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Deep Borehole Emplacement Mode Hazard Analysis (DBEMHA): Wireline vs. Drill String

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Outline

- **Purpose and approach**
- **Treatment of consequences**
- **Categories of failures/errors**
- **Choice of hazard analysis method**
- **Event Tree/Fault Tree example from YMP PCSA***
- **Event Tree/Fault Trees for wireline emplacement**
  - Drop-in-hole hazard
  - Stuck-in-hole hazard
- **Component failure databases (probabilities, frequencies)**
- **Future work, including drill string emplacement hazards**
- **References**

* Yucca Mountain Project Pre-closure Safety Analysis

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Purpose and Approach

- **Discriminate between emplacement mode options (*drill string* vs. *wireline*), according to**
  - What accidents could occur and how likely are they during deep-borehole emplacement of waste packages
- **Primary steps/aspects of hazard/risk analysis:**
  1. Hazard identification and event sequence construction (*what can happen?* – *"causes"*)
  2. Consequence analysis (*what are the consequences if it happens?*)
  3. Frequency/probability analysis (*how likely is it to happen?*, including uncertainty ranges)
  4. Risk calculation (*how bad is it?* – product of frequency and consequence)
  5. Decision analysis (*how should we proceed in light of the risk?*)

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Top Events for DBEMHA

- **Cause ⇒ Event ⇒ Consequence**
- **Prevention & Mitigation ⇒ Safety Functions/Barriers in the Design**

"Bow-tie" Diagram*

Often used for risk analysis in the oil industry

- **Major Top Events for DBEMHA:**
  - Uncontrolled drop of waste package(s) or equipment (junk) into borehole
  - Waste package(s) stuck in borehole (in guidance casing)

* Burtonshaw-Gunn, S. A. 2009. *Risk and Financial Management in Construction*, Fig. 3-8, ISBN 978-0-5660-8897-1, Ashgate, also Gower at www.gpmfirst.com

Some Assumptions & Simplifications

- **Accident analysis begins subsequent to bolting of shipping cask to wellhead (i.e., handling activities prior to that do not discriminate between options)**
- **Only internal events for now (i.e., omit external events such as seismicity, weather-related events, external fires, aircraft collisions, site-wide power failure etc.)**
- **Typical risk consequences not considered at this point, such as**
  - Personnel risk (e.g., injury or fatality)
  - Environmental risks (e.g., groundwater contamination; biota damage)
- **No malevolent acts (such as purposely dropping a package, or terrorism)**
- **No simultaneous initiating events (standard PRA practice because of low probability and because either event ceases operations)**

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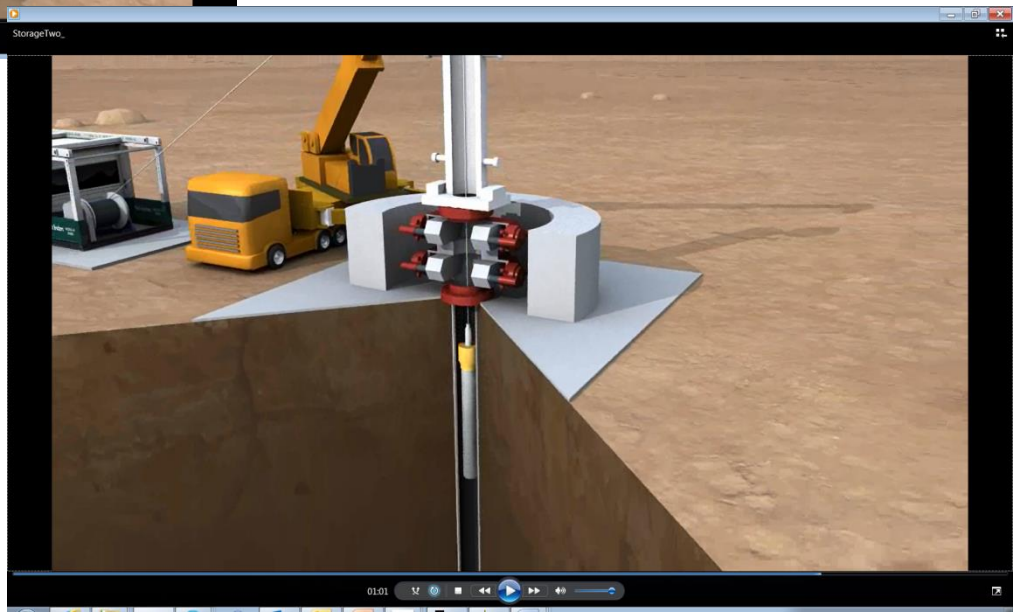
Wireline Emplacement in Deep Borehole

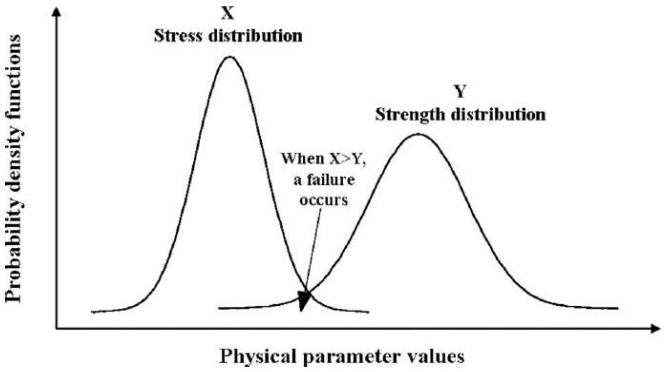
← Attach cable head to waste package

Lower waste package through BOP and downhole →



Three categories for failures/errors

- **Hazardous events can result from either actions (e.g., human acts) or component failures (e.g. battery, sensor) or a combination—three major categories….**
- **Passive component failures (near top of a fault tree)**
  - Includes components such as the waste package, guidance casing, and passive BOP components
  - Conditional failure probability requires an engineering calculation (fragility or damage analysis) using process models to determine probability of damage/failure, P_f, from mechanical stress (e.g., due to dropping or bumping), *or* an assumption or literature search



$$P_f = P(X \geq Y) = \int_{-\infty}^{+\infty} f_y(y) \left[\int_{y}^{+\infty} f_x(x)\, dx \right] dy$$

*from Huang and Jin (2009)

- **Active component failures:**
  - Includes components such as electric cablehead release, wireline winch, wireline sheave wheels, interlock systems, cranes, active BOP components (rams), UPS, batteries, diesel generators, wireline (fatigue), etc.
  - Failure probability (“demand”-based) or failure frequency (time-based) come from industry and governmental reliability databases for electro-mechanical equipment
- **Human errors/failures**

Choosing a Hazard Evaluation (HE) Method

- **From: *CCPS (Center for Chemical Process Safety) 1992. Guidelines for Hazard Evaluation Procedures, 2nd Edition,* AIChE:**
  - "Selecting an appropriate HE technique is more an art than a science"
  - Detailed flow charts and criteria for choosing the best HE method (seven pages)

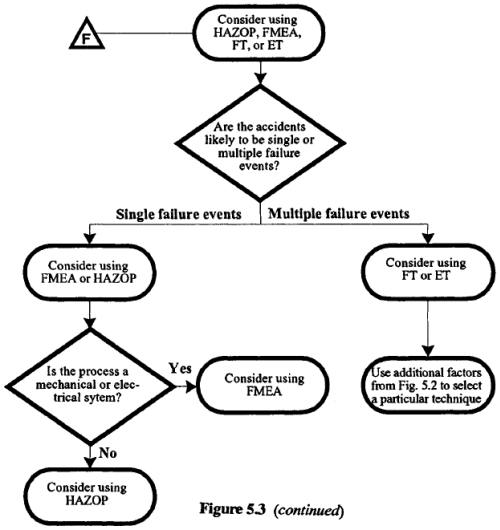


Figure 5.3 (*continued*)

