Deep Borehole Disposal Waste Emplacement Mode Cost-Risk Study - 16346

Ernest Hardin*, Karen Jenni**, Andrew Clark*, John Cochran*, John Finger***, S. David Sevougian* and Jiann Su*
* Sandia National Laboratories, PO Box 5800 MS 0747, Albuquerque, NM 87185-0747 (ehardin@sandia.gov)
** Insight Decisions, LLC, 2200 Quitman St., Denver, CO 80212
*** Consultant to Sandia National Laboratories

ABSTRACT

An engineering study has developed alternative concepts for waste packaging and for emplacing/retrieving packages in deep boreholes. The study compared costs and risks associated with emplacement using wireline vs. drill-string technologies. Selection of a method is needed to proceed with demonstration as part of the Deep Borehole Field Test being conducted by the U.S. Department of Energy, Office of Used Nuclear Fuel Disposition.

Each emplacement method was described as a series of steps, and each step was analyzed for potential to cause any of four off-normal events including drops and getting stuck. Each such event was supported by a fault tree. The hazard analysis identified a number of improvements including: 1) impact limiters; 2) safety systems; 3) instrumentation; and 4) methods to mitigate casing collapse or borehole debris during operations. Off-normal events were related in a top-level event tree with normal and off-normal outcomes. Costs were estimated for each outcome (including recovery and decontamination). A panel of subject matter experts was convened to review the study and provide key inputs.

The wireline method is less costly for normal operations, while the drill-string method has advantages if waste packages become stuck. The wireline method has a lower aggregate probability of accidents resulting in waste package breach. The integrated probability of off-normal events is on the order of a few percent per borehole, and engineered measures are quite important to prevent and mitigate accidents, limiting radiological consequences. Development of these measures during design will help to further improve system reliability.

INTRODUCTION

The deep borehole disposal (DBD) concept consists of drilling a deep borehole into crystalline basement rock, emplacing packages containing nuclear waste into the lower portion of the borehole, and sealing the upper part of the borehole. DBD of HLW has been considered an option for geologic disposal for many years [1]. International efforts over the last half-century on disposal of HLW and SNF have primarily focused on mined repositories. More recently, an updated conceptual evaluation of DBD and a preliminary performance assessment have been completed [2,3]. These studies have identified no fundamental flaws regarding safety or implementation of the DBD concept.

The disposal concept [4] calls for drilling one or more boreholes into crystalline basement rock to a depth of 5 km, emplacing waste packages (WPs) in the lower 2 km, and sealing and plugging the upper 3 km. The disposal zone (DZ) in a single borehole could contain about 400 WPs, each with length of up to 5.5 m. The borehole seal system primarily would consist of alternating layers of compacted bentonite clay, long-lived cement, and cement/crushed rock backfill.

This paper describes waste packaging concepts, and two alternative methods for emplacing packages in a borehole: the wireline and drill-string concepts. It then presents a study of the costs and hazards associated with each method, develops risk insights, and recommends the wireline method.

Description of Waste Packaging

Packaging concepts are intended to isolate waste at 1-atm internal pressure, in a downhole environment that has:

- Temperature up to 170°C at 5 km depth, depending on the geothermal gradient
- Pressure up to 65 MPa (5-km depth with average borehole fluid density 1.3× pure water)
- Chemical corrosion environment likely to be concentrated NaCl or $CaCl_2$ brine

The concept for a reference size WP that fits into a 0.43-m (17-inch) diameter borehole inside a guidance casing with 0.34-m (13-3/8 inch) outer diameter [3], would have:

- Maximum outer diameter of 0.28 m
- Overall length up to 5.5 m (accommodating 5-m long waste forms)
- Dry loaded maximum weight 2,100 kg or buoyant weight 1,755 kg in pure water
- Penetrating radiation (e.g., packages with Cs/Sr capsules may have contact gamma dose rate at the surface of several hundred rem per hour)
- Heat output (e.g., 100 to 500 W per meter depending on age and mode of packaging)
- Nominal containment lifetime of 10 years, allowing for delay in operations and uncertainty in the corrosion rate

WPs for DBD could accept pre-canistered bulk waste (e.g., granular solids) in thin-wall canisters loaded at waste-generator facilities, or they could be loaded directly with bulk granular waste. An example of the former type with internal-flush geometry for accepting pre-canistered waste, is shown in Fig. 1. Package-package connections for drill-string emplacement would include: 1) a threaded connection to the package below; and 2) a threaded connection to the package or drill pipe attachment above. Connections for wireline emplacement of individual packages would include a releasable latch and fishing neck on top, and an impact limiter on the bottom (Fig. 2). The impact limiter would prevent package failure in the event of a drop in the borehole or during handling at the surface.

For a string of 40 packages threaded together and hung in the borehole, the maximum axial tensile load from the combined weight would be 686 kN (70 MT) (buoyant weight in pure water). A compressive load of similar magnitude would be produced with the string set on the bottom. Other loads include set-down loads during emplacement, bending or buckling, and axial forces exerted during fishing of stuck packages. Packages must maintain containment during emplacement, and possible retrieval and fishing operations, until borehole plugging and sealing are complete. A minimum factor of safety against yielding in response to all of these conditions is being used for mechanical analysis, and a value of 2.0 is proposed [5].

