Life-Cycle Risk Analysis for Department of Energy (DOE) Wastes in Shallow Land Burial – 9390

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ABSTRACT

Hundreds of thousands of cubic meters of hazardous chemical and radioactive wastes generated from past nuclear materials production have been buried at various U.S. Department of Energy (USDOE) sites. Until the past few decades, these wastes were often buried in shallow, unlined pits and trenches and covered with soil allowing for contaminant release and migration and potential human exposure with concomitant safety and health concerns. The waste inventory in shallow land burial is large and the types of buried wastes are highly variable. Radioactive wastes, some intensively radioactive, may be inter-mixed with hazardous wastes making their ultimate disposal highly problematic if they are exhumed. Contaminants have migrated from the original burial sites. Inconsistency in past regulatory approaches and agreements concerning disposal alternatives has resulted in neither a consistent basis for site remediation nor transparency to stakeholders.

To provide a foundation for risk-informed decision-making, a framework was developed for the consistent and transparent evaluation of the life-cycle risks and risk trade-offs to the general public and workers associated with the ultimate disposal of wastes in shallow land burial. Risk is but one of the inputs needed (along with cost, technical feasibility, cultural and societal impacts, etc.) to make a risk-informed decision. Use of this framework to provide the risk inputs needed for decision-making differs from existing approaches by providing a basis for evaluating relevant life-cycle risks and risk tradeoffs. These risks involve not only the commonly evaluated exposure risks from chemicals and radionuclides to the general public and workers but also accident risks (e.g., slips, trips, falls, etc.) to workers. Accident risks are often found to dominate the overall risks for required remedial activities; however, these risks are inconsistently and infrequently evaluated as a matter of standard practice.

The framework was applied using expert judgment to the Idaho Site Subsurface Disposal Area (SDA). The SDA represents a shallow land burial of mixed wastes. The expert evaluation identified critical components needed to guide further analysis of life-cycle risks for the waste sites. The evaluation further suggested that a targeted retrieval alternative based on those areas posing highest risks should be considered for site disposition. The results of the evaluation were presented to the Idaho Site Citizen's Advisory Board, who strongly endorsed the clarity of the approach and the results. To further evaluate the framework, a screening risk tool was developed in GoldSim. The risk tool provides a platform for quantitatively evaluating the life-cycle risks needed as input to decision-making for shallow land burial site disposition. The results from applying the risk tool to the SDA compared favorably those from applying the framework using expert judgment, especially in terms of identifying high-risk tasks in the proposed remedial actions. The evaluations illustrated the effectiveness, flexibility, and value of the approach in providing risk information needed to make an informed remedial decision.

INTRODUCTION

Before 1970, hundreds of thousands of cubic meters of transuranic, low-level, and mixed low-level wastes generated from nuclear materials production were buried at sites across the U.S. Department of Energy (USDOE) Complex. Most of these wastes were buried in shallow unlined pits and trenches and covered with soil creating the potential for contaminant migration and exposure with concomitant safety and health concerns. Not only is the buried waste inventory large but the waste types are highly variable and often inter-mixed with hazardous wastes making their retrieval, treatment, and disposal difficult. Inconsistency in regulatory approach and agreements, concerning disposal alternatives (i.e., manage the wastes in-place or retrieve the wastes for treatment and disposal either on- or off-site) provides neither a consistent basis for site remediation nor transparency to stakeholders.

To provide a foundation for risk-informed decision-making, a framework has been developed for the transparent and consistent technical evaluation of the life-cycle risks and risk trade-offs (both to the general public and workers) associated with buried waste disposition and site remediation. Risk is one of the inputs needed (along with costs, technical feasibility, cultural and societal impacts, etc.) to make a risk-informed decision. Use of this framework to provide the risk information needed differs from existing approaches by providing a basis for consistently evaluating relevant life-cycle risks and risk tradeoffs involving the general public and workers. The framework has been applied to shallow land burial sites at USDOE sites with very different climactic conditions; the results for the Idaho Site Subsurface Disposal Area (SDA) will be presented.

FRAMEWORK DEVELOPMENT

A general risk analysis framework was developed to assess the life-cycle risks and risk trade-offs associated with USDOE buried waste disposition and site remediation activities. A simplified version of the conceptual framework is depicted in Figure 1. The framework outlines the general process for estimating and comparing the risks and risk trade-offs involved with either 1) managing buried wastes in-place or 2) retrieving, treating, and disposing wastes in an appropriate area elsewhere. The risk analysis framework is both iterative and tiered so that each successive assessment tier builds on each preceding phase (when necessary) and represents an increase in sophistication (e.g., in terms of modeling) and required site-specific information to better characterize or reduce uncertainty and increase the accuracy in the risk input to the decision-making process. Brief descriptions of the analysis phases follow.