- **After DOE 1997: *DOE Standard: Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports.* DOE-STD-1027-92:**
  - For a Nuclear Hazard Category 2 Facility (facility with a potential for "significant on-site consequences):

Type/Complexity of Facility	Recommended Hazard Evaluation Method
Low-Complexity	Checklist Analysis or other simple "Hazard Analysis"
Single-Failure Electro-Mechanical Systems	Failure Modes and Effects Analysis (FMEA)
Systems with Redundant Barriers or Requiring Multiple Failures	Event Tree Analysis (ETA)
Large, Moderately Complex Processes	Fault Tree Analysis (FTA)
Complex Fluid Processes	Hazard and Operability Studies (HAZOP)
High Complexity Facilities	Integrated Event Tree and Fault Tree Techniques (ETAs/FTAs)

← **YMP PCSA***

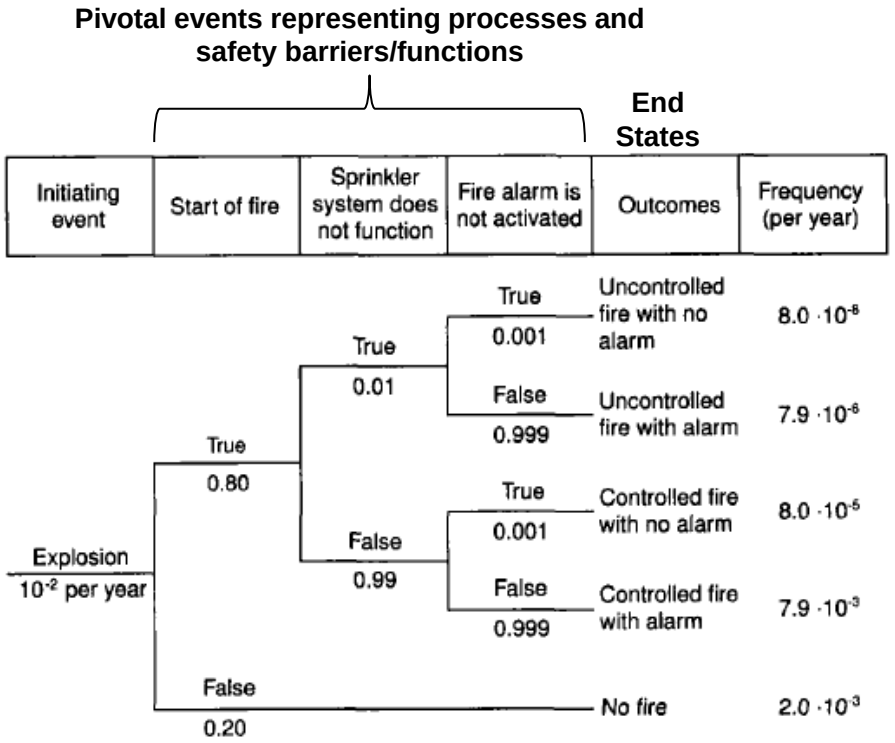
* Yucca Mountain Project Pre-closure Safety Analysis

Event Tree Analysis (ETA)

- **Major steps in an event tree analysis (e.g., after Rausand and Hoyland 2004; CCPS 1992), an *inductive* technique:**

1. Identification of an *initiating event (hazard)* causing the accident or failure
2. Identification/design of *safety functions* /barriers/procedures to mitigate the initiating event—failure of a barrier results in an *"intermediate" or pivotal event*
3. Construction of the *event tree**
4. Description of the resulting accident *event sequences*
5. Calculation of *frequencies/probabilities*:

frequency of end state(s) = frequency of initiating event × probability of each intermediate event



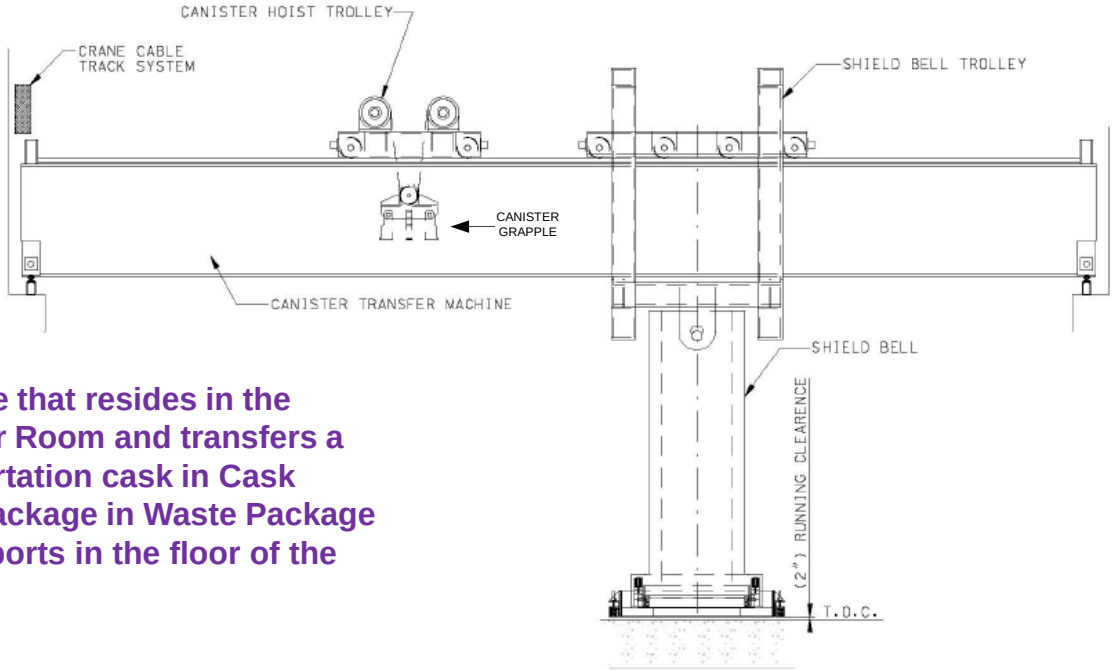
Example event tree*

*Convention: Upper branches represents success ("true"), while lower branches represent failure ("false").

* Taken from Rausand, M. and A. Hoyland 2004. *System Reliabiltiy Theory: Models, Statistical Methods, and Applications, Second Edition*, John Wiley & Sons, Inc., Hoboken, NJ.