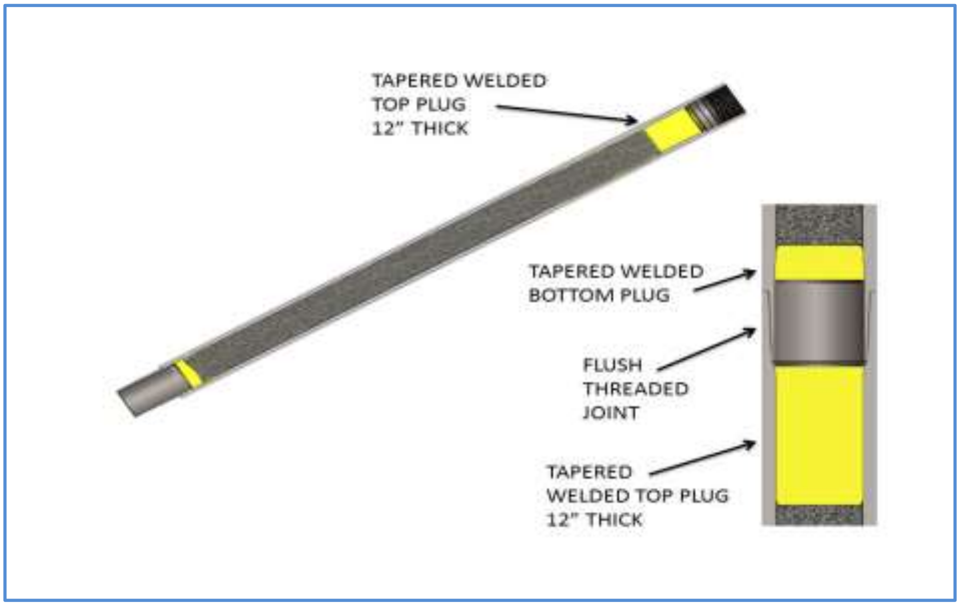

Fig. 1. Waste package concept (internal-flush example shown).

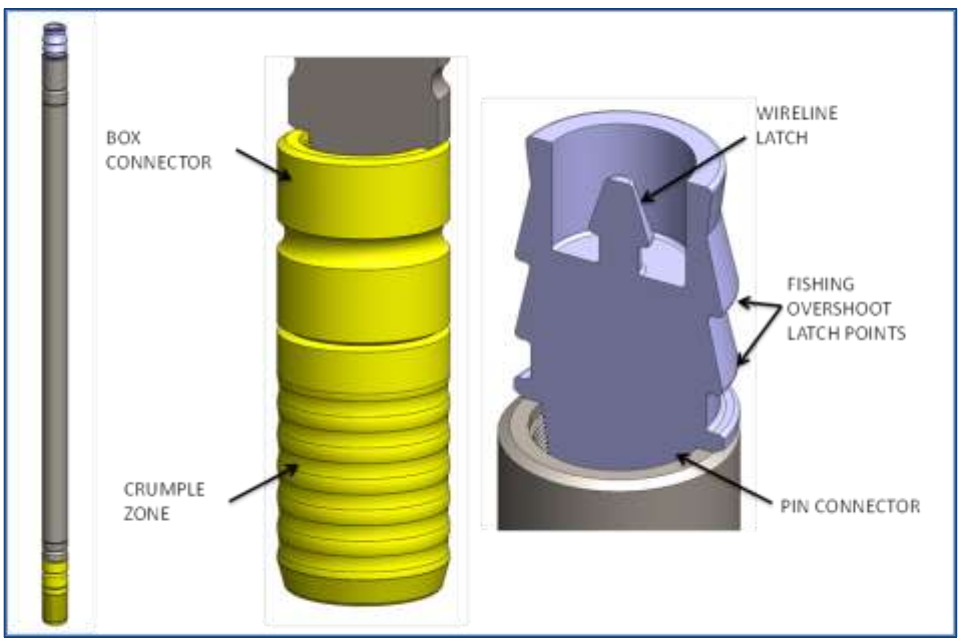

Fig. 2. Modular impact limiter and wireline latch/fishing neck.

Package Configuration for Drill-String Emplacement

The first (lowermost) package in a string of packages for emplacement will be an instrumentation package containing no waste. This lead-package would have a weak point so that if the string became stuck during lowering, it could break away to facilitate retrieval of the waste packages. The instrumentation package would also initiate the assembly of a string at the surface, and would be designed to crush in response to excessive loads associated with setting the string down on the borehole bottom during emplacement. A release mechanism (a J-slot safety joint was proposed [3]) would be threaded onto the topmost package in each string. The safety joint would be released once the string is on the bottom, and it would allow for re-engagement if retrieval is necessary.

Package Configuration for Wireline Emplacement

WPs for wireline emplacement would essentially be the same, but emplaced individually on an electric wireline. The upper end would have a neck that mates with an electrically actuated releasable cable head (Fig. 2). The lower end would attach an impact limiter. Packages must sustain the compressive load of a stack of up to 40 during emplacement, combined with external pressure loading, with an acceptable factor of safety [5].

DESCRIPTION OF EMPLACEMENT CONCEPTS

This section briefly describes the alternative emplacement concepts, which are further elaborated in a companion paper [4]. For both the wireline and drill-string concepts, the 0.38-m (13-3/8 inch) tieback guidance casing linked with a DZ liner of the same diameter, would provide a continuous pathway for lowering WPs to the DZ.

Drill-String Emplacement – After drilling and construction of the disposal borehole are complete, and the drilling rig is moved off, a number of modifications would be made: basement construction, surface pad installation, transfer carrier installation, emplacement (workover) rig setup, and installation of the safety system, control room and ancillary surface equipment.

The basement (Fig. 3) would serve two main functions: 1) provide a shielded facility to house the blowout preventer (BOP) and equipment for handling WPs, and 2) reduce the height requirement for lifting the transfer cask, and for elevation of the emplacement rig. The BOP stack would include an annular preventer to seal around waste packages or drill pipe, an "elevator" ram configured as a pipe ram to grip package strings at the joints, a blind ram to close the borehole when not in use, and any other valving or equipment required. Equipment for making up WP strings would include remotely operated power slips and power tongs (Fig. 3).

