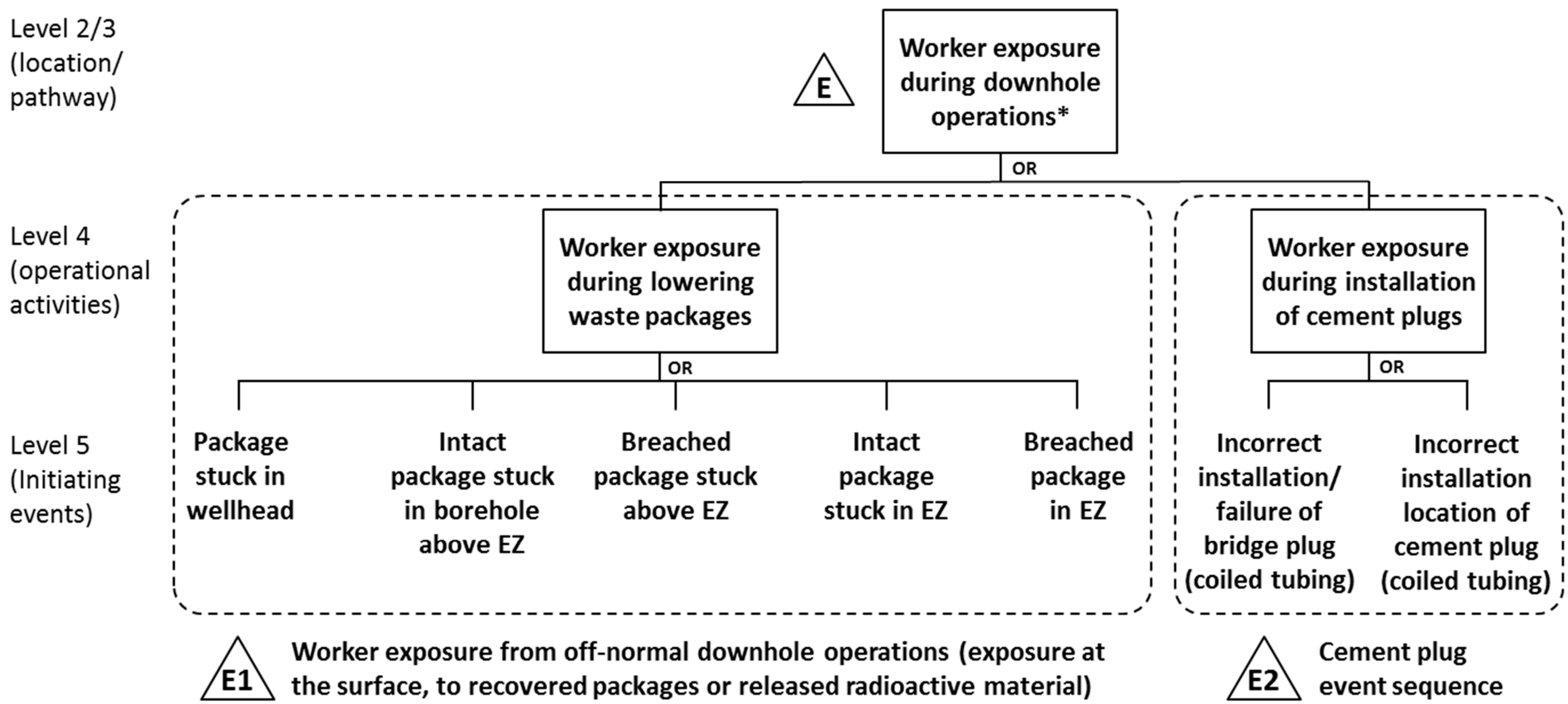
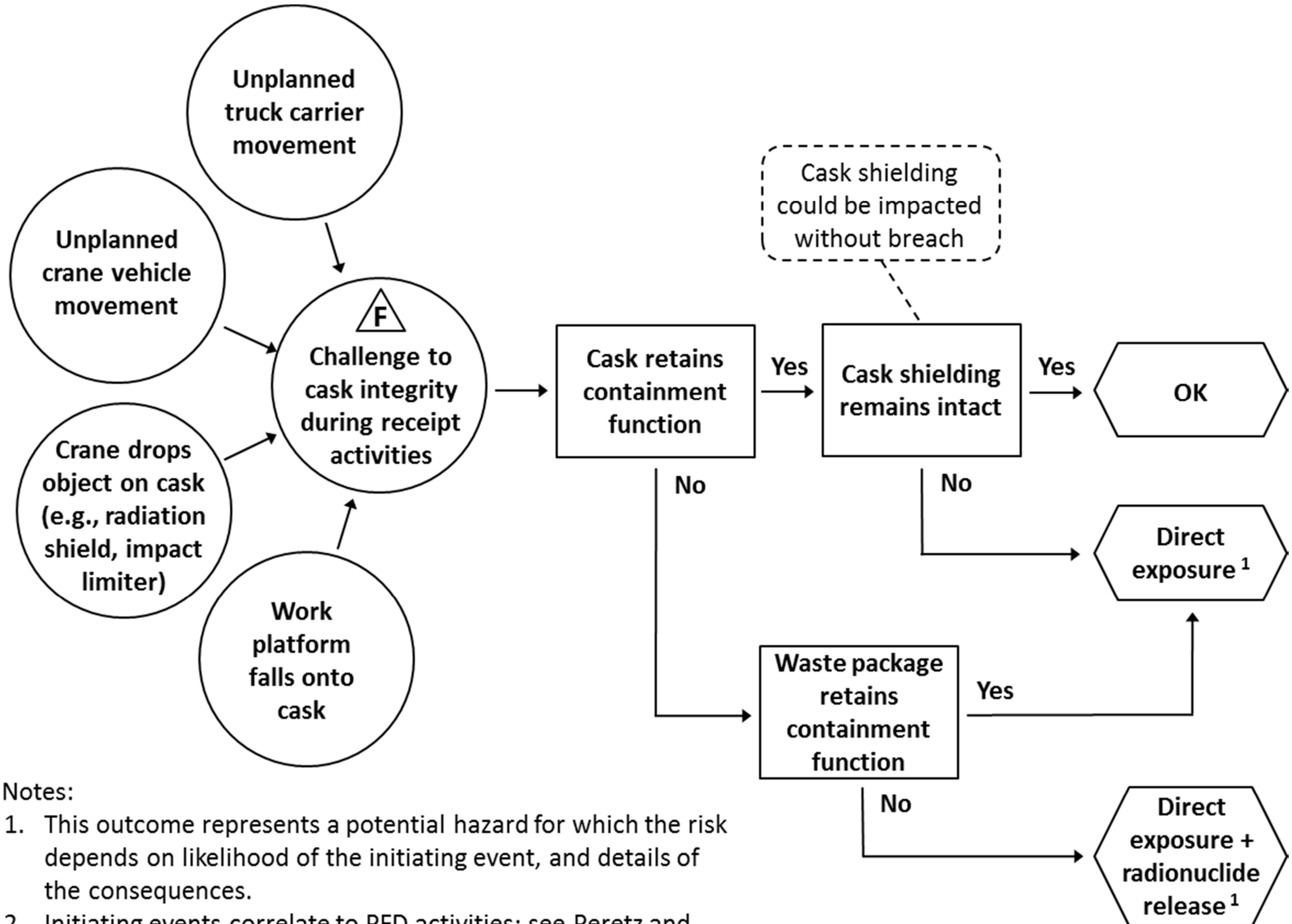


Figure 2. Preliminary master logic diagram for DBD operations, continued (sheet 8 of 8).

Table 4. Example HAZOP parameters and deviations (based on BSC 2008a, Table 1).