Example from Yucca Mountain Pre-Closure Safety Analysis (PCSA)

- **PCSA used a well-established methodology codified in various NUREGs of the U.S. NRC (e.g., see NRC 1983)**
- **Combines ETA and FTA:**
  - Each "pivotal event" (i.e., intermediate event) in the PCSA event sequences was decomposed using a *fault tree* to define its probability of occurrence
- **Example hazardous events associated with Canister Transfer Machine (CTM) operations inside the Canister Receipt and Closure Facility (CRCF):**



CTM: An overhead fixed crane that resides in the second-floor Canister Transfer Room and transfers a waste canister from a transportation cask in Cask Unloading Room to a waste package in Waste Package Loading Room, via two large ports in the floor of the Canister Transfer Room

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Example Event Tree/Fault Tree Combination for Canister Transfer Machine (CTM)

Safety barriers/intermediate events →

INIT-EVENT	Canister Containment Remains Intact: CANISTER	Shielding Remains Intact: SHIELDING	HVAC Confinement Maintain: CONFINEMENT	Moderator Prevented from Entering Canister: MODERATOR	#	END-STATE-NAMES
Structural Challenge to Canister					1	OK
					2	DE-SHIELD-LOSS
					3	RR-FILTERED
					4	RR-FILTERED-ITC
					5	RR-UNFILTERED
					6	RR-UNFILTERED-ITC

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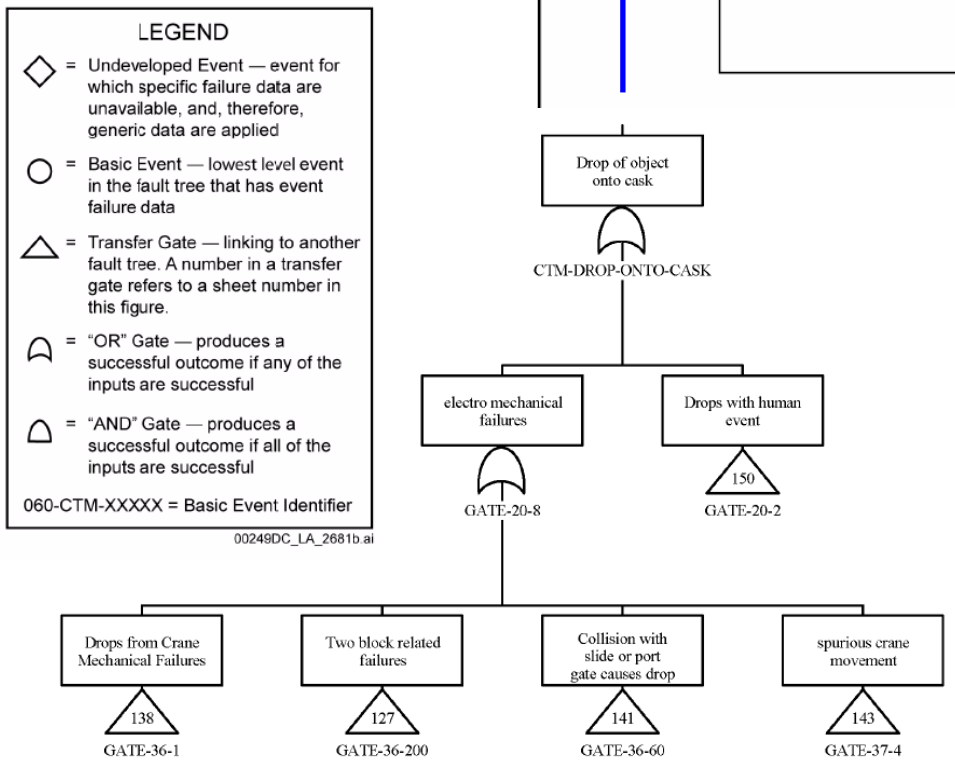
End states

1. **OK**
2. **Direct exposure, shielding loss**
3. **Radionuclide release, filtered by HVAC**
4. **Radionuclide release, filtered by HVAC, also important to criticality**
5. **Radionuclide release, unfiltered by HVAC**
6. **Radionuclide release, unfiltered by HVAC, also important to criticality**



- **Top or Initiating Event in DBEMHA:**
  - Drop event that could affect waste package containment
  - Stuck event that could affect waste package containment

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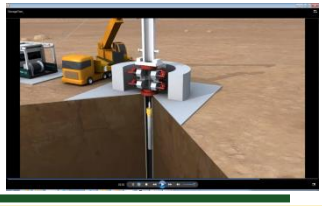
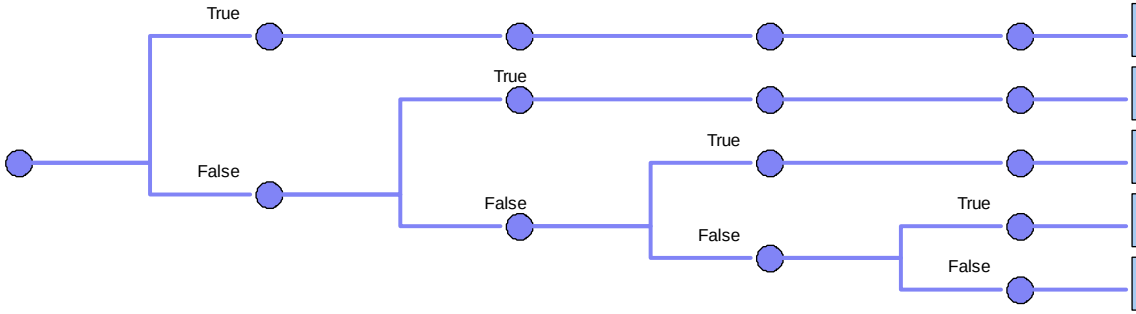
"Stuck in Hole" Event Tree for *Wireline* Emplacement



- **Generated with SAPHIRE v8.1.24**
- **Top and intermediate events in fault tree shown in blue; basic events shown in purple**

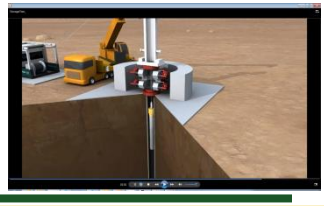
Number of Emplaced WPs - Wireline	WP Freely Reaches Emplacement Zone	WP Stuck in Emplacement Zone	Fishing Attempt Successful	Waste Package NOT Breached by Fishing	#	End State (Phase -)	Comments (Phase -)
NUM-WP-WIRE	WIRE-WP-NOT-STUCK	WP-STUCK-IN-EZ	FISH-SUCCESS	WP-NOT-BREACH-FISH			



1	OK-CONTINUE	Outcome F
2	STUCK-EZ-NO-BREACH	Outcome D
3	FISHED-NO-BREACH-ABANDON	Outcome E
4	STUCK-ABOVE-EZ-NOBREACH	Outcome G
5	STUCK-ABOVE-EZ-BREACHED	Outcome A

Outcome		Key Assumptions	Occupational Safety	Detectable Radiation Leakage	Incremental Cost (> normal wireline ops)
A	WP(s) breached above disposal zone (e.g. by fishing)	Fishing successful; borehole decon, sealing, plugging	TBD (primary risk may be radiological exposure during repair of critical equipment)	Yes	Fishing and remediation; delay; decon; loss of hole
B	WP(s) breached in emplacement zone	No fishing; borehole decon, sealing, plugging		Yes	Remediation; delay; decon; loss of hole
C	WP(s) dropped into disposal zone (or something dropped onto WPs); no breach	Fishing successful; WP(s) retrieved, inspected, replaced; borehole useable		No	Fishing (incl. string); delay; WP transport, inspection and replacement
D	WP(s) stuck in disposal zone; no breach	No fishing or further emplacement; cementing, sealing, plugging per plan		No	Delay; loss of disposal capacity
E	WP(s) stuck above disposal zone; no breach	Fishing successful; WP(s) retrieved; no further emplacement; cementing, sealing, plugging per plan		No	Fishing; delay; loss of disposal capacity
Normal operations; emplace 400 WPs					
F1	Drill-string	None	See above	No	See cost memo
F2	Wireline			No	Zero