Following the Woodward-Clyde (1983) concept [6], a track-mounted transfer carrier would deliver the shipping cask over the last 15-m distance to the borehole (Fig. 4). It would consist of a platform mounted to powered wheel trucks that run on a steel track. The track would be part of a rigid steel frame anchored to a reinforced concrete surface pad. The track would be approximately 2 m wide, straddling the borehole and precisely aligned before erecting the emplacement rig or bringing WPs to a disposal site. After emplacement of approximately 10 strings of packages, with intervening cement plugs, the workover rig would be used for final sealing and plugging.

Wireline Emplacement – After drilling and construction of the disposal borehole are complete, and the drilling rig is moved off, a number of modifications would be made including: surface pad installation, shield construction, and headframe and wireline hoist installation (Fig. 5).

A concrete pad would be poured around the well head, including footings for a headframe. The shield would surround the BOP, or else the BOP could be re-installed below grade. A modern electric wireline would be used such as Schlumberger Tuffline®, on a modern hoist. This example uses double steel armor fully blocked with a high-temperature polymer. It has a working load limit of at least 80 kN (8,200 kg), which is roughly twice the combined buoyant weight of the cable, cable head, wireline logging tool string, and WP.

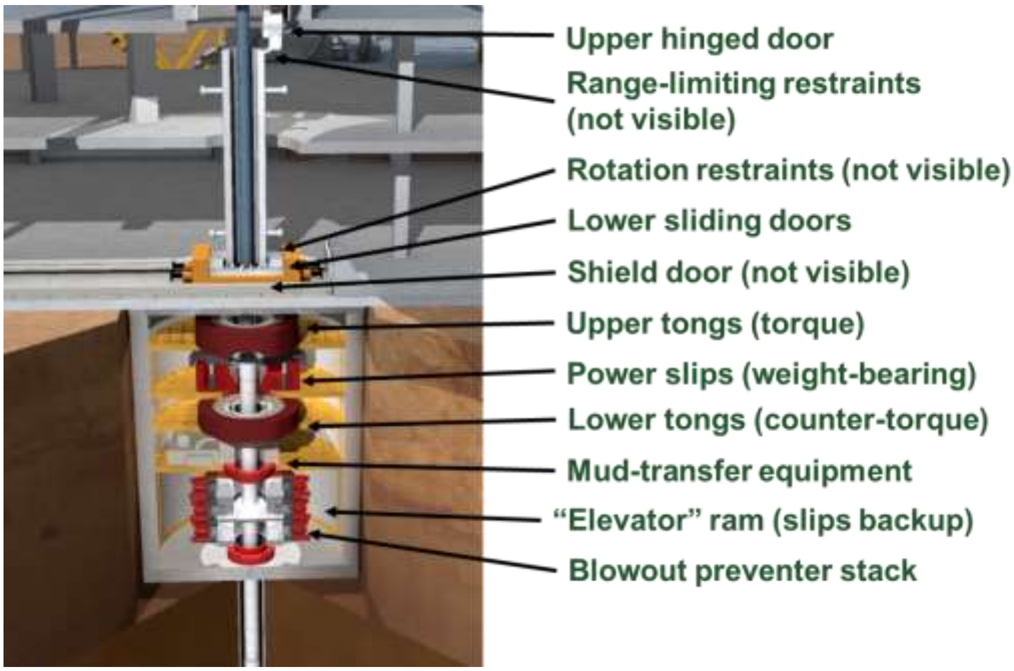

Fig. 3. Cutaway visualization of the transfer cask aligned over the borehole, and basement equipment.

Fig. 4. Visualization of the transfer cask set on the transfer carrier, for locating waste packages directly over the borehole and under the drill rig.

Support of the wireline sheave over the borehole would be provided by the steel headframe, which would be removed after wireline operations are complete. A fixed headframe would be more reliable than truck-mounted cranes for waste emplacement operations. An electrically actuated cable head would release WPs after lowering to emplacement position. Examples include the Haliburton RWCH® (releasable wireline cable head). Off-the-shelf tools would be modified to minimize the length and cost of hardware left in the hole with each package, and to reduce the probability of accidental release while under load. After waste emplacement, a workover rig would be mobilized for final sealing and plugging.

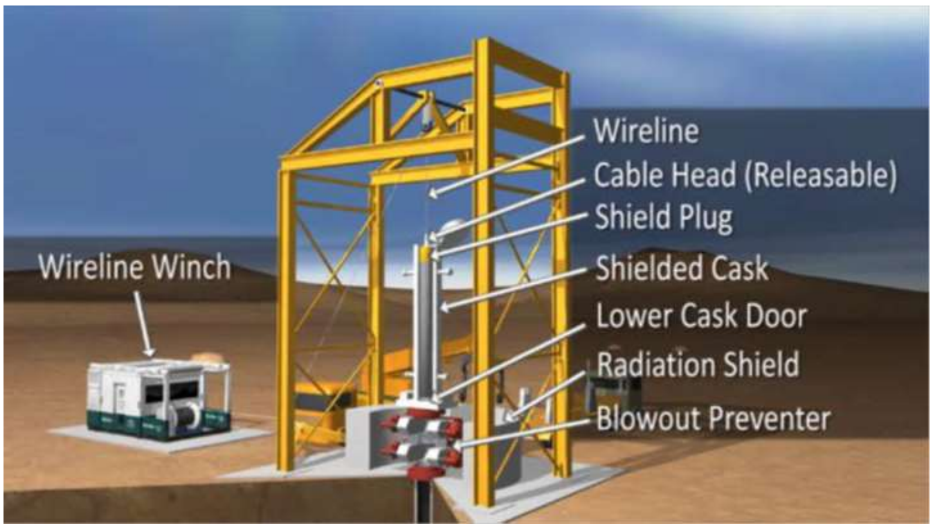

Fig. 5. Cutaway visualization of BOP shield, and transfer/shipping cask in position for waste emplacement.