Preanalysis activities are undertaken before any technical evaluation of the waste site is performed and thus are not shown in Figure 1. Before remedial actions are considered, a site must be identified as posing unacceptable risks. Site identification can take place in many ways. For example, sites are often identified for action from information supplied by states or waste handlers. Citizens can also petition the U.S. Environmental Protection Agency (USEPA) to investigate a site. Once a suspect site is identified, a preliminary site characterization should be performed to identify what is known about site conditions and contaminants and hazards. If there is no immediate, legal mandate for site remediation, the next of the evaluation calls for a qualitative assessment of existing site conditions.

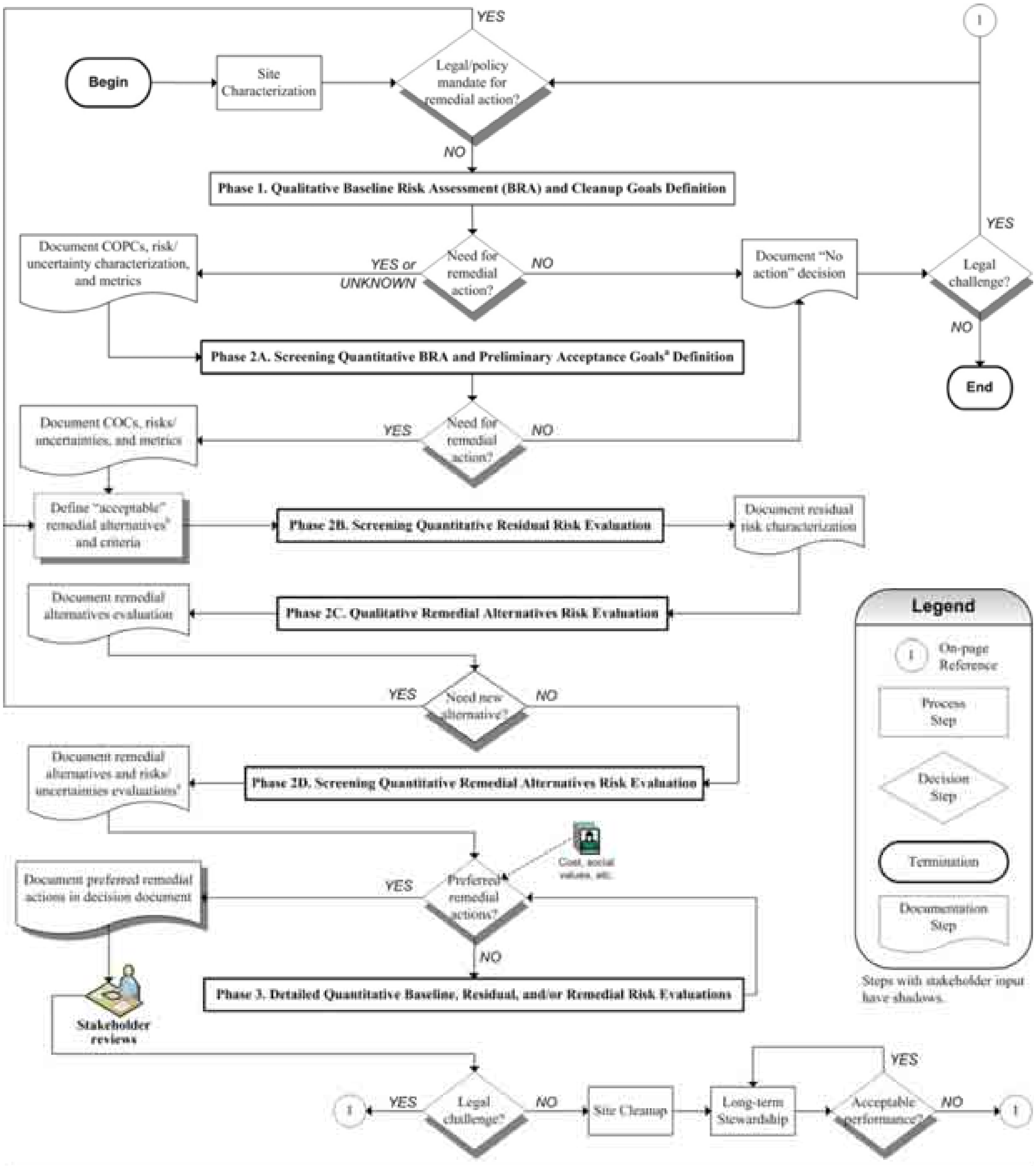
Phase 1: Qualitative Baseline Risk Assessment and Cleanup Goals Definition