"Stuck in Hole" Fault Tree for *Wireline* Emplacement



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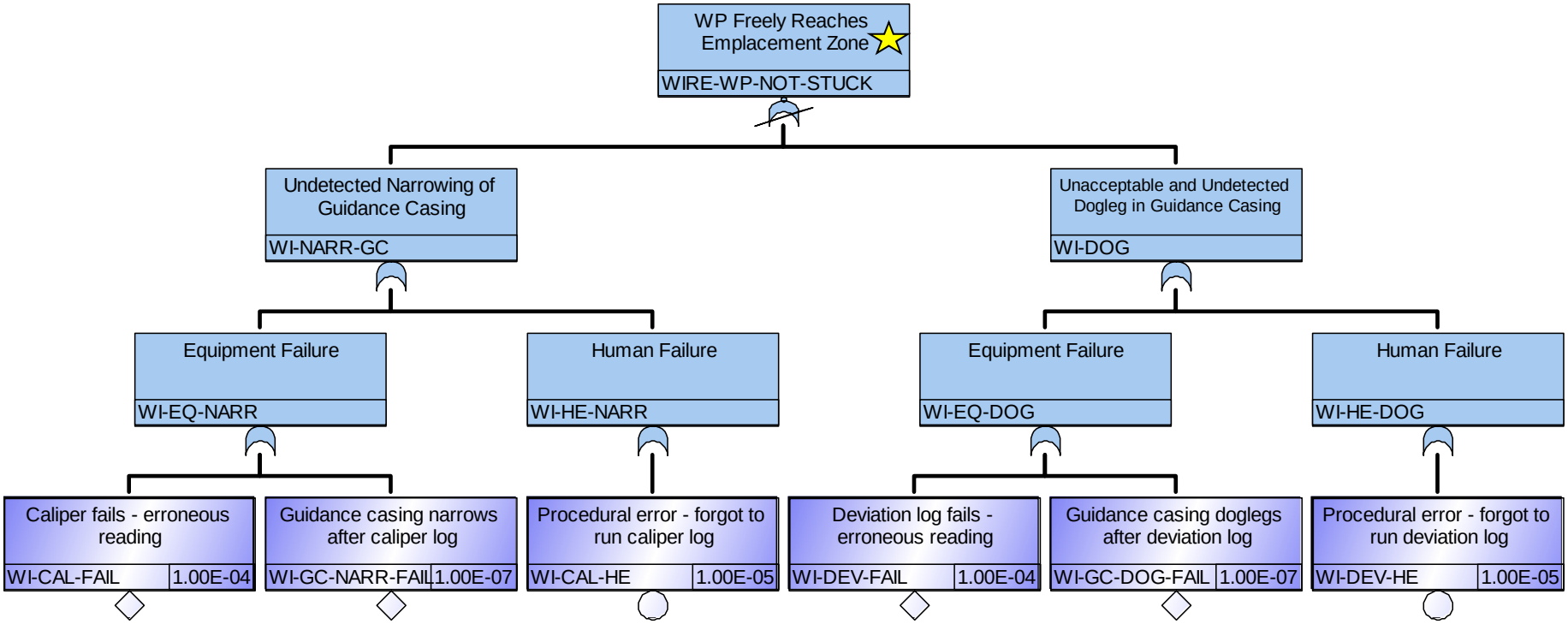

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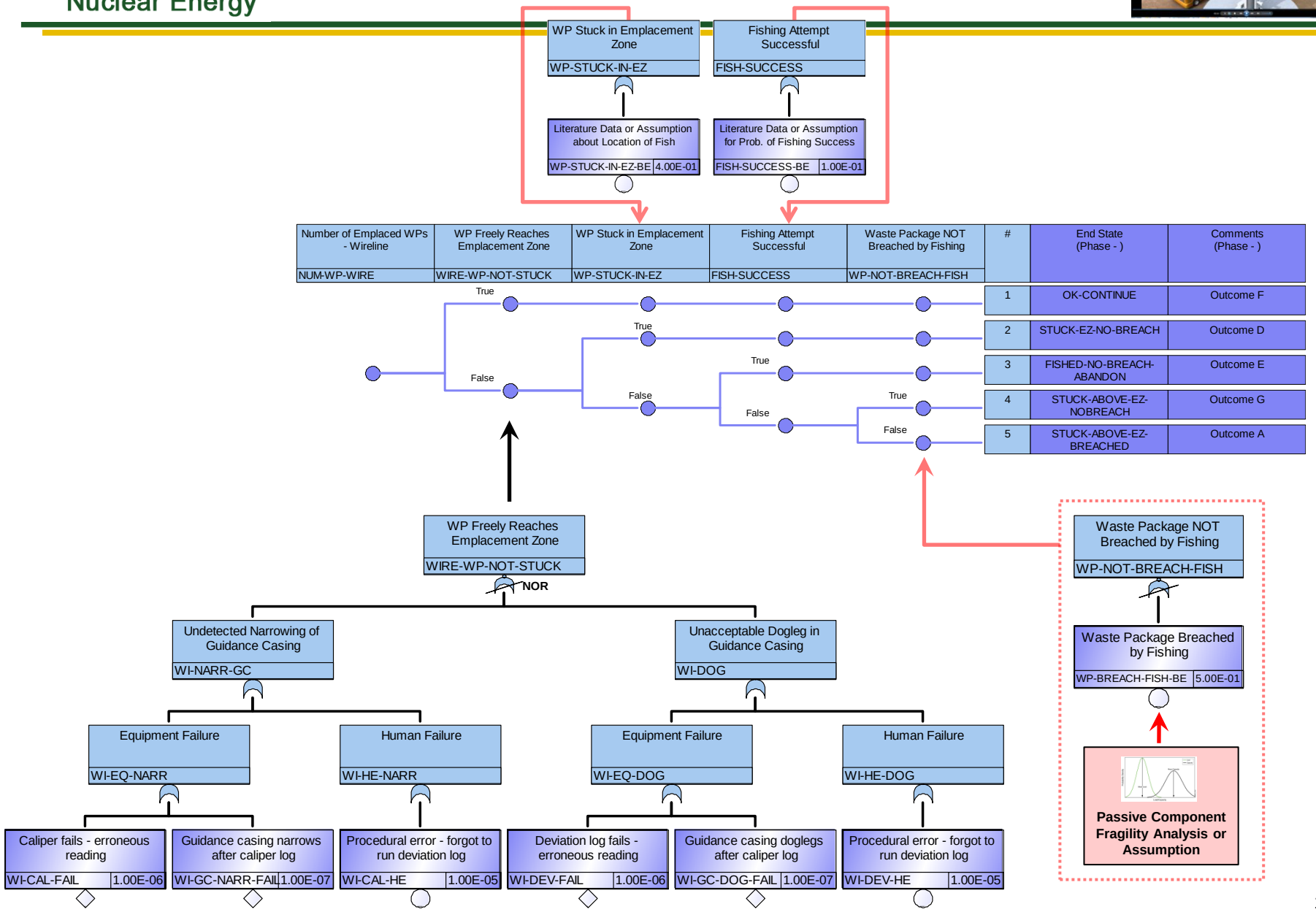
Combined "Stuck in Hole" Event and Fault Trees for *Wireline* Emplacement



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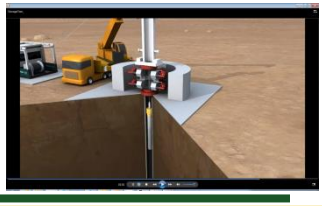
"Drop in Hole" Event Tree for *Wireline* Emplacement