Emplacement Rate-of-Progress – Drill pipe would be used to lower a string of WPs to the desired depth, up to approximately 4,760 m (total depth minus the length of a package string). Assuming the crew can make up or break down one triple-stand of drill pipe every 5 min, the rate of progress is about 300 m/hr [3]. Thus, lowering a string of WPs would take 15 hr, and the round-trip time including release would be 32 hr (allowance for string set-down and release).

The rate of lowering WPs by wireline would be comparable to lowering bridge plugs (1,800 m/hr [3]). The rate would be controlled by the package sink rate, which in turn would depend on geometry, weight, and fluid viscosity. Assuming a sink rate of 0.5 m/sec is feasible, and that the wireline would be respooled at twice this rate, the round-trip time would be approximately 6 hr (allowance for release, and slower lowering where needed for safety).

With guidance casing running from the surface to total depth, and the borehole filled with an emplacement fluid, it could be possible to allow WPs to sink freely into disposal position ("drop-in" method). Terminal velocity was estimated by Bates et al. [7] to be 2.5 m/sec for similar WPs. Impact limiters on the bottom of each package would readily absorb the energy of impact at this velocity, assuring package integrity in the event of accidental drop in the borehole.

Logistical Controls on Emplacement Schedule – One shipping cask, containing one WP, would be ready each day for emplacement during prototypical DBD operations. The turnaround time for a shipping cask would be at least three days drawing from previous experience [8], but three or more units could be active simultaneously, giving throughput of one WP per day. In addition, placing and curing cement plugs would require additional time. Thus, approximately 430 workdays would be needed to emplace 400 WPs and 10 cement plugs, for either wireline or drill-string emplacement. One advantage of such a schedule is that most operations would be conducted during daylight hours.

Discussion of Coiled Tubing

Note that either the drill-string or wireline emplacement concept could be adapted to use coiled steel tubing for lowering packages. Coiled tubing could push packages into the hole (if permitted) to accelerate emplacement or to free stuck packages. Coiled tubing is available with electrical conductors that could operate an electrically actuated releasable cable head. For the drill-string method coiled tubing could replace the workover rig for emplacement, whereas for the wireline method it could replace the wireline hoist. The coiled tubing method would probably resemble the drill-string method because strings of connected WPs would be emplaced to manage the fatigue life of the tubing. Service life is a few hundred trips at most, particularly if they are deep trips. Thus, a basement such as that described for drill-string emplacement would be needed to assemble the strings.

The cost and potential safety implications associated with tubing fatigue, and the added expense of assembling package strings, mean that coiled tubing operations would likely be more costly than wireline operations. Note that even with wireline emplacement operations, coiled tubing would still be used to set cement plugs.

COST-RISK STUDY DESCRIPTION

A cost-risk study was done to support recommendation of an emplacement concept for handling, emplacement, and retrieval of WPs for the Deep Borehole Field Test (DBFT) being conducted by the U.S. Department of Energy, Office of Used Nuclear Fuel Disposition. This section briefly describes the methodology, the inputs, risk insights developed, and the recommendation.

Study Steps

Multi-attribute utility analysis is straightforward in concept. Three steps are typically followed: 1) identify objectives that an "ideal" alternative would achieve, 2) define a set of performance measures that define each objective, and 3) identify alternatives. Each alternative is evaluated using the performance measures. Then, for each alternative the objectives can be combined using a value model to create a single metric that directly supports a recommendation. The following discussion of hazard analysis, event tree/fault tree analysis, and modeling of normal and off-normal outcomes, shows how this process was implemented.

Hazard Analysis

Each emplacement method was described operationally as a series of steps leading to normal emplacement. Each step was analyzed for its potential to initiate any of four off-normal events:

- Dropping a WP or a string of WPs, from the surface into the borehole.

- Dropping a single WP, or a string of drill pipe lowering a string of WP, on the trip into the borehole.
- Dropping a wireline or a string of drill pipe onto WPs already emplaced.
- Getting one or more WPs stuck above the DZ.

If any one of these off-normal events occurs, uncertainty remains about what would happen next. Figures 6 and 7 show event trees that summarize the sequence of events that would follow the occurrence of any one of these off-normal events, for wireline and drill-string emplacement.

The events along the top of each figure, moving left to right, are the four off-normal events (i.e., types of drops, and getting stuck). For each event the upper branch indicates a favorable outcome (no drop, not stuck, etc.) and the lower branch indicates occurrence of the off-normal event. The probabilities for each off-normal event are calculated in the fault trees, as discussed below.

Subsequent to any off-normal event, there are contingent events that can lead to different outcomes. For each off-normal event involving a drop, there is uncertainty about whether a WP