This phase of the analysis calls for a *qualitative* assessment of site conditions and potential hazards using existing information and expert judgment to determine if sufficient information exists to make a remedial decision and, if so, if remedial actions are required based on the qualitative information available. The intent of this initial evaluation is intended to provide an organizational basis for evaluation.

The basic building blocks of the qualitative baseline risk assessment are illustrated in Figure 2. The foundation for the analysis is the set of four elements suggested in the National Academies *Red Book* [1] (i.e., hazard identification, dose-response assessment, exposure assessment, and risk characterization). These elements are supplemented with information concerning land use and receptors. The analysis in the block builds from the bottom up in terms of the information needed to complete each step. This information is updated during subsequent steps in the assessment process shown in Figure 1 as new information is obtained and/or is needed to perform more detailed assessments.

A critical step is the development of a baseline conceptual site model (CSM). Conceptual site models graphically illustrate the relationships between contaminant sources and potential receptors via transport pathways and exposure routes. The CSM ties together essential risk concepts and aids in developing scenarios in a transparent manner. Using the CSM as a guide, a qualitative analysis is performed to identify critical uncertainties and information gaps that might impact the ability to make a decision. A qualitative analysis is performed to evaluate site hazards. Site hazards and risks can be placed in the context of the risk-triplet [2] by defining scenarios (i.e., “what can go wrong” in terms of, e.g., contaminant release, migration, and exposure) and consequences linked by likelihood of exposure.

Preliminary cleanup goals for both the assessment and proposed remedial actions are defined with stakeholder input to direct future work. These goals are *high-level concepts* representing desired outcomes of the proposed remedial actions. Examples may include CERCLA evaluation criteria (i.e., protect human health and the environment, short-term effectiveness, volume reduction, etc.). These goals are *not* synonymous with specific target levels (e.g., preliminary remediation goals, soil screening levels, etc.) for remedial actions, which are developed later.



Notes:

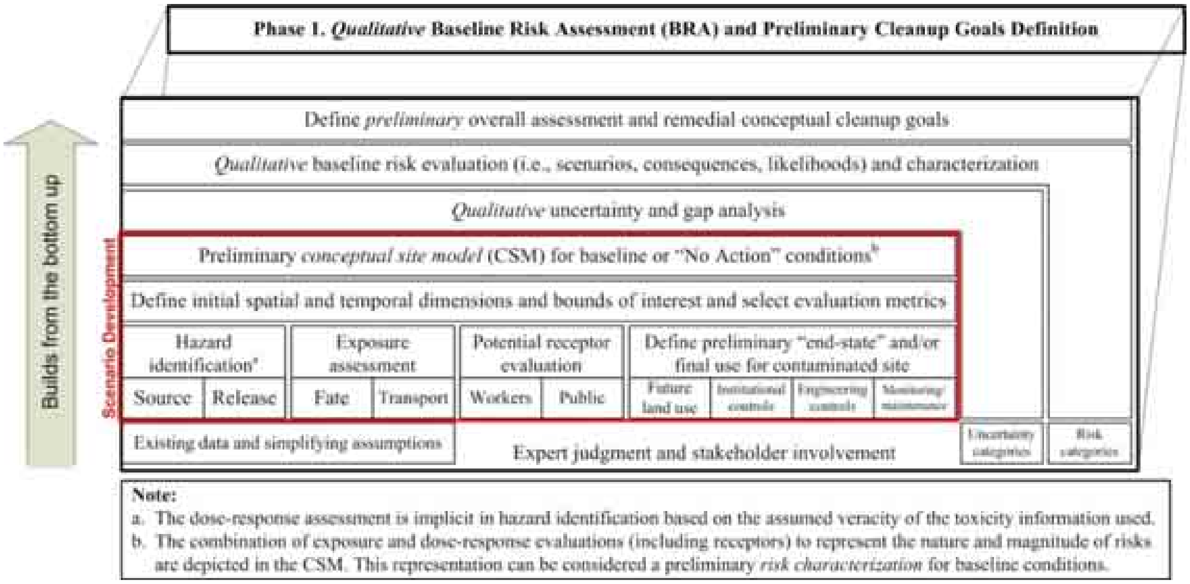
a. For example, preliminary acceptance goals (PAGs) can represent preliminary remediation goals (PRGs) per CERCLA (USEPA 1991).

b. Three of the nine CERCLA evaluation criteria (i.e., effectiveness, implementability, and cost) may be used as suggested in 40CFR300; others should be included as mandated.

c. For this study, the two general categories of remedial alternatives are retrieval/treat/dispose and contain in-place. However, the decision to take no action can also be a viable alternative depending upon the results of the various assessments.