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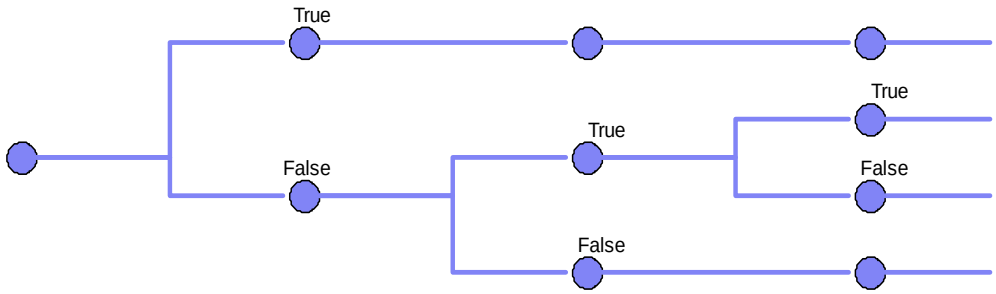
- **Top and intermediate events in fault tree shown in blue; basic events shown in purple**

Number of Emplaced WPs - Wireline	Drop Event Does NOT Occur ★	Wireline -- Waste Package NOT Breached by Drop	Successful Fishing of Dropped WP	#	End State (Phase -)	Comments (Phase -)
NUM-WP-WIRE	WL-NO-DROP	WL-WP-NOBREACH-DROP	FISH-SUCCESS-DROP			
				1	OK-CONTINUE	Outcome G
				2	OK-FISH-CONTINUE	Outcome C
				3	OK-PLUG-CONTINUE	Outcome C*
				4	DECON-SEAL-ABANDON	Outcome B



Outcome		Key Assumptions	Occupational Safety	Detectable Radiation Leakage	Incremental Cost (> normal wireline ops)
A	WP(s) breached above disposal zone (e.g. by fishing)	Fishing successful; borehole decon, sealing, plugging	TBD (primary risk may be radiological exposure during repair of critical equipment)	Yes	Fishing and remediation; delay; decon; loss of hole
B	WP(s) breached in emplacement zone	No fishing; borehole decon, sealing, plugging		Yes	Remediation; delay; decon; loss of hole
C	WP(s) dropped into disposal zone (or something dropped onto WPs); no breach	Fishing successful; WP(s) retrieved, inspected, replaced; borehole useable		No	Fishing (incl. string); delay; WP transport, inspection and replacement
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E	WP(s) stuck above disposal zone; no breach	Fishing successful; WP(s) retrieved; no further emplacement; cementing, sealing, plugging per plan		No	Fishing; delay; loss of disposal capacity
Normal operations; emplace 400 WPs					
F1	Drill-string	None	See above	No	See cost memo
F2	Wireline			No	Zero

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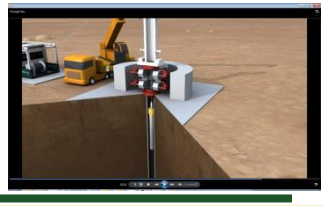
"Drop in Hole" Fault Tree for *Wireline* Emplacement



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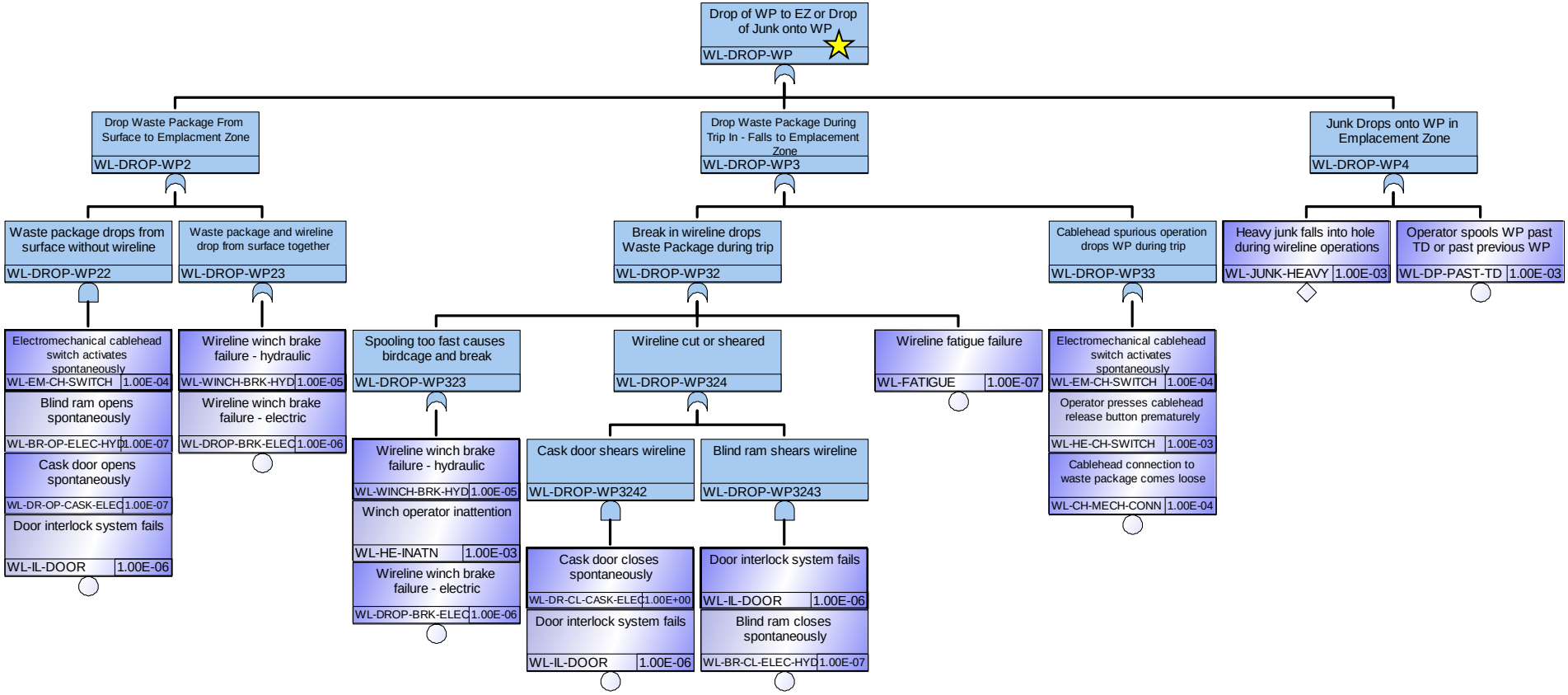
- **Top and intermediate events in fault tree shown in blue; basic events shown in purple**
- **Probabilities are just placeholders**



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Combined "Drop in Hole" Event and Fault Trees for *Wireline* Emplacement

Number of Emplaced WPs - Wireline	Drop Event Does NOT Occur	Wireline -- Waste Package NOT Breached by Drop	Successful Fishing of Dropped WP (Prob. by assumption)	#	End State (Phase -)	Comments (Phase -)
NUM-WP-WIRE	WL-NO-DROP	WL-WP-NOBREACH-DROP	FISH-SUCCESS-DROP			
	True			1	OK-CONTINUE	Outcome G
		True		2	OK-FISH-CONTINUE	Outcome C
	False	True	False	3	OK-PLUG-CONTINUE	Outcome C*
		False		4	DECON-SEAL-ABANDON	Outcome B

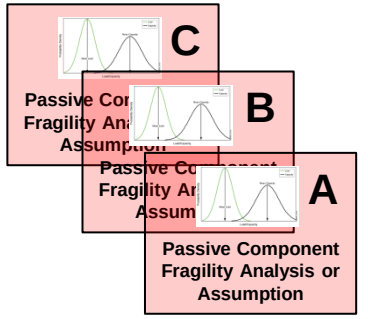
C
Complement of: Junk Drops onto WP in Emplacement Zone
WL-DROP-WP4
- Heavy junk falls into hole during wireline operations — WL-JUNK-HEAVY 1.00E-03
- Operator spools WP past TD or past previous WP — WL-DP-PAST-TD 1.00E-03