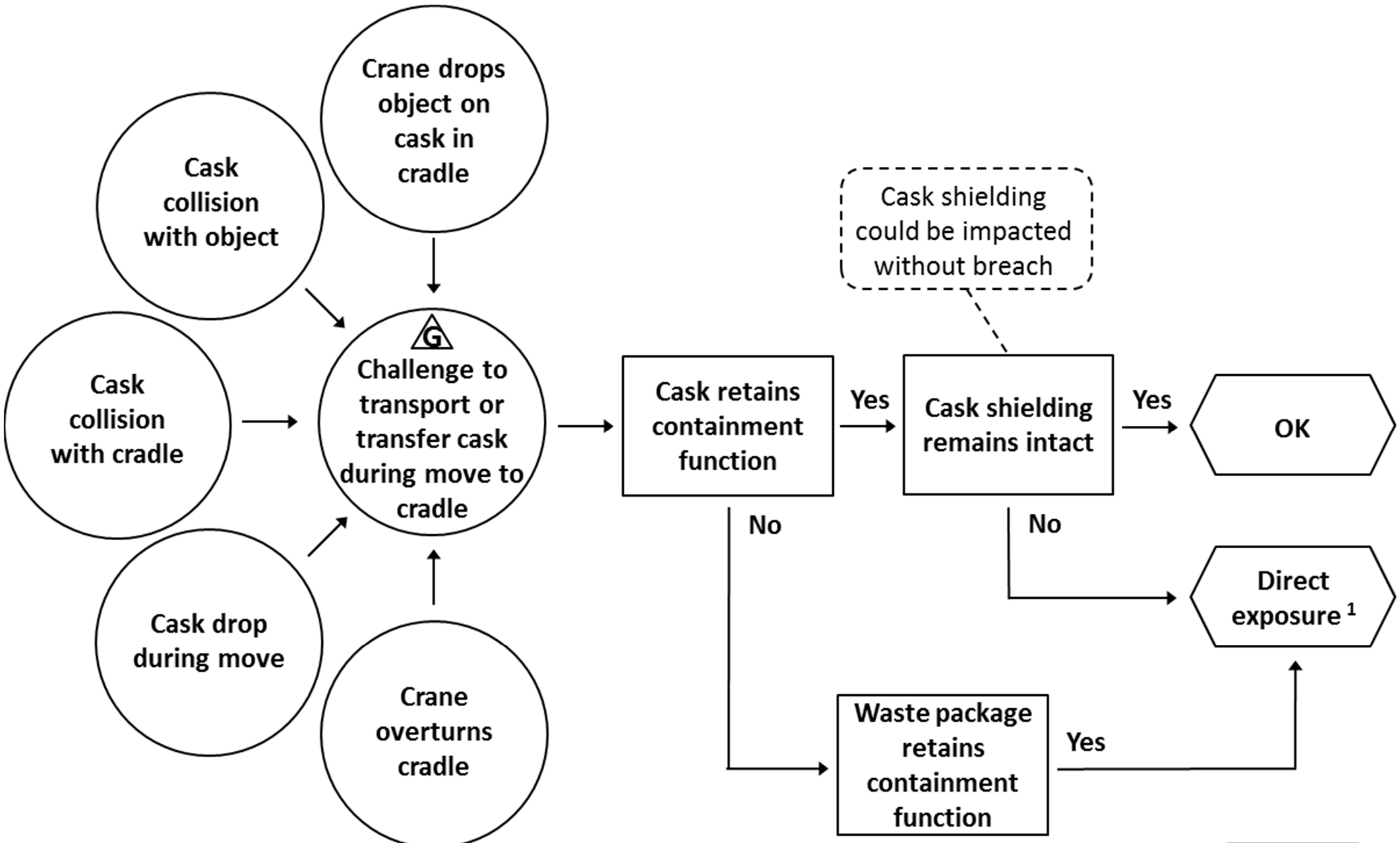
Basic HAZOP parameters:		• Speed • Travel or distance • Direction • Load • Lift • Temperature
Other suggested HAZOP parameters:		• Maintenance • Control System • Visual/Communication • Installation • Alignment
HAZOP Guideword	**Meaning**	**Comments**
No	Negation of design intention	No part of design intention is achieved, or nothing else occurs
Less (lower)	Quantitative decrease	Less than required for success of design intention
More (higher)	Quantitative increase	Greater than required for success of design intention
Part of	Qualitative decrease	Only some intentions are achieved
As Well As	Qualitative increase	All design and operating intentions are achieved together with some additional activity
Reverse	Logical opposite of intention	For example reversed flow, reversed chemical reaction, opposite movement, etc.
Other Than	Complete substitution	No part of original intention is achieved, and something quite different happens.
Modified from *Guidelines for Hazard Evaluation Procedure*s, Table 6.14, as noted by BSC (2008a).		



Notes:

1. This outcome represents a potential hazard for which the risk depends on likelihood of the initiating event, and details of the consequences.
2. Initiating events correlate to PFD activities; see Peretz and Hardin (2017) for details.

Figure 3. Preliminary event sequence diagrams for DBD operations (sheet 1 of 7).



Notes:
1. This outcome represents a potential hazard for which the risk depends on likelihood of the initiating event, and details of the consequences.
2. Initiating events correlate to PFD activities; see Peretz and Hardin (2017) for details.

Figure 3. Preliminary event sequence diagrams for DBD operations, continued (sheet 2 of 7).

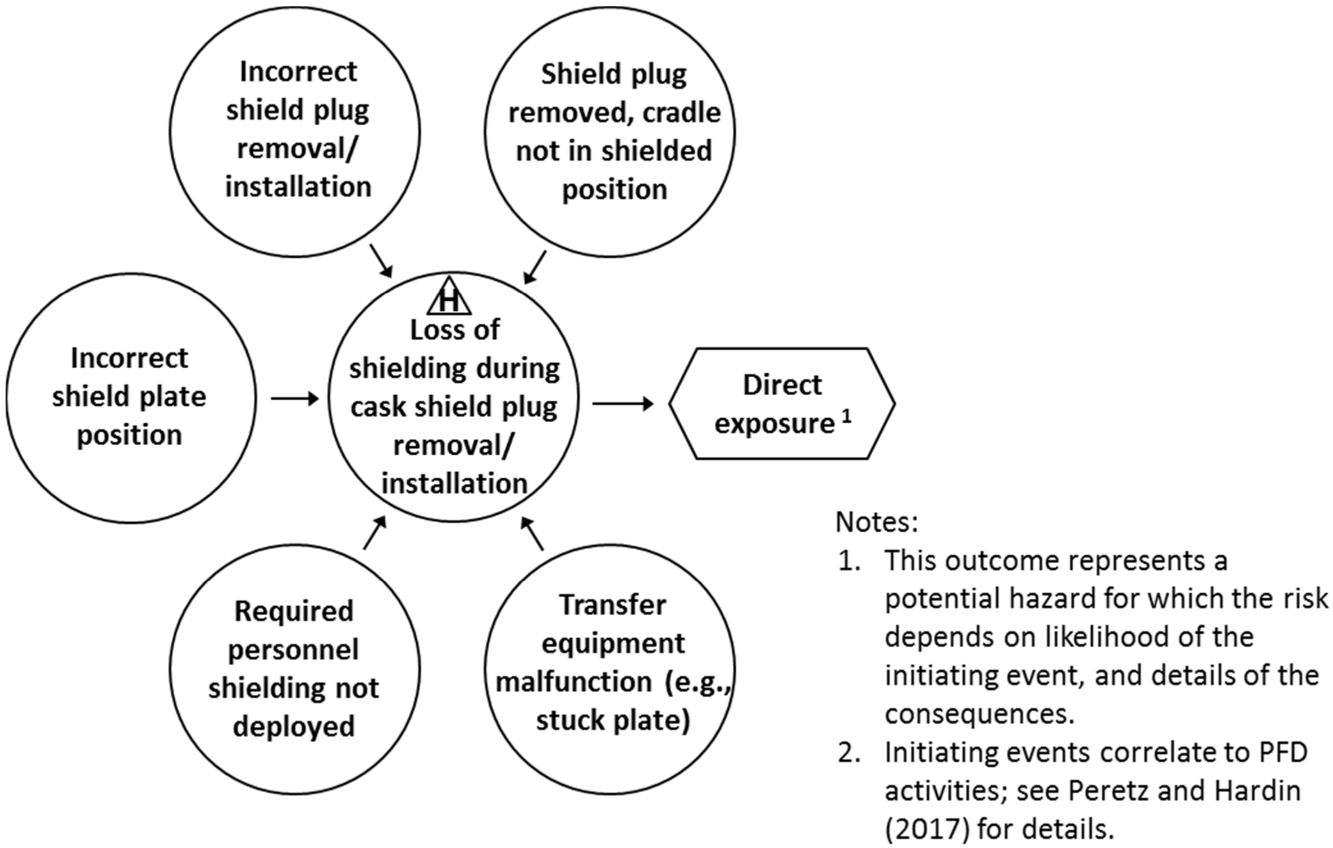


Figure 3. Preliminary event sequence diagrams for DBD operations, continued (sheet 3 of 7).