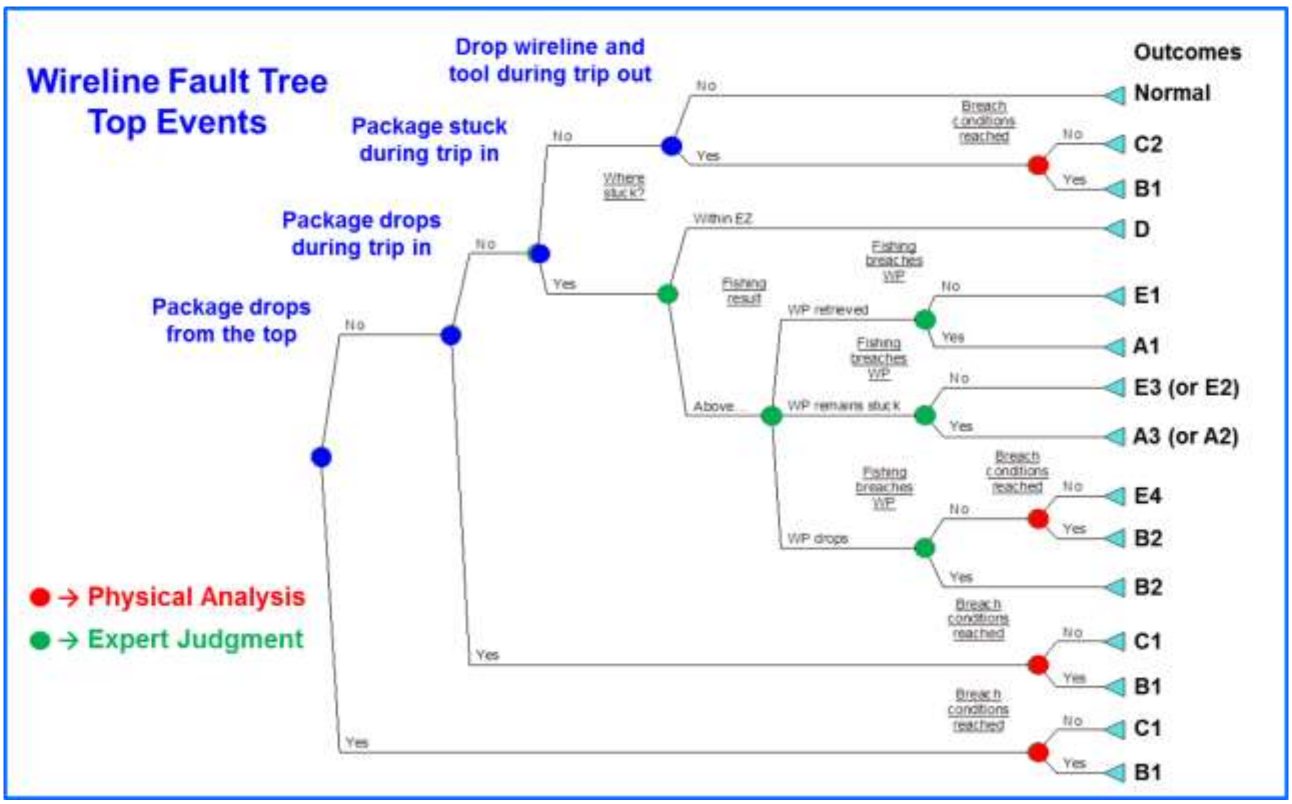

Fig. 6. Wireline event tree, per waste package, with outcomes illustrated.

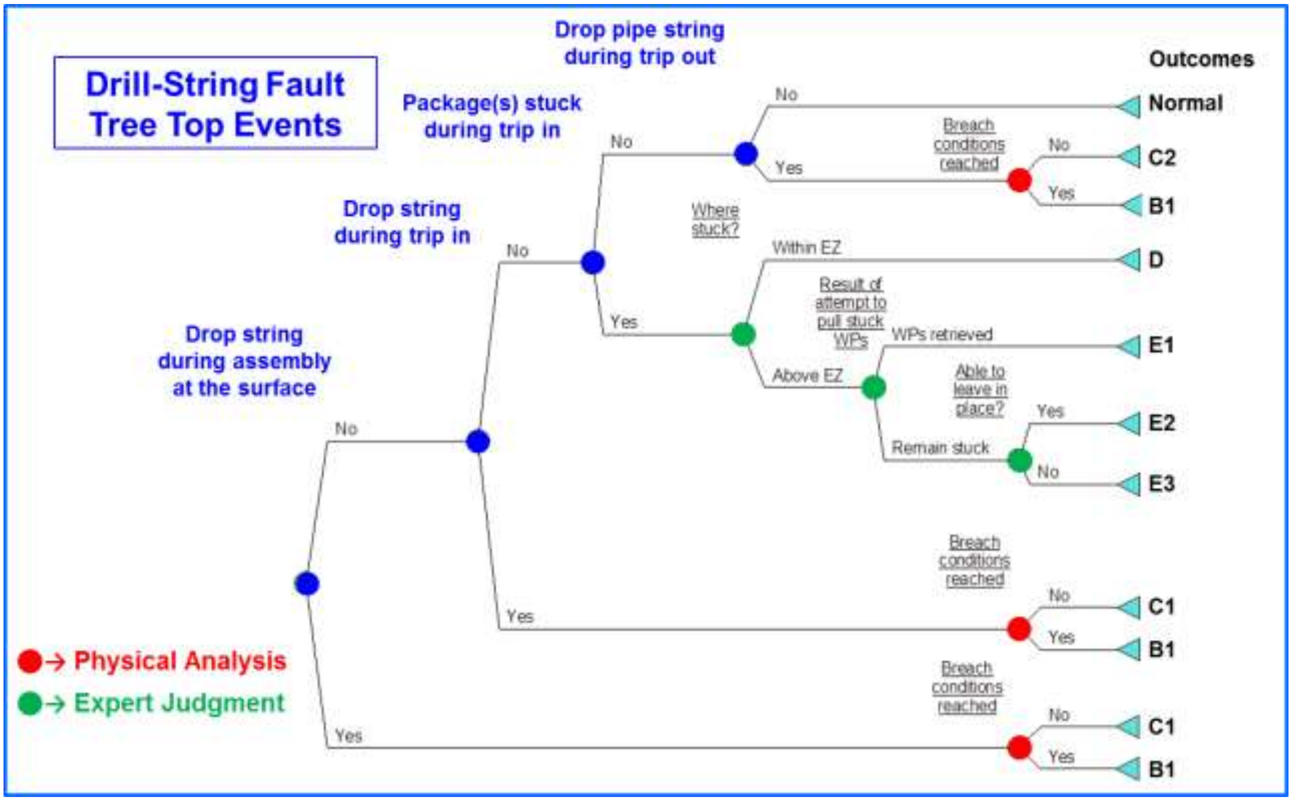

Fig. 7. Drill-string event tree, per waste package string, with outcomes illustrated.