B
Complement of: Drop Waste Package From Surface to Emplacment Zone
WL-DROP-WP2
- Waste package drops from surface without wireline — WL-DROP-WP22
  - Electromechanical cablehead switch activates spontaneously — WL-EM-CH-SWITCH 1.00E-04
  - Blind ram opens spontaneously — WL-BR-OP-ELEC-HYD 1.00E-07
  - Cask door opens spontaneously — WL-DR-OP-CASK-ELEC 1.00E-07
  - Door interlock system fails — WL-IL-DOOR 1.00E-06
- Waste package and wireline drop from surface together — WL-DROP-WP23
  - Wireline winch brake failure - hydraulic — WL-WINCH-BRK-HYD 1.00E-05
  - Wireline winch brake failure - electric — WL-DROP-BRK-ELEC 1.00E-06

A
Complement of: Drop Waste Package During Trip In - Falls to Emplacement Zone
WL-DROP-WP3
- Break in wireline drops Waste Package during trip — WL-DROP-WP32
  - Spooling too fast causes birdcage and break — WL-DROP-WP323
    - Wireline winch brake failure - hydraulic — WL-WINCH-BRK-HYD 1.00E-05
    - Winch operator inattention — WL-HE-INATN 1.00E-03
    - Wireline winch brake failure - electric — WL-DROP-BRK-ELEC 1.00E-06
  - Wireline cut or sheared — WL-DROP-WP324
    - Cask door shears wireline — WL-DROP-WP3242
      - Door interlock system fails — WL-IL-DOOR 1.00E-06
      - Cask door closes spontaneously — WL-DR-CL-CASK-ELEC 1.00E+00
    - Blind ram shears wireline — WL-DROP-WP3243
      - Door interlock system fails — WL-IL-DOOR 1.00E-06
      - Blind ram closes spontaneously — WL-BR-CL-ELEC-HYD 1.00E-07
  - Wireline fatigue failure — WL-FATIGUE 1.00E-07
- Cablehead spurious operation drops WP during trip — WL-DROP-WP33
  - Electromechanical cablehead switch activates spontaneously — WL-EM-CH-SWITCH 1.00E-04
  - Operator presses cablehead release button prematurely — WL-HE-CH-SWITCH 1.00E-03
  - Cablehead connection to waste package comes loose — WL-CH-MECH-CONN 1.00E-04

Wireline -- Waste Package NOT Breached by Drop
WL-WP-NOBREACH-DROP

Waste Package Breached by Drop
WL-WP-BREACH-DROP-BE 1.00E-05



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Reliability Failure Databases for Frequency/Probability*

1. **Component failure event databases, e.g.,**
   - GIDEP (Government Industry Data Exchange Program) in the U.S.
2. **Accident and incident databases, e.g.,**
   - WOAD (World Offshore Accident Databank), by DNV (Det Norske Veritas)
   - Oil and Gas UK (co-sponsored by the UK Health and Safety Executive)
   - PSID (Process Safety Incident Database), by AIChE
3. **Component reliability databases, e.g.,**
   - OREDA (Offshore Reliability Database), by DNV
   - NPRD (Nonelectronic Parts Reliability Database), by RAIC, a DoD center
   - PERD (Process Equipment Reliability Database), by AIChE
4. **Common cause failure databases**
   - CCFDB (Common-Cause Failure Database), by the U.S. NRC
5. **More than thirty databases and reliability sources cited in YMP PCSA**

* First four major categories of "hardware" reliability databases are according to Rausand and Hoyland (2004), Sec. 14.2. Also, see Vinnem (2007), Sec. 5.9.

Future Work

- More detailed wireline fault tree?
- Generate a detailed fault tree for drill string emplacement (see back-up slides)
- Determine available accident frequencies and failure probabilities that are applicable to wireline and drill string emplacement operations
- Convene an expert panel to review event trees, fault trees, accident frequencies, and failure probabilities


Thanks for your attention!

Back-up Slides

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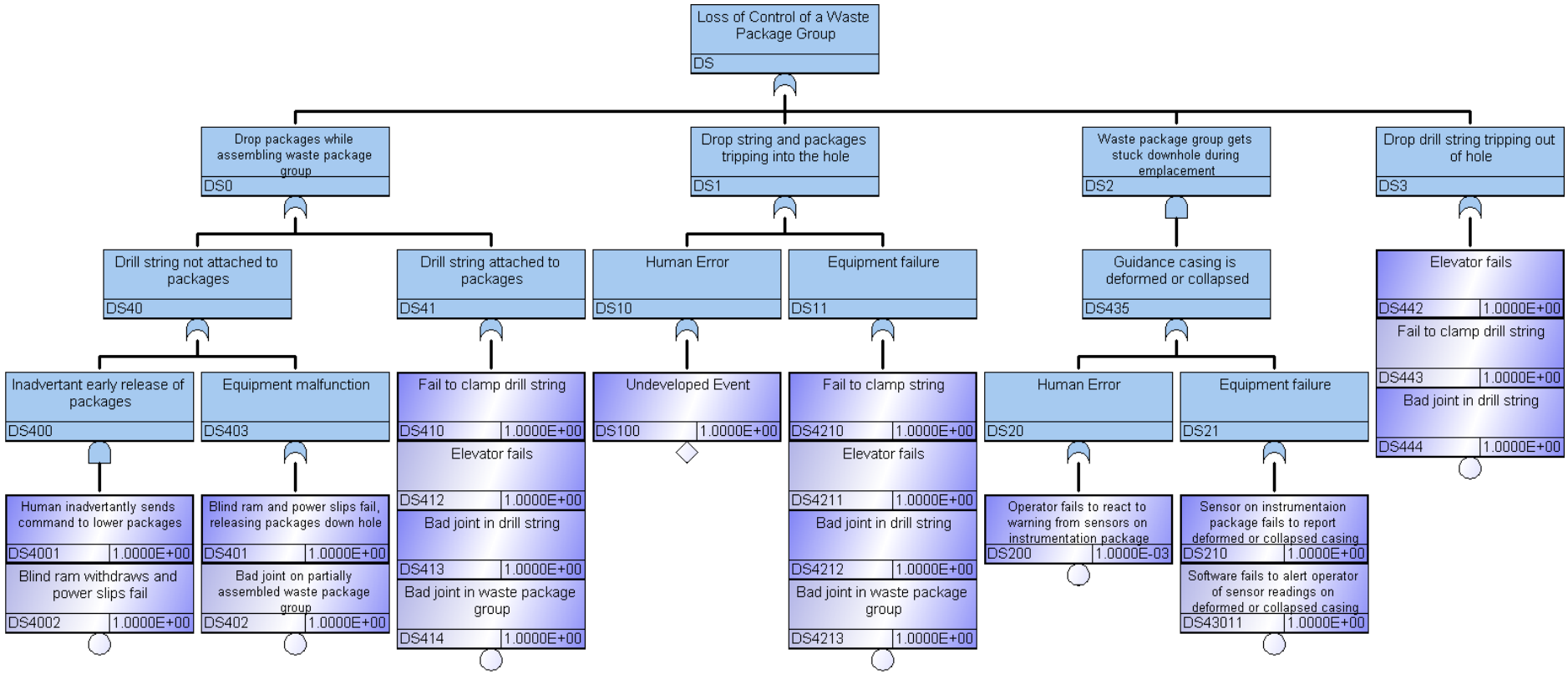
Preliminary Fault Tree for *Drill String* Emplacement