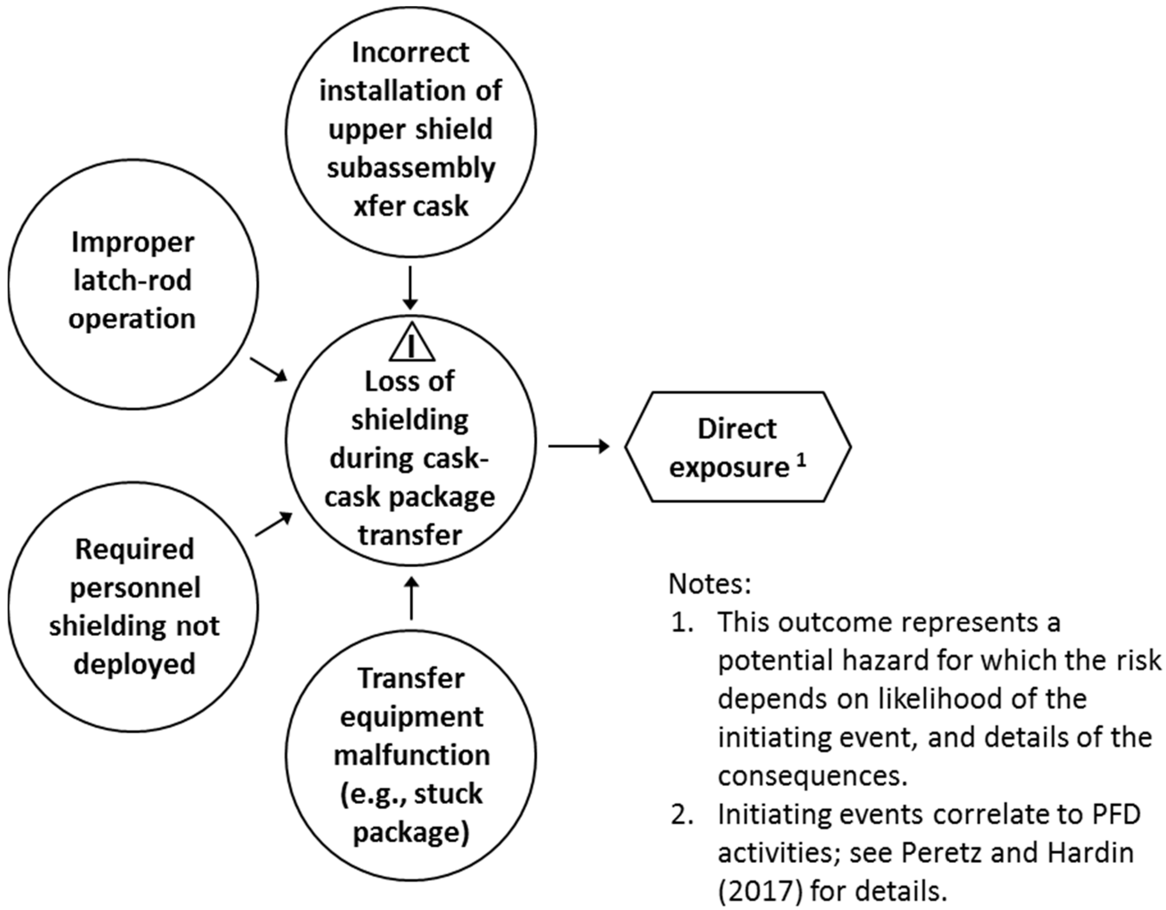
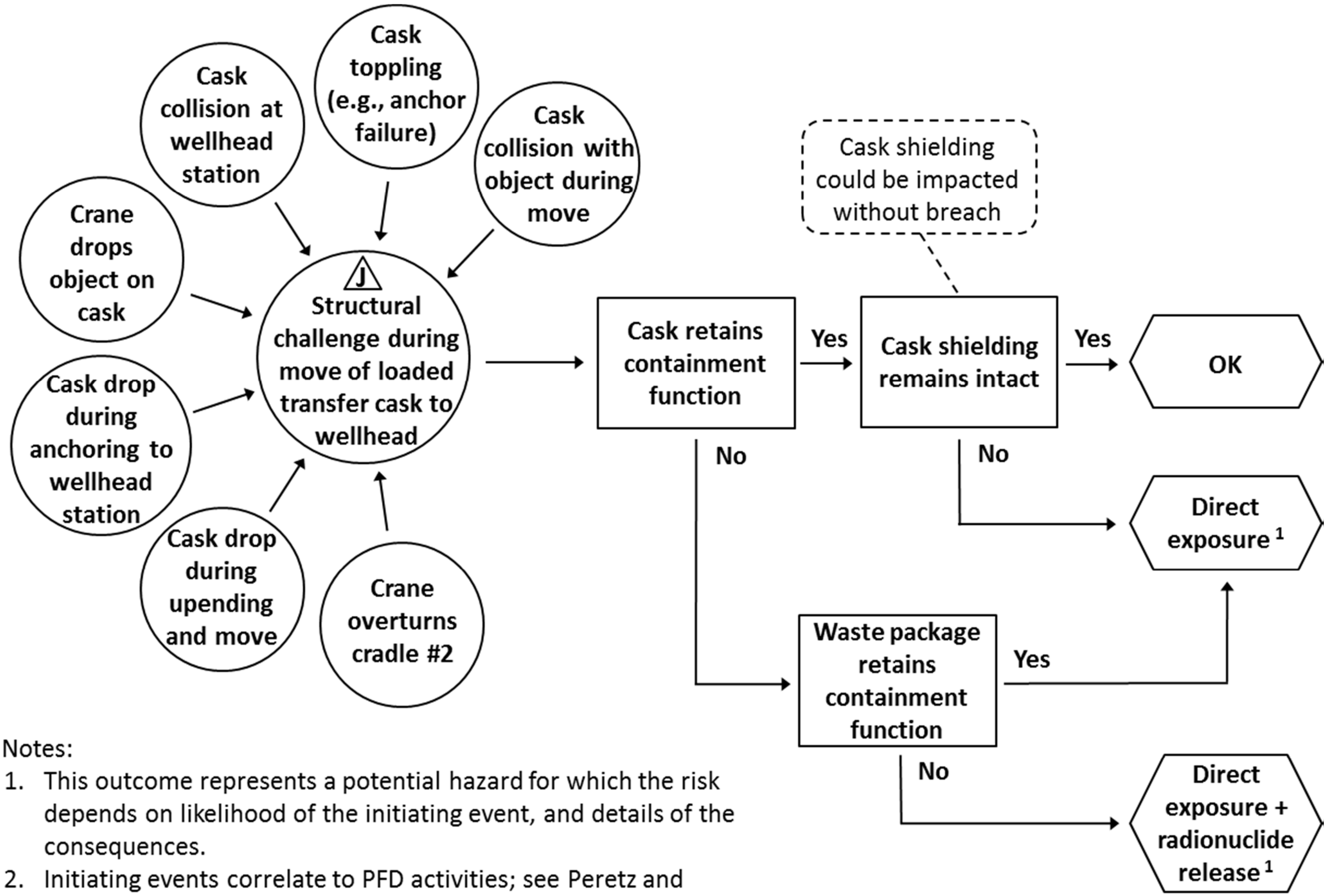


Figure 3. Preliminary event sequence diagrams for DBD operations, continued (sheet 4 of 7).



Notes:
1. This outcome represents a potential hazard for which the risk depends on likelihood of the initiating event, and details of the consequences.
2. Initiating events correlate to PFD activities; see Peretz and Hardin (2017) for details.

Figure 3. Preliminary event sequence diagrams for DBD operations, continued (sheet 5 of 7).

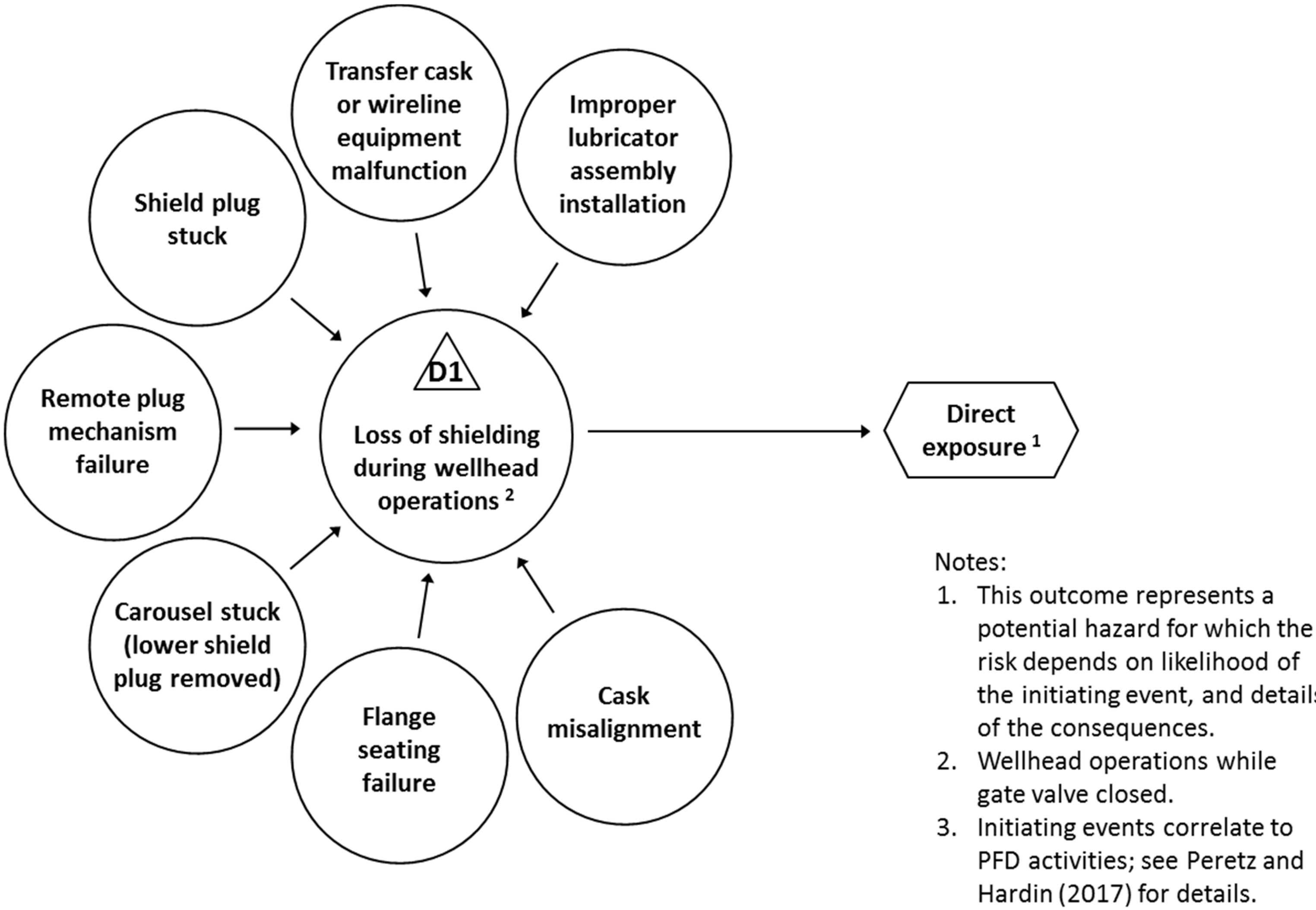
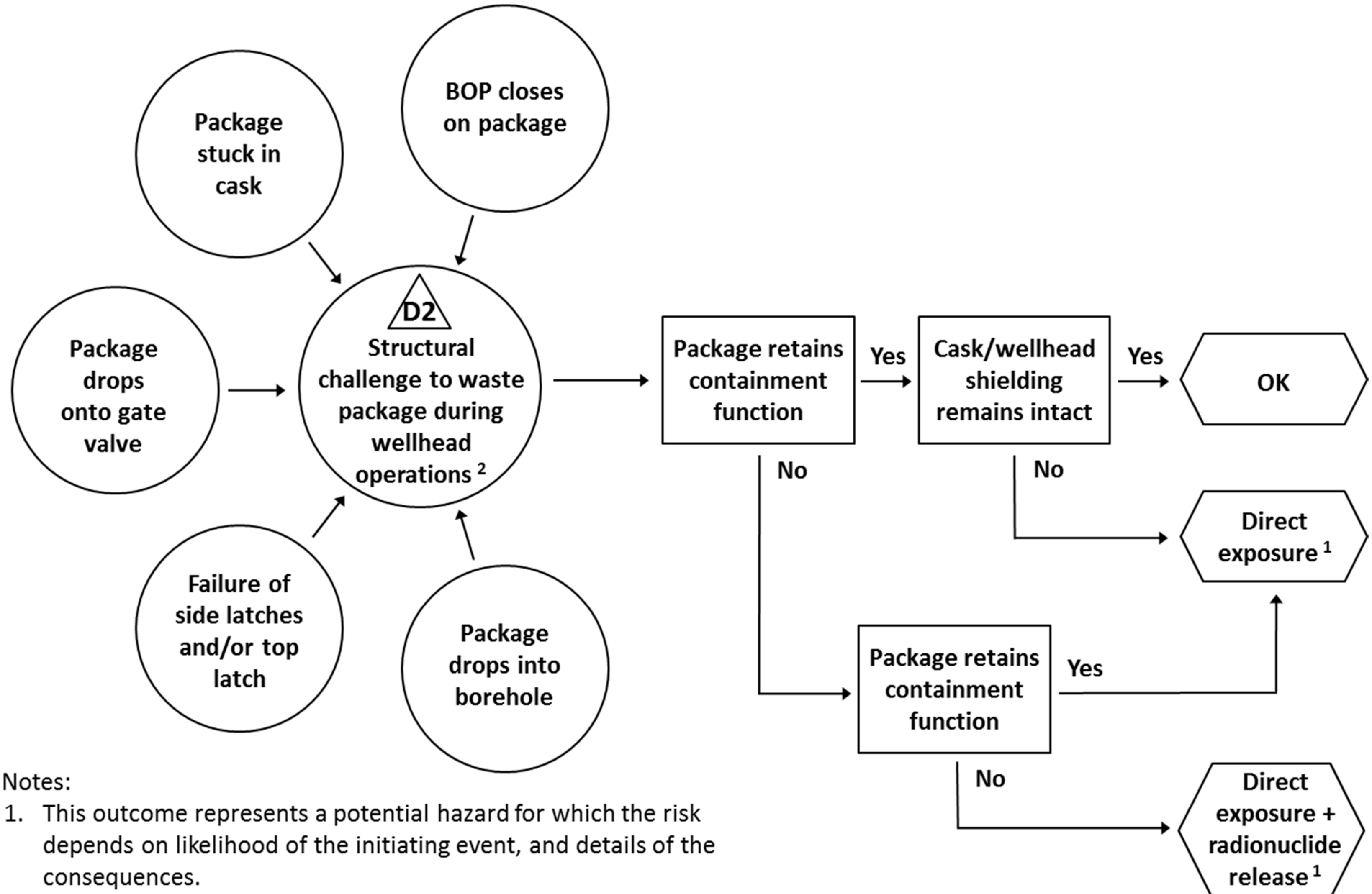