is breached. If a WP or WP string becomes stuck during emplacement, there is uncertainty about where it is stuck, and the ability to retrieve or "fish" it successfully from the borehole. The set of possible outcomes is represented by the branches of the event trees on the right-hand side (Figures 6 and 7). Costs were estimated for normal operation (successful emplacement of 400 packages) are estimated to be $42.0M and $23.5M for drill-string and wireline methods, respectively. The cost estimate for each off-normal outcome was based on a specific mitigation strategy including recovery and decontamination if needed [5]. While many costs are uncertain, the costs of operating the drill rig or wireline unit are by far the largest contributors. These costs are time-dependent, so the total time required is the most important factor. Costs and durations for normal and all off-normal outcomes are summarized in Table I.

TABLE I. Estimated Durations and Costs Associated With Normal and Off-Normal Outcomes

Outcomes	**Radiological Release**	**Drill-String**		**Wireline**	
		Days	**Cost ($M)**	**Days**	**Cost ($M)**
A1	Yes	965	$ 346	965	$ 308
A2	Yes	1,330	$ 328	1,330	$ 309
A3	Yes	1,005	$ 350	966	$ 309
B1	Yes	945	$ 325	945	$ 302
B2	Yes	1,330	$ 337	1,330	$ 314

C1	No	409	$ 43	409	$ 25
C2	No	407	$ 44	407	$ 28
D	No	323	$ 42	323	$ 29
E1	No	600	$ 74	600	$ 45
E2	No	965	$ 120	965	$ 92
E3	No	640	$ 78	601	$ 46
E4	No	600	$ 54	600	$ 44
F (normal)	No	430	$42	430	$ 23

Fault Trees - Each off-normal event is supported by a fault tree used to estimate its probability. Engineering measures were added where practical, to prevent or mitigate the identified failures. The resulting sets of basic events were arranged using fault tree logic implemented in SAPHIRE software [9]. An example fault tree for dropping packages from the surface to the DZ, with wireline emplacement is presented in Fig. 8.

During hazard analysis a number of conceptual design improvements were identified that could significantly decrease the probability of basic events at the lower level of the fault trees, and of secondary conditional events on the event trees. These include: 1) impact limiters on the bottom of each WP or string of WPs; 2) functional safety system that mitigates the consequences of human error and equipment malfunction; 3) leading instrumentation packages for drill-string emplacement as discussed previously; and 4) methods for monitoring potential borehole casing collapse prior to and during emplacement operations.

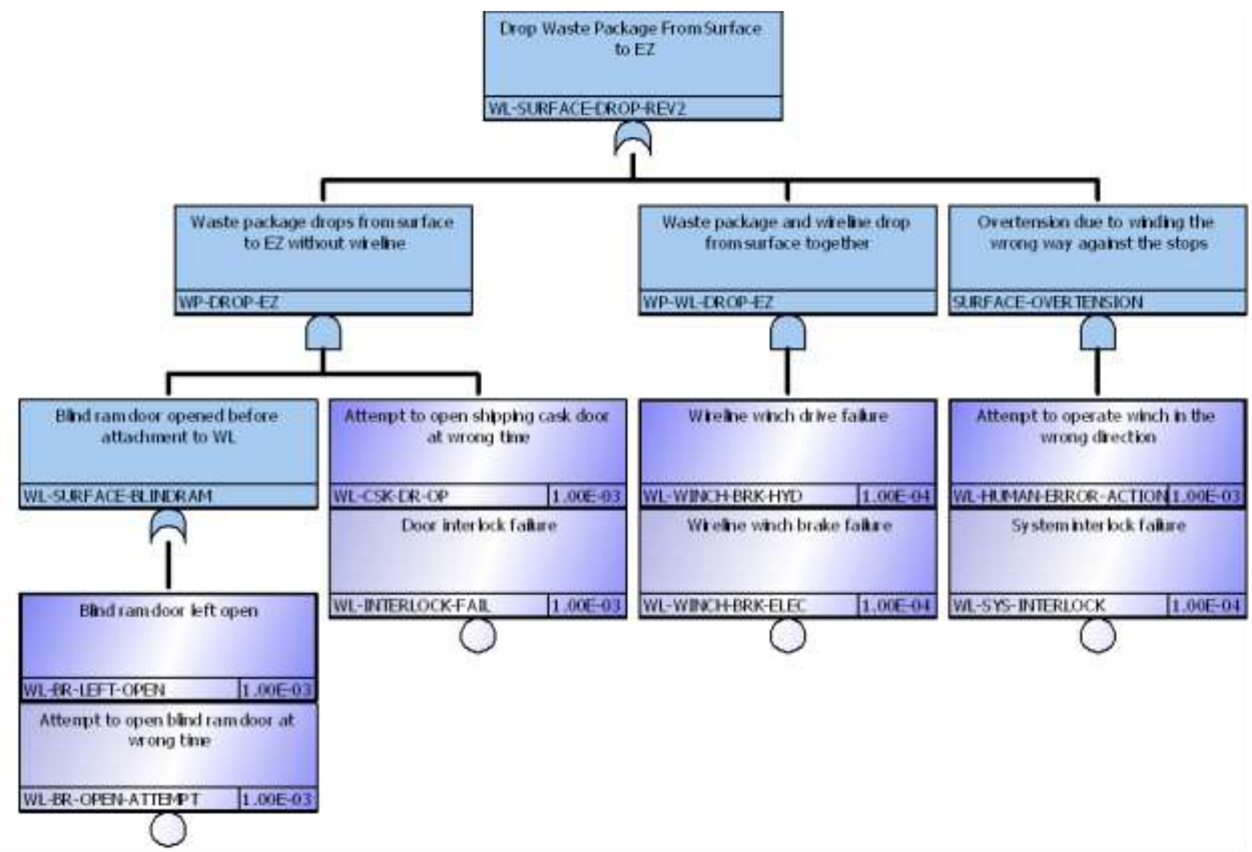

Fig. 8. Fault tree for dropping waste packages from the surface to the disposal zone, with wireline emplacement. Basic events feed upward with AND/OR logic to determine the top event.