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*** From BSC (2009, Sec. C1.2): "The data source had to be widely available, not proprietary." References from Table C1.2-1 and Sec. C5.**

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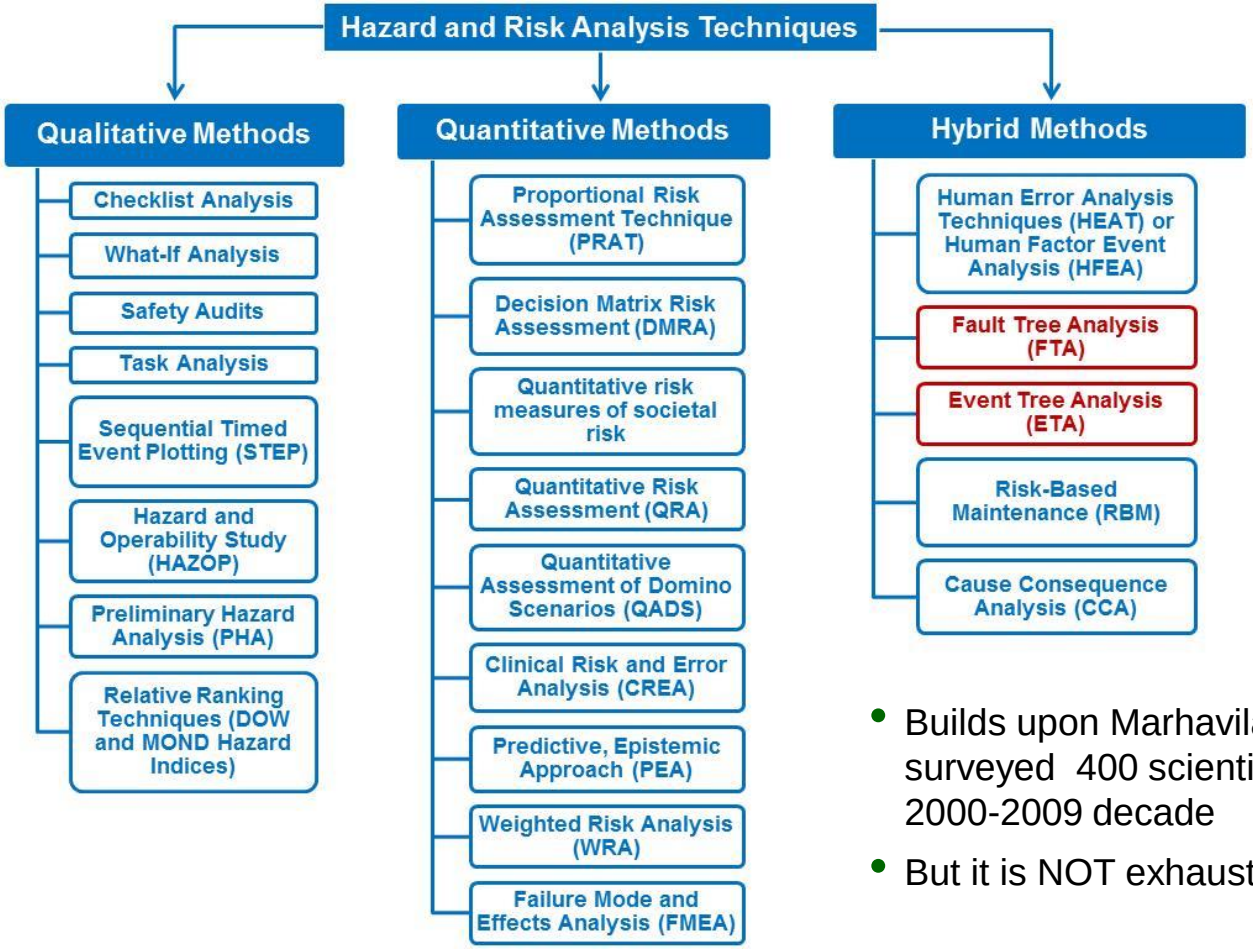
Risk/Hazard Analysis Techniques

- **After Matanovic et al. 2014, *Risk Analysis for Prevention of Hazardous Situations in Petroleum and Natural Gas Engineering:***



- Builds upon Marhavilas et al. (2011), who surveyed 400 scientific papers from the 2000-2009 decade
- But it is NOT exhaustive; others like BBN

Fault Tree Analysis (FTA)—with an example from the YMP PCSA*

- **Five major steps in an fault tree analysis (e.g., after Rausand and Hoyland 2004), a *deductive* technique:**
  1. Definition of the problem and the boundary conditions, including definition of "top event"
  2. Construction of the fault tree, backwards from "immediate cause events" (just below top event) to a level of "basic events" or causes
  3. Identification of minimal "cut sets"**
  4. Qualitative analysis of the fault tree
  5. Quantitative analysis of the fault tree

** Minimal "cut set" = *smallest combination of basic events (e.g., component failures) which, if they all occur or exist, will cause the top event to occur*

Fault tree for one of the *initiating events* that might compromise a canister in the YMP Canister Transfer Machine (CTM)

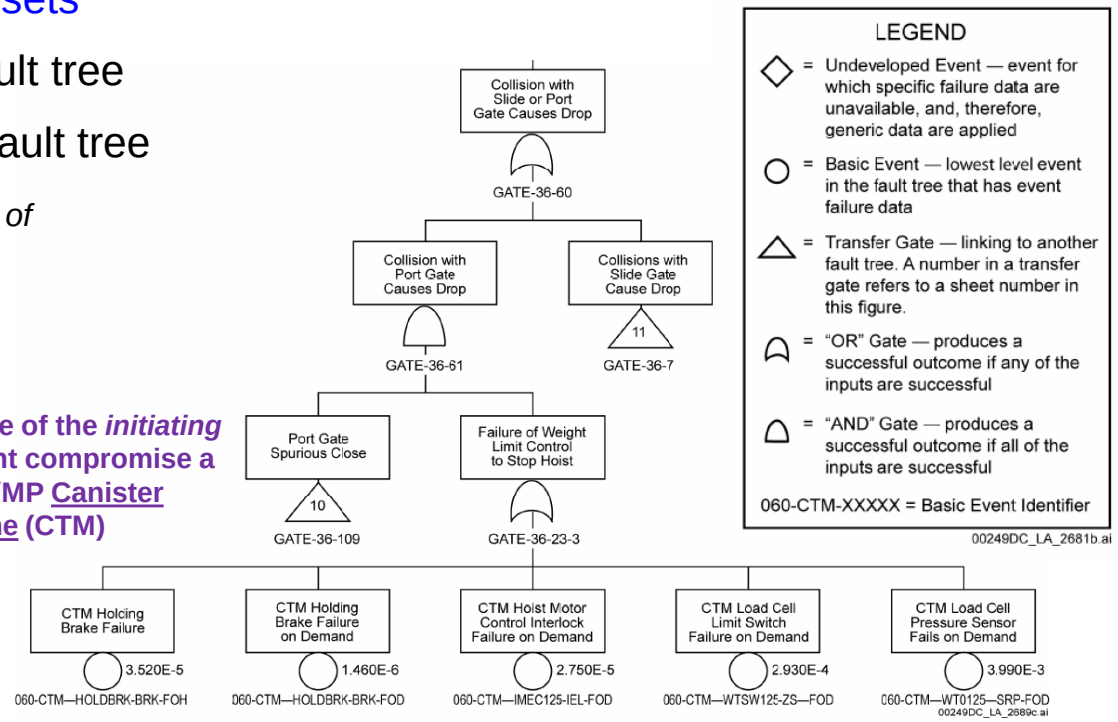


Figure 1.7-8. Example of Fault Tree of the Preclosure Safety Analysis (Sheet 9 of 12)

NOTE: CTM = canister transfer machine.

DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application Safety Analysis Report*. DOE/RW-0573, Revision 1.

Strengths of Fault Tree Analysis

- **Easily combines human and equipment failure (both of which are expected to be possible in DBH emplacement)**
- **Can be used to derive the probability of complex intermediate ("pivotal") events in an event sequence**

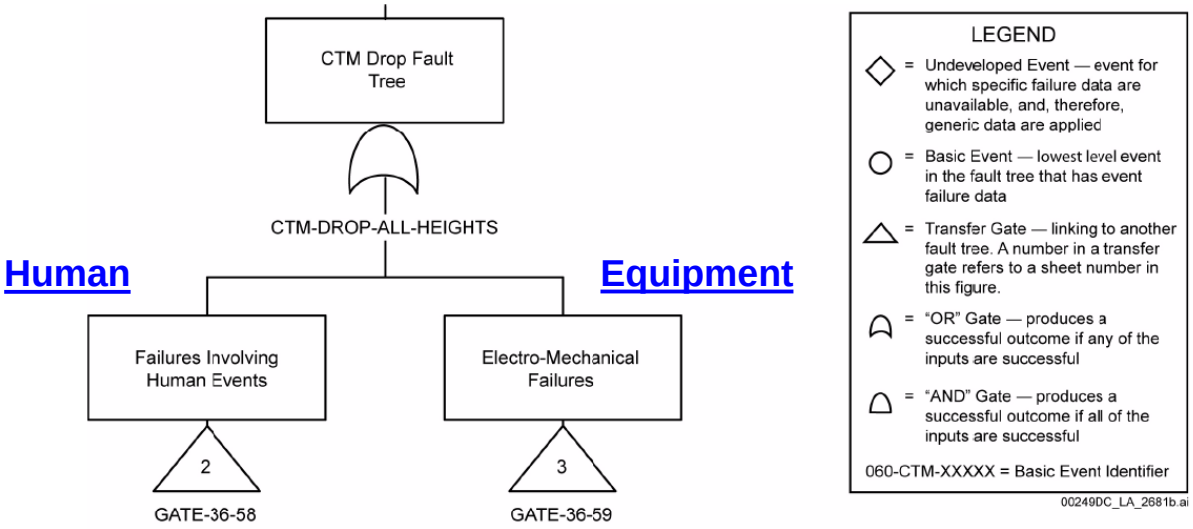


Figure 1.7-8. Example of Fault Tree of the Preclosure Safety Analysis (Sheet 1 of 12)

NOTE: CTM = canister transfer machine.

Source: BSC 2008 [DIRS 180095], Attachment B, Section B4.4.1.8.

DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application Safety Analysis Report*. DOE/RW-0573, Revision 1.

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Potential "Internal" Hazardous Events for *Wireline* Emplacement—based on emplacement steps

Event ID	Event Identifier	Description of Potential Hazardous Event (based on sequential emplacement steps)	Risk Mitigation Measures, Assumptions, and Other Notes	Screening Decision (include/exclude)
	TOP EVENT	***Drop waste package to emplacement zone or junk onton waste package***		include
	Immediate-cause event	Drop waste package during surface operations	Risk prevention measure: Cask/wellhead-safety-door/blind-ram interlock system	include
	Immediate-cause event	Drop waste package during trip into hole		include
	Immediate-cause event	Junk drops onto waste package		include
	Intermediate event	Waste package drops from surface without wireline attached		include
	Intermediate event	Waste package drops from surface with wireline attached		include
	Intermediate event	Wireline breaks during during trip in		include
	Intermediate event	Cablehead releases accidentally during trip in		include
	Intermediate event	Spooling wireline too fast causes bird cage	Risk prevention measure: Automated speed and tension control on wireline winch	include
	Intermediate event	Wireline cut or sheared		include
	Intermediate event	Cask door shears wireline		include
	Intermediate event	Blind ram shears wireline		include
	TOP EVENT	***Waste package stuck in borehole (in guidance casing)***		include
	Immediate-cause event	Undetected narrowing of guidance casing	Risk prevention measure: Run caliper log prior to lowering a waste package	include
	Immediate-cause event	Undetected dogleg in guidance casing	Risk prevention measure: Run deviation log prior to lowering a waste package	include
	Undeveloped event	Guidance casing becomes misaligned or narrows after caliper log		include
	Undeveloped event	Guidance casing doglegs after deviation log		include
	Undeveloped event	Caliper log fails – gives undetected erroneous readings		include
	Undeveloped event	Deviation log fails – gives undetected erroneous readings		include
	Basic event	Cask door closes spontaneously		include
	Basic event	Cask door opens spontaneously		include
	Basic event	BOP blind ram closes spontaneously		include

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Potential "Internal" Hazardous Events for *Wireline* Emplacement—based on emplacement steps (cont.)

Event ID	Event Identifier	Description of Potential Hazardous Event (based on sequential emplacement steps)	Risk Mitigation Measures, Assumptions, and Other Notes	Screening Decision (include/exclude)
	Basic event	BOP blind ram opens spontaneously		include
	Basic event	Wireline fatigue failure	Risk prevention measure: Schlumberger TuffLINE cable	include
	Basic event	Wireline winch brake failure (hydraulic)		include
	Basic event	Wireline winch brake failure (electric)		include
	Basic event	Door interlock system fails		include
	Basic event	Electrical-mechanical switch in cablehead malfunctions and releases waste package early		include
	Basic event	Cablehead connection to waste package comes loose		include
	Basic event	Heavy junk falls into borehole		include
	Basic human event	Operator spools waste package "past TD" or "past previous waste package"	Risk prevention measure: Procedural and software controls; "crush box" on bottom of waste package	include
	Basic human event	Forgot to run caliper log prior to lowering a WP		include
	Basic human event	Forgot to run deviation log prior to lowering a WP		include
	Basic human event	Winch operator inattention		include
	Basic human event	Operator pushes cablehead release button prematurely		include
	Basic event	BOP (blind ram) closes on the spontaneously waste package	Risk prevention assumption: Waste package is strong enough to be structurally unaffected.	exclude
	Basic event	Lower cask door closes spontaneously on the waste package	Risk prevention assumption: Waste package is strong enough to be structurally unaffected.	exclude
	Basic event	Cable head fails to release while package is at TD	May not result in a hazardous event; only requires an extra trip in and out to fix the cable head	exclude
	Basic event	Cable head releases on trip out with waste package still attached, releasing package to free fall to the bottom	May not result in a hazardous event, since the package should reach the emplacement zone; also requires previous failure of cable head release at TD	exclude
	Basic event	Upper cask door closes spontaneously after cable head is attached but while lower cask door is still closed.	Risk prevention measure: A restraint to prevent upper door closing is set prior to cable head attachment. Furthermore, the package has "nowhere to go" at this point, so no significant damage.	exclude
	Basic human event	Prior to attachment of cable head, the operator mistakenly opens the lower door on the shipping cask instead of the upper one, dropping package onto the blind ram in the wellhead below	Risk prevention measure: Door/ram/wireline hoist interlock system, including a "deadman" lock out (in case of loss of power or inadvertent energization). This event is not considered to be hazardous enough to include in the analysis.	exclude
	Basic human event	Cable head pulls loose, dropping the package on the lower cask door, because operator accidentally tried to spool the cable upward beyond the range-limiting pin	Risk prevention assumption: Such a drop within the cask would be small and not cause damage to the package, the cask, or the lower door.	exclude