Figure 3. Preliminary event sequence diagrams for DBD operations, continued (sheet 6 of 7).



Notes:

1. This outcome represents a potential hazard for which the risk depends on likelihood of the initiating event, and details of the consequences.
2. Wellhead operations while gate valve closed.
3. Initiating events correlate to PFD activities; see Peretz and Hardin (2017) for details.

Figure 3. Preliminary event sequence diagrams for DBD operations, continued (sheet 7 of 7).

Method Summary (External Initiating Events)

Treatment of external initiating events will involve:

E1. Assess internal initiating events to determine which can be initiated externally (i.e., seismic ground motion), and compiling new sets of top events. As a simplification, the conditional probability of failure for each component can be set to zero for Category 1, and failed states can be assigned for Category 2 as appropriate.

E2. Check for other failed states or externally initiated failure modes that are not directly associated with the internal initiators.

E3. Assess the performance of support equipment (crane, headframe, hoist, wireline equipment). The design-basis seismic event will be imposed as a criterion on design or selection of these components. As a simplification, the conditional probability of failure for each component can be set to zero for Category 1, and failed states can be assigned for Category 2 as appropriate (some components may continue to function after a Category 2 event).

E4. Construct fault trees as necessary where logical relationships are needed to represent internal contributions to outcomes from external initiating events.

E5. Compose new ESDs that summarize externally initiated failed states and system responses.

E6. Assess system responses (worker exposures resulting from failed states; see discussion on qualitative description of consequences).

E7. Sum probabilities for all outcomes.

E8. Identify SSCs relied upon to limit consequences (as potentially important to safety).

Additional guidance for treatment of external initiating events is provided in the assumptions (Section 4).

4. Assumptions for Risk Analysis

The following assumptions are proposed to allow a generic (non-site specific) analysis of worker radiological safety, and to simplify the analysis. Sources for information that may be needed for risk assessment of the type described in this report, include guidelines from siting regulations (10CFR960), and regulator reviews of Safety Analysis Reports (NUREG-1949 Volume 2; NRC 2015).

Scope of Waste Disposal Activities

1. No waste storage – Waste will not be stored at the disposal site, so a license under 10CFR72 is not required, and storage or aging will not be part of a license under a disposal regulation such as 10CFR63. For implementation of DBD this means that waste shipments will be received just-in-time, and that lag storage to accommodate schedule disruptions, emplacement stoppages due to weather, etc., will be performed elsewhere. We note that transportation rules for particular projects may allow for a few days of temporary storage involving the safe and secure parking of waste transportation vehicles.

2. No waste re-packaging – Transportation and transfer casks, and the wellhead station, will be routinely surveyed for radioactive contamination. Waste packages suspected of leakage and/or contamination, prior to emplacement in a deep borehole, will be returned to the point of origin for further inspection, decontamination, and rework if necessary.

3. Waste types for disposal – DBD would be used for high-level waste (HLW) streams of limited scope (see assumptions from SNL 2016). For purposes of analysis these wastes are

assumed to be solid (possibly particulate), and gamma emitting such that shielding is required for waste handling operations, but not fissile, and not neutron-emitting so that neutron shielding is not required. Neutron shielding would not pose a serious challenge to the conceptual design, and could take the form of an added layer of solid or liquid hydrogenous material on the outside of the casks (e.g., as described by NAC International 2008).

4. Single borehole campaign – A single-borehole campaign is assumed for analysis, such as that which could be used to dispose of the full inventory of sealed capsules containing Cs and Sr from irradiated fuel processing at Hanford. The duration of this campaign as estimated previously (SNL 2016) is assumed to be approximately two years for drilling, construction, emplacement (one WP per day during emplacement operations), sealing, and plugging.
5. Multiple borehole campaign – A multi-borehole campaign will be assumed separately for analysis. The number of boreholes for the multi-borehole case is assumed to be 100, without specifying the waste form beyond the characteristics assumed in this report. The duration for the multi-borehole campaign is assumed to be 50 years. Each borehole would take 2 years as noted above, with emplacement activity for approximately 1 year of that. The schedule of activities may not be important to the risk assessment, but if necessary may be assumed:

# Boreholes Active at a Time	Duration of Phase (yr)	Total # Boreholes in Phase
1	6	3
3	10	15
5	32	80
2	2	2

6. Use of a purpose-built transfer cask – As stated in Section 2 and by SNL (2016), a double-ended cask, such that WPs can be loaded or unloaded at either end, is needed for DBD emplacement and retrieval. The capability may also be important for recovery from off-normal downhole conditions. On the other hand, existing licensed transportation casks are single-ended, being loaded and unloaded from the same end. For the conceptual design (SNL 2016) a purpose-built double-ended transfer cask was adopted for use with a currently existing transportation cask (NAC International 2008). This selection impacts risk assessment for surface operations because it requires transfer to another cask, but it does not require successful licensing of a double-ended transportation cask with additional features for coupling to a borehole.
7. Site area – The site area is assumed to be sufficient to accommodate drilling and workover activities, construction of surface facilities, surface waste handling, downhole emplacement operations, transport vehicles, and other site operations needs.

Compliance with Other Regulations

8. No interference between occupational and radiological safety measures – The same measures to avoid cask drops, collisions, unplanned movement, etc. will support both occupational and radiological safety. Where additional measures are used for occupational safety, they do not increase radiological risk.

9. Regulations and permitting – For purpose of analysis, it is assumed that legal and regulatory requirements associated with permitting and pre-closure operations (i.e., drilling, construction of surface facilities, and waste handling and emplacement) are achievable using the conceptual approach to DBD operations (summarized in Section 2, based on SNL 2016). The regulatory environment varies from state to state and for Federal versus private land. Potentially directly relevant requirements include the use of a blowout preventer, and incorporating the transfer cask and associated components into the wellbore pressure control envelope, both of which are incorporated in the current conceptual design (SNL 2016).