The functional safety system (interlocks) is an important “backstop” to mitigate the impact of human errors in operating the WP handling and emplacement system. The safety system would consist of integrated state-sensors and actuator controls linked by programmable logic. Standards are available for designing and rating the performance of functional safety systems [10]. The system would be designed to improve reliability for each emplacement function, but not necessarily the same level for every function. For example, greater reliability is needed if a single human error could lead directly to a drop.

Intrinsic engineered safety features can also be incorporated in the design such as the breakaway sub, common electrical plugs for actuation and safety circuits, and pins or ledges on cask doors to prevent opening while bearing the weight of a WP [5].

Given the number of repeated operations involved with emplacing hundreds of WPs in each disposal borehole, the integrated probability of off-normal events is on the order of a few percent per borehole, even with small probabilities for basic events (Fig. 8). Thus, engineered measures to prevent and mitigate accidents are quite important to the safety of deep borehole waste emplacement operations, and preventing possible radiological consequences. Development of these measures during disposal system design will help to further improve system reliability.

Expert Panel – A panel of experts was convened to bring a broader perspective to the analysis and to review technical aspects of the cost-risk model [5]. Subject-matter experts were chosen to represent drilling and wireline operations, nuclear material handling, safety control systems, risk analysis, and other areas. The expert panel:

- Reviewed the two emplacement modes and the hazards analysis to identify what can “go wrong” during emplacement. The panelists identified a number of modifications to the emplacement concepts that would significantly reduce risks.
- Reviewed the hazard analysis, categorizing basic events in the fault trees into order-of-magnitude groupings based on estimated probability of occurrence.
- Provided strategies for fishing WP(s) stuck in the borehole, and estimated the probabilities for different fishing outcomes.
- Reviewed the approach to worker radiological exposures, occupational safety, and estimation of cost and duration for the identified outcomes.

COST-RISK STUDY RESULTS

Based on the initial inputs (hazard analysis and event probabilities) the cost-risk study results are summarized in Table II. The likelihood of emplacing 400 WPs without incident (without a drop, and without getting stuck) is better for drill-string emplacement, primarily because of the greater probability of getting stuck with wireline emplacement. However, the probability that an off-normal event occurs leading to breach of a WP is about 55 times greater for the drill-string option, mainly because of the high incidence of WP breach if a heavy string is dropped during drill-string emplacement, and the effective use of impact limiters that mitigate the consequences of single-package drops during wireline emplacement. Even though the estimated costs of remediating some off-normal outcomes are high (Table I) the probabilities of most of those outcomes are relatively low, so the expected cost (Table II) for each option is dominated by normal operations. Based on lower expected cost and duration, and significantly lower probability of a radiological release, the wireline emplacement method is recommended.

Sensitivity Analyses

Sensitivity analyses were conducted to explore the impacts of changes in various inputs, and to test whether there are credible circumstances where the preference for wireline emplacement over drill-string emplacement could be reversed. The first set of sensitivity analyses focused on the event probabilities, the second set focused on the failure probabilities. Of the various sensitivity analyses performed [5] sensitivity to input probabilities was found for:

- **Uncertainty about the likelihood of breaching a WP while attempting to fish or remove a stuck package or package string** – Fishing is the only mechanism by which a WP can be breached during wireline emplacement, whereas for drill-string emplacement there are several larger contributors to the possibility of breach. For wireline operations to have the same risk of radiological release as drill-string operations, the probability of a breach while fishing would have to be 15% to 20%, and even so the probabilistically weighted cost for wireline emplacement remains $20M less than for drill-string.
- **Uncertainty about the likelihood of WP breach from drop events** – This sensitivity analysis compared the options after assuming both a lower probability of breach from dropping a WP string (drill-string emplacement) and a higher probability of breach for dropping single WPs (wireline emplacement). The results are sensitive only to dramatic changes. If the probability of a breach from WP-string drops is decreased to 50% (from 100%), and the probability of a breach from single-WP drops is increased to 5% (from zero), the drill-string option is still 3 times more likely to cause a radiological release.

TABLE II. Cost-Risk Study Results Summary Based on Initial Inputs

	Initial Results	
	Wireline	**Drill-String**
Probability of incident-free emplacement of 400 WPs	**96.81%**	**99.22%**
Approximate total costs if successful ($M)	**23.5**	**42.0**
Expected performance against the defined performance metrics		
Expected value of costs ($M), considering both normal and off-normal events	**23.7**	**43.9**
Expected total time of operations (days), considering both normal and off-normal events	**430**	**434**