Limited Use of Hazardous Materials

10. No hazardous materials – During normal waste handling and emplacement operations hazardous materials will not be used except fuels and lubricants, sealed-source geophysical tools, and cements, which are commonplace in oil-and-gas borehole operations. Use of such hazardous materials will not increase radiological risk except for internal fire and certain external events addressed in this analysis. (Note that borehole cuttings and wasted borehole fluids, without radioactive contamination, may be designated as hazardous wastes by local regulations.)

Ease and Cost of Siting, Construction, Operation, and Closure

11. Suitable landform surface characteristics – Favorable surface characteristics for DBD surface operations can be assumed for this analysis, including stable surface geology and uniform (flat) topography (surface hydrology is discussed below). Such characteristics are assumed to be suitable for reasonable construction of graveled roads in remote locations, with the configuration and load-bearing capacity for safe and secure transport of waste.
12. Suitable subsurface rock characteristics – The scope of guidelines in 10 CFR 960.5 includes rock characteristics pertaining to ease of constructing and operating a mined geologic repository. Such characteristics may also affect construction and operation of boreholes for DBD. For purposes of analysis, suitable rock characteristics can be assumed that allow for safe DBD construction and operation.
13. Suitable surface hydrologic characteristics – DBD disposal surface facilities will not be located in wetland areas or watershed settings where there is the potential for direct, adverse environmental impacts. The site for DBD would be engineered to sustain heavy precipitation without detrimental effects, and the intensity considered in that analysis would be at least that corresponding to Category 1 event. A predictive-engineering approach might not be sufficient to describe a Category 2 event because of limited observational data for extreme weather over very long time frames. However, a different approach in analysis and controls on DBD operations is assumed for mitigation of the effects of extreme precipitation. For example, constructed boreholes have casing cemented to great depth, and are fluid-filled during operations, so they would not be compromised by surface erosion resulting from a beyond-Category 1 precipitation event. Further, that heavy precipitation is predictable and occurs over durations of many hours so that DBD operations would be suspended and demobilized before waste packages could be compromised.
14. Suitable subsurface hydrologic characteristics – Subsurface hydrology is considered in site characterization and site suitability determination for DBD, which will be verified during construction of each borehole. Such determination is assumed to assure that subsurface

hydrologic characteristics have no significant effect on radiological safety of DBD operations.

Site Remoteness and Control

15. Population density and distribution – DBD is assumed to be sited in a remote region with appropriate separation from centers of population (e.g., tens of kilometers), and further, to be remote from permanent habitations (e.g., distance of at least 10 km).
16. Site ownership and control – The implementing agency for DBD is assumed to have full site ownership and control, of an area containing the controlled area and including additional area as appropriate.
17. Offsite installations and operations – DBD operations are assumed to be conducted in remote settings separated from offsite installations and operations, especially ones involving radioactive materials, by sufficient distance that they present no significant additional radiological hazard to DBD workers or members of the public. Such remote locations are assumed to be accessed by improved, graveled roads with appropriate controls on public access.

Environment, Socioeconomics, and Transportation

18. Environmental quality – The DBD operation is assumed to contribute no significant potential for environmental impacts (such as wetland impacts discussed above) that should be taken into account in the design of DBD equipment and operations, apart from the fate of radioactive waste, and the proper and compliant use of hazardous materials discussed above (fuels and lubricants, sealed-source geophysical tools, cements, and possibly borehole fluids and cuttings).
19. Socioeconomic impacts – The potential for socioeconomic impacts is assumed to have no significant bearing on the design of DBD equipment and operations.
20. Transportation – The manner and routing of safe and compliant waste transportation to the remote DBD site is assumed to have no impact on DBD equipment and operations, except for the transportation cask and truck transport. For this analysis, it is assumed that WPs are delivered to the DBD site one at a time, on a just-in-time basis, in a single-package cask such as the existing LWT® cask from NAC International. The choice of a single-package transport cask is consistent with delivery of packages by truck, over improved gravel roads. Use of a cask that contains multiple WPs is possible, but involves heavier loads and the complication of onsite storage.

Loss of Cask Shielding Function

21. Cask containment and loss of shielding – Loss of containment may occur when a shielded plug is dislodged by impact (Sprung et al. 2000). A plug need be dislodged only a few millimeters to break its seal, which is relatively straightforward to simulate. The resulting loss of shielding is more difficult to simulate, and gamma scattering occurs anyway, so loss of shielding is typically associated with loss of containment, and is assumed in this analysis.
22. Cask deformation and loss of shielding – Loss of shielding (possibly without loss of containment) can occur with lead shielded casks, by slump of the lead caused by impact. The accelerations calculated in Appendix A are assumed to be insufficient to cause significant slumping of the shield layers in the transportation and transfer casks.

Assumptions Affecting Treatment of Internal Initiating Events

23. Potential internal initiating events – A survey of potential internal initiating events, using the events identified BSC (2008a, Table 10) with the addition of events and categories specific to DBD, is shown in Table 5. As noted in the table annotations some of the events are not credible for DBD.
24. Safety functions of supporting equipment – The DBD system for receipt, handling, and emplacement of waste packages includes major components such as the crane for unloading transportation casks, headframe, hoist for moving the transfer cask, wireline hoist, and wireline logging equipment. In the discussion of initiating events, the reliability of certain aspects of the performance of these components has been implicitly assumed. For example, the crane, headframe, and hoist for cask handling and movement are assumed to be reliable except for the possibility of drops or collisions.
25. Internal flooding – DBD operations are assumed to be performed in the open, on an engineered pad with drainage features, so that flooding from internal causes is not credible. No fissile materials will be handled so the potential for flooding is much less important.
26. Fire suppression – Availability of a robust fire suppression system is assumed, with redundant capabilities (e.g., water and foam), pre-arranged for access to all vehicles, casks, generators, and other equipment on the pad. Note the assumption above on waste types (non-fissile).
27. Safe shutdown – The waste handling and emplacement system is assumed to have internal, intrinsic capability for safe shutdown if one of a list of off-normal events occurs. For example, cranes and hoists are assumed to arrest all load movement if power failure occurs. Where safe shutdown must occur across different self-contained subsystems, it may be directed by an integrated functional safety system.
28. Maximum cask drop height – The maximum drop is assumed to be 3 m, corresponding the lift height (from bottom of cask) to clear the transport vehicle, and to clear equipment at the transfer station and the wellhead station.
29. Pad for surface DBD operations – Waste receipt, handling, and emplacement operations will take place on a pad (which may be the former drill pad), constructed of at least 60 cm of compacted gravel with appropriate grade and drainage features. The subgrade material is assumed to be stable and compliant. The size of the pad will be at least 100 m square, sufficient to set up the operations area around the borehole, surrounded by access, parking, supporting equipment, and facilities for waste fluid management (normal operating conditions). It is expected that the former drill pad will be 2.5 to 5 acres, and thus provide the room needed for DBD operations (although rework of the pad base may be required).
30. Recovery from off-normal event sequences – For event sequences resulting in system damage, recovery operations are beyond the scope of this study. Thus, the refinement of conceptual design for WP handling and emplacement, may not consider recovery from WPs becoming stuck or breached downhole. However, some consideration may be given to features of surface equipment that could facilitate recovery from drops, equipment malfunction, etc.

Table 5. Survey of internal initiating events.

Potential Internal Initiating Event	Comment
General:	
Flooding from pipe failure	Not credible for operation of portable equipment in open (not confined) spaces.
Flooding from actuation of fire suppression	
Large fire, internally caused	Not credible with limited amounts of combustible materials, and fire suppression.
Electrical fire	Mitigate by safe shutdown features, electrical shutoffs, and fire suppression.
Localized fire with fuel present	Vehicle fires mitigated by safe shutdown and fire suppression.
Excessive temperature (excluding fire)	Mitigate by procedural controls, where necessary.
Loss of generator power	Mitigate by safe shutdown features.
Transportation cask movement:	
Transport cask vehicle collision (onsite)	
Crane drops object (e.g., impact limiter) onto cask	
Crane drops transportation cask onto ground surface	Assume maximum drop height of 3 m, established by crane setup and procedural controls.
Crane drops transportation cask onto equipment (e.g., cradle)	
Unplanned crane or transportation vehicle movement	Mitigate using the functional safety system, as appropriate.
Incorrect position or movement of cradle for cask	
Loaded cask collides with object/equipment during move	
Shield plug dislodges from cask	
Work platform falls or collapses onto cask	
Cask-to-cask transfer:	
Cask-cask misalignment	
Failure of shield plate actuation (e.g., becomes stuck)	
Cask shield plug becomes stuck	
Waste package stuck in transportation cask	
Shield plug bolts fail or become stuck	
Transfer cask movement:	
Hoist drops transfer cask onto ground surface	Assume maximum drop height of 3 m, established by crane setup and procedural controls.
Hoist drops object (e.g., impact limiter) onto cask	
Hoist drops cask onto equipment (e.g., wellhead station)	
Unplanned hoist movement	Mitigate using the functional safety system, as appropriate.
Incorrect position or movement of cradle for cask	
Loaded cask collides with object/equipment during move	
Shield plug dislodges from transfer cask	
Side-latches fail to grip transfer cask	
Shield plug flange mechanism fails or becomes stuck	
Wellhead setup:	
Misplacement of transfer cask	
Failure of carousel actuation	Access for repair in unshielded work environment.
Failure of kneeling jacks	
Unplanned carousel movement	
Toppling of transfer cask on wellhead station	
Failure of remotely operated shield plug removal mechanism	Mitigated by repair capabilities.
Flange actuation fails	
Wellhead equipment (valve, blowout preventer) actuation fails	
Pressure “kick” with valve open	Mitigated by well pressure control envelope.

Potential Internal Initiating Event	Comment
Wireline emplacement operations:	
Misassembly of latch or cable head	Addressed by previous risk analysis for emplacement mode selection (see SNL 2016, Appendix A).
Electromechanical latch not secure	
Waste package falls a short distance while attached to wireline	
Wireline hoist failure	
Wireline instrumentation failure (e.g., loss of power)	
Cable damage (leads to break if undetected)	
Gauge ring fails to remove debris (package can get stuck)	
"Other" debris in borehole	
Casing collapse	
Waste package becomes stuck above emplacement zone	
Waste package becomes stuck in emplacement zone	
Waste package drops from surface	
Waste package drops during trip in	
Latch fails to release	
Wireline drops on trip out	
Recovery from off-normal downhole conditions:	
Inadequate shielding at the surface during package recovery	Planning and risk analysis for recovery operations would be performed (and reviewed) on an as-needed basis and are beyond the scope of this study.
Failure of remotely operated equipment (e.g., casing cutting, decontamination)	
Radionuclide release and radiation exposure from contaminated borehole fluid	
Release and exposure from contaminated solids (e.g., drill pipe and casing)	
Failure of washdown system for contaminated components	

Assumptions Affecting Treatment of External Initiating Events

31. Potential external initiating events – A survey of categories of potentially significant external initiating events is shown in Table 6. As noted in the table annotations some of the events are not credible for DBD.

32. Safety functions of supporting equipment – As stated above for internal events, the DBD system for WP receipt/handling/emplacement includes major components such as the crane, headframe, hoist, and wireline equipment. The capability of these components to perform their safety functions needs to be supported by assessment of responses to design basis external events (e.g., seismic ground motion, extreme weather, external fire). The response to Category 2 ground motion and faulting also needs to be assessed to determine whether worker exposure limits could be exceeded.

33. Tectonic characteristics (seismicity) – Tectonic activity results in faulting and ground motion hazards to DBD operations. Ground motion is identified as an external initiating event (Section 3). As a design basis, events with less than 2% probability within 50 years (2,500-year recurrence) of peak ground acceleration greater than 0.16 g, is assumed to be sustained during DBD surface operations without damage or radiological incident. This magnitude is generally indicative of an area of tectonic stability. Such an event (0.16 g) is less frequent, and thereby more intense, than a Category 1 event, supporting a conservative design approach. For Category 2 events (500,000-year recurrence) a peak ground acceleration of 0.5 g is assumed. This is a somewhat ad hoc selection for risk analysis, that is intended to guide selection of reasonable (and not excessive) DBD design features.

34. Extreme ground motion –Peak ground acceleration greater than 0.5 g may be possible at the Category 2 level depending on site conditions, and may result in waste package breach with release of radioactive material. It can be assumed that procedural controls will be developed for DBD operations, that would be invoked after any off-normal event that could cause breach, for detecting and mitigating releases. Protocols would be implemented to stabilize released material from atmospheric dispersion (e.g., immediate application of adhesive chemical foam), and hydrologic transport (e.g., erection of a temporary structure). Additional planning, design, and review activities would precede further mitigation activities.
35. Tectonic characteristics (faulting) – Fault offset would have minimal impact on a constructed borehole, because the surface casing is robust and cemented to great depth. However, an offset could disrupt surface operations by toppling casks, equipment, etc. For this reason it is assumed that boreholes will be located with appropriate standoff from indications of past fault offsets in near-surface sediments. This approach is assumed to mitigate the faulting hazard for Category 1 events because the associated seismic magnitude is limited, and slip on any new (unmapped) fault through a DBD operational area would be too small to result in radiological consequences. For Category 2 events it is assumed that only capable faults (evidence of past events indicating sufficient likelihood) would be included in the assessment, so that the likelihood of unknown, capable faults is insignificant, and impact is limited to ground motion.
36. Limits on non-seismic geologic events – The possibility of non-seismic events such as landslides, karst collapse, or volcanism is assumed to be very remote, and will be addressed during characterization for DBD. The DBD system for WP receipt/handling/emplacement would not reasonably be designed to withstand such events.
37. Limits on extreme weather – Extreme weather (high winds, tornadoes, hurricanes, lightning) is assumed to have no significant effect on radiological safety of operations, because: 1) procedural controls will suspend operations such as cask lifts when appropriate to do so; 2) all SSCs will be electrically grounded in a manner known to limit lightning damage; 3) cask handling equipment (cradles, headframe, wellhead station) will be well anchored and designed to survive design-basis wind loading (in addition to seismic ground motion); 4) supporting equipment will also be well-anchored and designed to survive design-basis wind loading; and 5) DBD boreholes are intrinsically resistance to damage from extreme weather because of multiple, heavy, cemented casings and wellhead equipment. The intensity of design-basis wind loading will be greater than Category 1, and consistent with the probability level of the seismic design basis (2,500-year recurrence). Management of the hazard from extreme weather will be similar to managing operations on a large drilling rig (offshore or land-based). The hazard from extreme weather is site-dependent and the approach represented by this assumption will be reviewed if and when site-specific information becomes available.
38. Limits on external flooding – Flooding may occur from extreme precipitation, but impact to DBD operations will be limited by: 1) mitigating flood control excavation at DBD sites; 2) procedural controls that suspend operations, particularly when extreme precipitation is imminent; and 3) intrinsic resistance of DBD boreholes to damage from flooding, as noted above for extreme weather.

39. Limit on loss of power or cooling – DBD operations will not use offsite power, and will not rely on central cooling. For onsite power the system for WP receipt/handling/emplacement, including support equipment, will tolerate loss of power without initiating failed states that cause radiological consequences.
40. Limits on aircraft crash hazard – The DBD site is assumed to be sufficiently remote from airports with commercial or heavy military traffic, and situated on flat terrain, so that the aircraft crash hazard probability is comparable to the smallest found anywhere in the conterminous U.S. The likelihood of an aircraft crashing directly into a waste cask is assumed to be less than Category 2 based on the incidence of crashes over remote regions, and an assumed footprint for DBD operations.
41. Limits on nearby industrial/military accidents (incl. transportation) – Sites for DBD are assumed to be sufficiently remote from industrial or military facilities (e.g., at least 10 km) that impacts from those facilities on DBD operations, and radiological doses from those facilities at points of compliance for DBD operations, are insignificant.
42. Limits on onsite hazardous materials release – Hazardous materials will not be used for DBD operations (with the exception of fuel and radioactive waste). Fuel release is treated by considering internal fire to be the most severe potential impact on operations, and hazards from radioactive waste is the focus of the assessment.
43. Limits on external fire – We assume that the DBD campaign will be conducted in sparsely vegetated terrain, and that vegetation will be removed to a safe distance so that a large fire cannot damage the operations area. Also, that procedural controls will cause operations to be safely suspended in the event of a fire with potential to become a large fire in the vicinity.
44. Limits on extraterrestrial activity (meteorites, falling satellites) – These hazards are assumed to be excluded from assessment on the basis that they are less likely than Category 2.

Table 6. Categories of potential external initiating events

Potential External Initiating Event Category	**Recommendation for This Study**
Tectonic events (seismic ground motion and faulting)	Inclusion (see text)
Non-seismic geologic events (incl. volcanic activity)	Exclusion (see text) either because they are not workable for a generic analysis of DBD or they are sufficiently unlikely that they do not serve as reasonable bases for design.
Extreme weather (high winds, tornadoes, hurricanes, lightning)	
External floods	
Loss of power	
Loss of cooling capability	
Aircraft crash	
Nearby industrial/military accidents (incl. transportation)	
Onsite hazardous materials release	
External fire	
Extraterrestrial activity (meteorites, falling satellites)	

5. Summary

This report proposes an approach for assessing the radiological safety of deep borehole disposal (DBD) operations. The purpose of the assessment is to identify risk factors for disposal operations, to aid in design for the deep borehole field test engineering demonstration. As was the case for an earlier study (SNL 2016) the assessment will consider actual DBD operations, to develop conclusions that can be applied to the DBFT demonstration (which will be performed without using any form of nuclear waste). The assessment seeks to improve the conceptual design for DBD and the DBFT demonstration, by considering risks associated with the equipment and the activities that would be used for waste disposal. It is intended that by describing and analyzing disposal operations in detail, from waste package receipt to borehole closure, that additional active and passive safety functions and operational controls will be identified and incorporated in the design. The DBFT demonstration can then include features of the equipment and processes that are found to be important to safety.

The proposed methodology is probabilistic, and consistent with the approach required by 10 CFR 63, and based on probabilistic risk assessment concepts applied to the preclosure safety analysis for Yucca Mountain repository surface facilities (BSC 2008a,b). The approach involves describing DBD operations, identifying initiating event sequences, analyzing event probabilities, and characterizing (but not necessarily quantifying) radiological consequences. Actual implementation of the methodology is planned for follow-on companion reports. The approach follows steps I1 through I5 above for internal initiating events, and steps E1 through E8 for external initiating events.