Probability of radiation release (emplacement of 400 WPs)	**1.29E-04**	**7.04E-03**
Outcome Probabilities		
Probability of failure(s) leading to radiation release (Outcomes A1-A3, B1-B2)	**1.29E-04**	**7.04E-03**
Outcome A1: Stuck above DZ/breached/fished/no more disposal	1.16E-04	0.00E+00
Outcome A2: Stuck above DZ/breached/fishing failed/leave in place	2.32E-06	0.00E+00
Outcome A3: Stuck above DZ/breached/fished with casing/no more disposal	2.32E-06	0.00E+00
Outcome B1: Drop causes breach in DZ/complete hole/no more disposal	0.00E+00	7.04E-03
Outcome B2: Fishing causes breach in DZ/complete hole/no more disposal	8.24E-06	0.00E+00
Probability of a failure that does not result in radiation release but requires terminating disposal operations in the borehole (Outcomes D, E1-E4)	**8.45E-03**	**8.00E-04**
Outcome D: Stuck in DZ/complete borehole/no more disposal	4.29E-03	4.00E-04
Outcome E1: Stuck above DZ/no breach/fished/no more disposal	3.75E-03	3.82E-04
Outcome E2: Stuck above DZ/no breach/fishing failed/leave in place	7.49E-05	9.00E-06
Outcome E3: Stuck above DZ/no breach/fished with casing/no more disposal	7.49E-04	9.00E-06
Outcome E4: Drop to DZ during fishing/no breach/complete/no more disposal	2.66E-04	0.00E+00
Probability of a failure that leads to costs and delays, but does not require termininating disposal operations in the borehole (Outcomes C1, C2)	**2.33E-02**	**0.00E+00**
Outcome C1: Drop into DZ/no breach/continue disposal	2.17E-02	0.00E+00
Outcome C2: Drop wireline/pipe into DZ/no breach/continue disposal	1.58E-03	0.00E+00
Top level failure probabilities (likelihood of each of these types of failures occurring before 400 WPs are successfully emplaced)		
Drop one or more WPs from top	4.41E-05	4.07E-03
Drop one or more WPs during trip in	2.16E-02	1.59E-03
Drop wireline or drill-string on trip out	1.58E-03	1.39E-03
WP or WP string stuck	8.59E-03	8.00E-04

For sensitivity to failure probabilities, sensitivity was found for:

- **Operational and design changes aimed at reducing specific risks –** A key risk for wireline emplacement was found to be dynamic overtension during descent, leading to a wireline break. This sensitivity case assumed that operational changes decrease the probability of a dynamic overtension failure by a factor of 10. This change decreases the likelihood that a package is dropped on the trip in by nearly an order of magnitude, and increases the likelihood for wireline emplacement of 400 WPs without incident to 98.6%.
- **Likelihood that waste packages become stuck by debris –** This set of sensitivity analyses explored the impacts of reducing or increasing the basic event probabilities controlling getting stuck, by a factor of 10. Wireline results, in particular, are highly sensitive because: 1) debris was considered to be the principal way that a package could get stuck, and 2) the only way a package can be breached during wireline emplacement is if it gets stuck and is breached while fishing.
- **Likelihood of rigging failure while assembling package string**s **–** In the initial analysis a failure (drop) rate of 10^{-5} per lift was used for assembly of WP strings, for drill-string emplacement. This sensitivity case used a rigging failure rate of 10^{-4} per lift. Results are sensitive; the probability of incident-free emplacement of 400 WPs decreases to 96% (from 99%) and the probability of a radiological release increases to 4% per borehole. This represents a significantly higher risk and highlights the importance of rigging safety if drill-string emplacement is implemented.

Other sensitivity analyses produced little or no impact on the initial results [5]. These include an interpretation that reducing the number of WPs in a WP string (e.g., from 40 to 20 or fewer) would not improve overall safety because the increased risk from dropping the drill string on trips out offsets any decrease in risk from smaller WP strings.

REFERENCES

1. NAS (National Academy of Sciences), 1957. *The Disposal of Radioactive Waste on Land*. http://www.nap.edu/openbook.php?record_id=10294
2. Brady, P.V., B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard and Stein, J.S., 2009. *Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2009-4401, Sandia National Laboratories, Albuquerque, NM.
3. Arnold, B.W., P.V. Brady, S.J. Bauer, C. Herrick, S. Pye and J. Finger, 2011. *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2011-6749. Albuquerque, NM: Sandia National Laboratories.
4. Cochran, J.R. and E.L. Hardin, 2016. "Waste Handling and Emplacement Options for Disposal of Radioactive Waste in Deep Boreholes – 16277." *Proceedings: Waste Management 2016*. Waste Management Symposia, Phoenix, AZ.
5. SNL (Sandia National Laboratories), 2015. *Deep Borehole Field Test Specifications*. FCRD-UFD-2015-000132 Rev. 1. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition.

6. Woodward–Clyde Consultants, 1983. *Very Deep Hole Systems Engineering Studies*. ONWI-226. U.S. Department of Energy, Office of Nuclear Waste Isolation. Columbus, OH.
7. Bates, E.A., M.J. Driscoll and J. Buongiorno, 2011. "Drop-In Concept for Deep Borehole Canister Emplacement." *Proceedings of the 13th International High-Level Radioactive Waste Management Conference*. Albuquerque, NM. April 10-14, 2011. American Nuclear Society, Chicago, IL
8. Britten, J.M., 2013. "The Texas Solution to the Nation's Disposal Needs for Irradiated Hardware – 13337." *Proceedings: Waste Management 2013*. Waste Management Symposia, Phoenix, AZ.
9. Smith, C. J. Knudsen, T. Wood and K. Kvarfordt, 2012. *SAPHIRE 8. Computer software. Version 1.0*. Idaho National Laboratory and the U.S. Nuclear Regulatory Commission.
10. ISO (International Organization for Standardization) 2010. *Safety of machinery — General principles for design — Risk assessment and risk reduction*. International Standard ISO 12100.

ACKNOWLEDGMENTS

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This paper is approved for Unclassified, Unlimited Release (SAND2015-9775 C).