It is expected that implementation of this assessment will bring to light improvement in the DBD conceptual design documented previously (SNL 2016). Examples of such insights that have been tentatively identified so far in the progress of the assessment include:

- Anti-two-blocking safety features are assumed for the crane and hoist used to lift casks and other heavy items.
- Safer lifts could be achieved using in-line arrangement of transfer, washdown, and wellhead stations, and using a fixed headframe for all lifts between these stations (a crane would be used to move the transportation cask from the truck to cradle #1).
- Alarms are needed for radiation, dispersed radioactive material, internal fire, and explosion hazard conditions.
- An integrated functional safety system is needed to prevent or mitigate a range of potential initiating events, especially those caused by human error.
- A fire suppression system with loss-of-power capability and foam to immobilize hazardous materials, is needed to mitigate internal fire hazards.
- The transfer cask must withstand Category 1 ground motion when mounted on the wellhead carousel platform.
- Category 1 events should not have radiological consequences significantly greater than normal operations, nor should they cause the system to generate additional radioactive waste.

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Appendix A – Cask-Drop Fragility Analysis

Background

Waste packages will be received at a DBD site within a truck-mounted transportation cask such as the LWT® cask (NAC International 2008). During the emplacement process the cask will be lifted into a vertical orientation, up to 3 m off the ground to clear the truck mounted cradle. A drop from this height would impart additional loads on the waste package. This appendix reports analysis of such an impact to assess the deceleration and shock loads experienced by the waste package inside the cask.

The calculations reported here do not include the impact limiters used for over-the-road transport of the LWT® cask. Rather, the drop represented here would occur after those impact limiters are removed, during cask handling at the DBD site. The impact limiter installed on the lower end of the waste package would still be present. As described previously (SNL 2016) the intended function of this limiter is to mitigate the impact of dropping a WP in the borehole. For a 3-m drop in air at the surface such a limiter would absorb some (but not nearly all) of the energy of the drop, as discussed below. The internal limiter concept could be modified so that it mitigates both the borehole and vertical surface drops, but this was not attempted for the calculations reported here.

The similarity of size, shielding, and end plug design, between the LWT® cask and the transfer cask, means that the drop calculations described here could be applied to the transfer cask as well. The highest lift for the transfer cask is likely to be less than 3 m because the transfer station and the wellhead station would be constructed at grade level.

An end drop is selected for analysis because most of the cask movements described for DBD operations would be done in vertical orientation. Oblique drops are also possible, as are drops of a few feet onto a steel cradle with potential for cask penetration. These cases may be undertaken in future studies.

Model Setup

The NAC LWT® cask is modeled as a 316 stainless steel cylinder (neglecting the metallic lead layer). Nominal exterior dimensions for the cask are 0.73 m (28.8 in) x 5 m (200 in). The internal cavity is 0.36 m (14.0 in) x 4.4 m (173 in) and houses the waste package. A stainless steel lid seals the internal volume. As modeled, the mass of the NAC-LWT cask is approximately 13,600kg.

The waste package used in the model is the reference waste package design (SNL 2016, Section 3) with a nominal outer diameter of 0.27 m (10.75in) and wall thickness of 0.025 m (1.00 in). The waste package is constructed from P110 casing or tubing material (yield strength 110 ksi). Aluminum centralizers secure the waste package radially within the cask. The centralizers allow some axial movement between the cask and the waste package while keeping the waste package radially centered. The waste package has an impact limiter attached as shown in Figure A-1.

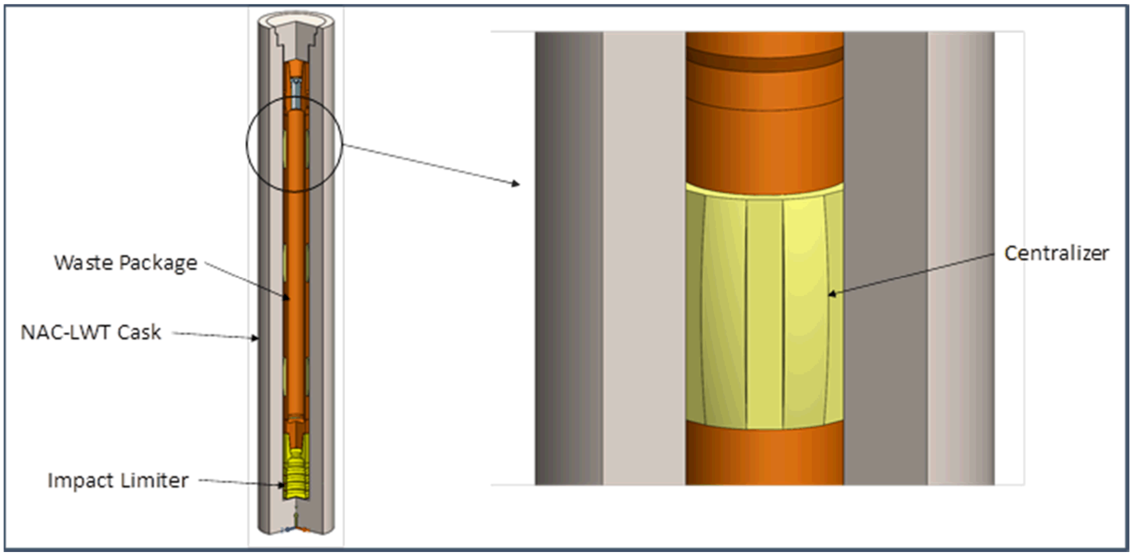

Figure A-1. Cask-drop model schematic.

The impact surface is assumed to be compacted gravel with a thickness of 0.6 m (24 in). The "stiffness" of the compacted gravel is given by the modulus of subgrade reaction (K_s) which has a wide range of values depending on the material and the condition of the surface. Stiffness values range from 300 to 450 psi/in. A nominal value of 350 psi/in was chosen for these simulations.

SolidWorks Simulation® software was used for free-body dynamic simulation. For drop test simulations, the program calculates impact and gravity loads on a rigid or flexible planar surface, with no other loads or restraints allowed. It uses an explicit time integration method, and automatically adjusts the critical time step based on the smallest element size and stability and accuracy criteria. Simulations were conducted out to 50 msec. The drop height was specified as 3m from the lowest point on the assembly which is the bottom face of the cask. The impact is assumed to be normal to the impact surface and gravity.

Results of Cask-Drop Simulation

A sensor was placed on the lower interior face of the waste package to track the model results over the duration of the simulation. The sensor location is highlighted in blue as shown in Figure A-2. The speed and von Mises stress over that period are plotted as well.

The results show that the maximum stress of approximately 4,200 psi occurs around 14 msec into the impact. The stresses decrease steadily after that. This delay in the maximum stress indicates that the waste package is gradually decelerating, due in part to the compliance of the impact limiter. The stresses on the sensor face remain relatively low compared to the yield strength of the material (even modified for elevated temperature).

The stress at other locations in the assembly are also captured in the simulation. A stress plot of the entire assembly at 14 msec is shown in Figure A-3. The entire cross-section of the impact limiter has exceeded its yield strength, indicating maximum crushing and energy dissipation. Although the impact limiter is absorbing some of the energy, there are still shock loads that reverberate through the waste package. The magnitude of these short-duration stresses in the waste package body reaches nearly 20 ksi.

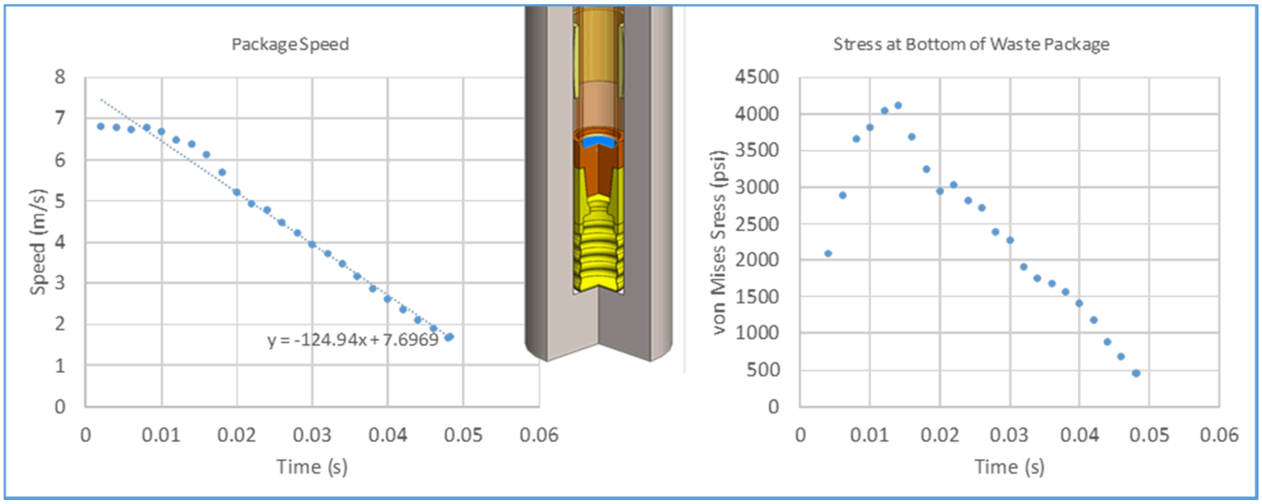

Figure A-2. Simulation results for vertical end-drop from 3 m onto compacted gravel.

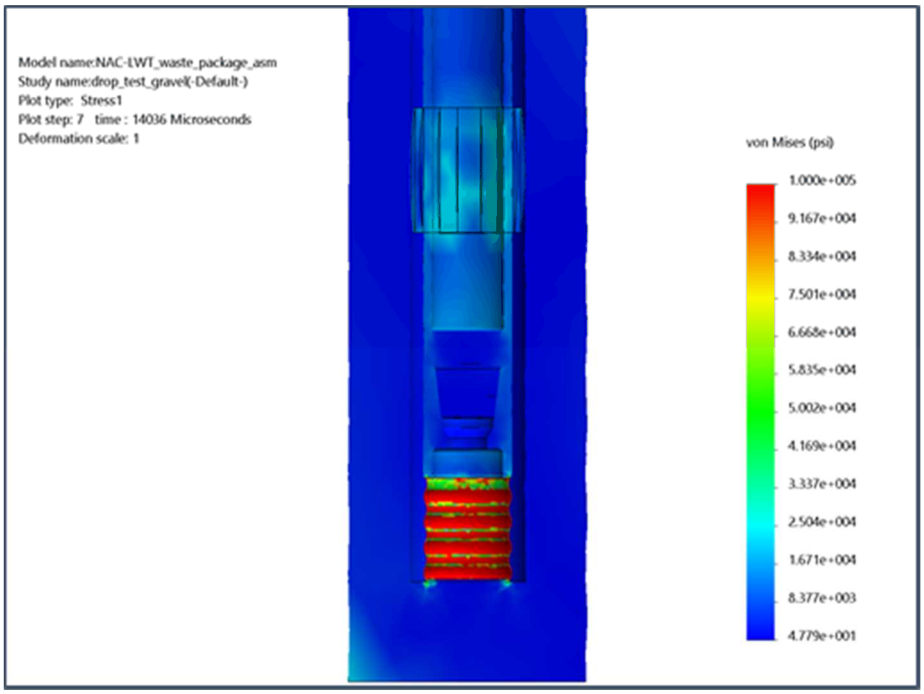

Figure A-3. Simulated stress condition (von Mises) at 14 msec for vertical end-drop from 3 m onto compacted gravel.

Analytical Solution for Cask Deceleration

Running the simulations described above to steady state (more than 50 msec) requires significant computational effort. Another approach to estimate the overall deceleration of the WP and cask is to model the assembly analytically. The impact between the cask and the ground is treated as a viscoelastic, Kelvin-Voigt impact model. Relative motion between the WP and the cask is modeled with a mass-spring-damper system. A schematic of the model is shown in Figure A-4.

The cask (m_1) and the waste package (m_2) are assumed to be connected by a spring (k_2) and a damper (b_2) (Figure A-4). The cask is connected to the impact surface with a spring (k_1) and a damper (b_1). The displacement from the neutral position for the ground surface and the WP are given by y_1 and y_2, respectively. The damping coefficients capture the energy dissipation that occurs during the impact while the spring elements represent the stiffness of the impacting surfaces.

Solving for the equations of motion for the above model results in a set of second-order ordinary differential equations (ODEs):

$$m_2\ddot{y}_2 + b_2\left(\dot{y}_2 - \dot{y}_1\right) + k_2\left(y_2 - y_1\right) = m_2 g$$
$$m_1\ddot{y}_1 + \left(b_1 + b_2\right)\dot{y}_1 + \left(k_1 + k_2\right)y_1 - k_2 y_2 - b_2\dot{y}_2 = m_1 g$$

The dot operator over a variable indicates the derivative of the variable with respect to time (or second derivative). The initial conditions are

$y_1(0) = 0$ and $y_2(0) = 0$

$\dot{y}_1(0) = (2gh)^{1/2}$ and $\dot{y}_2(0) = (2gh)^{1/2}$

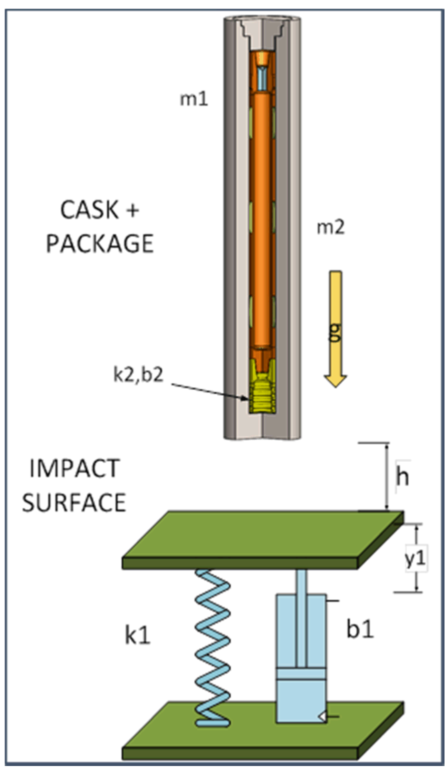

Figure A-4. Analytical model configuration.

The set of equations as solved using the ODE solver in MatLab. The span of simulation time used for analytical solution was 0 to 300 msec. The parameters and values used in the analysis are listed in Table A-1. The spring rate values are determined from the model for the impact limiter and literature for compacted gravel. The damping coefficient values were estimated in this analysis. Tests should be conducted to characterize the damping of the compacted gravel surface and the damping characteristics of the impact limiter.

Table A-1. Analytical solution model parameters and values.

Parameter	Value	Description
k_1	42.8e6 N/m^2/m	Compacted gravel sub grade modulus
b_1	1e6 N-sec/m	Compacted gravel damping coefficient (estimated)
m_1	13600 kg	Mass of NAC_LWT cask
k_2	80e6 N/m	Impact limiter axial spring stiffness
b_2	1e6 N-s/m	Impact limiter damping coefficient (estimated)
m_2	1300 kg	Waste package mass
h	3 m	Drop height

Figure A-5 shows results from the analytical solution. The maximum acceleration in the cask occurs at impact and is approximately 55 g. The subsequent decay in acceleration magnitude is caused by damping in the compacted gravel surface. The maximum acceleration in the waste package occurs at approximately 10 msec after impact. This is consistent with the numerical results shown in Figure A-2 where the maximum expected stresses were predicted to occur at 14 msec.

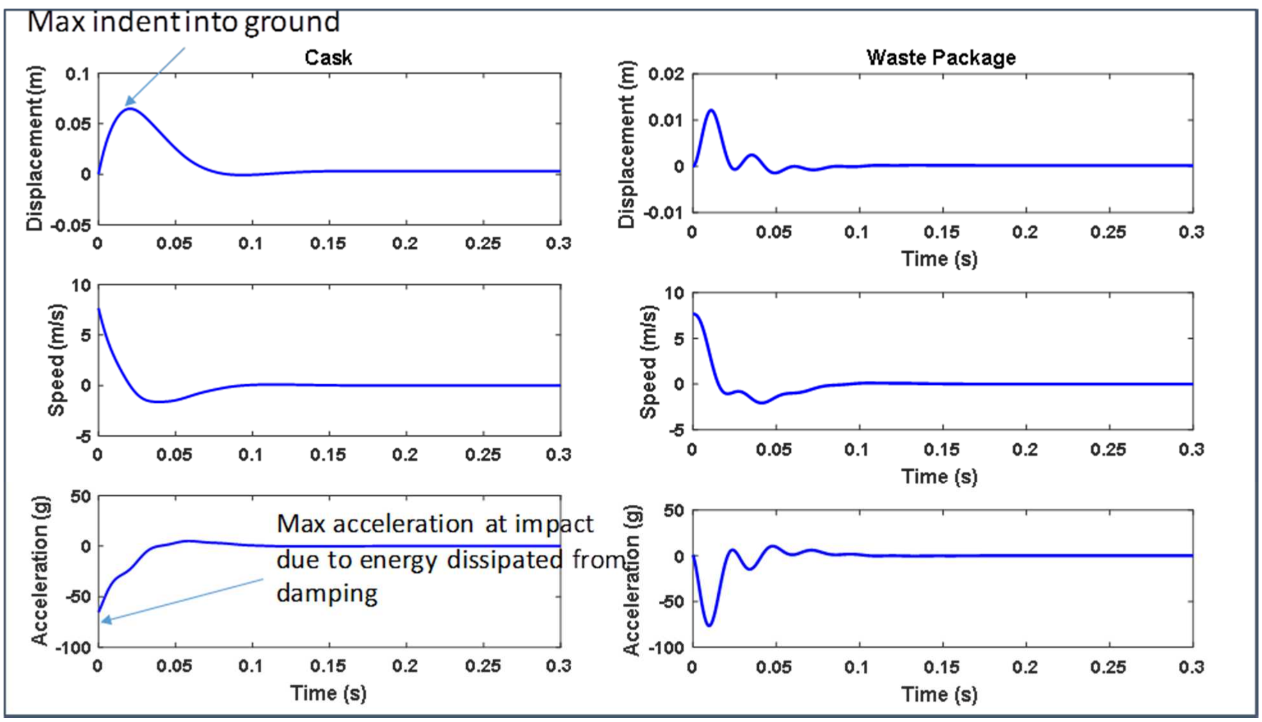

Figure A-5. Cask and waste package bulk acceleration due to impact.

Using the Kelvin-Voigt approximation it may be possible to tune the dynamic behavior of the impact based on the expected impact loading. For instance, to decrease the maximum acceleration in the WP, the impact limiter stiffness or the damping coefficient could be reduced. Although these results are in reasonable agreement with the numerical simulations, they are sensitive to the damping coefficient. Higher damping values result in larger accelerations that do not scale linearly.