Figure 1. Framework for Assessing Life-Cycle Risks for the Disposition of Shallow Land Burial Wastes [3].

If sufficient information exists to determine that no remedial action is required, this "no action" decision is documented for public review and comment as illustrated in Figure 1. However, a successful legal or regulatory challenge to the “no action” decision could restart the assessment. If remedial actions cannot be ruled out, then an initial set of contaminants of potential concern (COPCs) should be defined with corresponding transport pathways, exposure routes, and receptors (as used to develop the baseline CSM).



Note:

a. The dose-response assessment is implicit in hazard identification based on the assumed veracity of the toxicity information used.

b. The combination of exposure and dose-response evaluations (including receptors) to represent the nature and magnitude of risks are depicted in the CSM. This representation can be considered a preliminary *risk characterization* for baseline conditions.

Figure 2. Building Blocks for Phase 1: *Qualitative* Baseline Risk Assessment [3]

Phase 2: Screening Quantitative Baseline and Remedial Alternative Risk Analysis

If remedial action for a site cannot be ruled out, then a screening quantitative baseline risk assessment (BRA) and initial evaluation of remedial alternatives is performed. The results from Phase 1 are used to guide the screening quantitative BRA. Site-specific data should be used when available; however, for screening purposes, more general data can be used if there is sufficient basis that the resulting risks will not be significantly underestimated.

The steps in Phase 2A are quantitative analogues to those in Phase 1. The screening quantitative BRA is used to estimate risks and uncertainties assuming no remedial actions are taken. The information developed at this early stage should be commensurate with the importance of the remedial decision. For example, the Risk Assessment Guidance for Superfund suggests bounding risks be estimated [5]. However, both best estimate and bounding risks should be predicted because no single estimate can adequately communicate the risk [2][1]. Thus estimates of risks to receptors from potential exposures to site contaminants are needed results from Phase 2A. If there are contaminants to which receptors might be exposed that exceed regulatory or legal limits, then *acceptance goals* must be defined for site cleanup that represent specific contaminant levels or consensus metrics that correspond to the cleanup goals defined in Phase 1. The revised COPC list and preliminary acceptance goals are critical results of Phase 2A.

In Phase 2B a set of acceptable remedial alternatives is defined using expert judgment incorporating stakeholder input. One method of selecting alternatives uses three of the nine CERCLA evaluation criteria (i.e., effectiveness, implementability, and cost) to screen remedial alternatives as shown in Figure 1 [3]. After acceptable remedial alternatives have been identified, residual risks to the general public for each proposed alternative are estimated in Phase 2B in much the same way as baseline risks were estimated in Phase 2A. However, it is possible that none of the proposed remedial alternatives can be used to clean up the site to a protective state. In this case, either new remedial alternatives must be evaluated or a more detailed and accurate risk analysis may be pursued.

Phase 2C is the first involving evaluating remedial actions. The risks associated with chemical and radiation exposures as well as accidents (e.g., slips, trips, falls, etc.) for remedial workers are evaluated to provide a complete picture of the risks involved[2]. The first step in evaluating these risks is to identify the tasks comprising the

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[1] A probabilistic risk analysis may provide useful insights into the uncertainties and their potential impacts; however, a probabilistic analysis should be undertaken with care because of the time and resources required.

[2] Examination of accident risks, often neglected in risk assessments, is important because these risks may dominate those posed by both potential remedial actions [6] as well as the overall risks of dispositioning the wastes.

alternative, which can be readily captured in task lists and management flow diagrams[3]. For each task, a hazard analysis is performed to identify the frequency, elements of risk, likely receptors, basis for characterizing risk, and contribution to overall risk. An uncertainty and information gap analysis describing the key knowledge barriers, missing information, and uncertainties is also performed. Significant health risks from potential accidents and exposures to contaminants for proposed remedial activities are identified. The final step is to construct an integrated hazard and gap summary for the remedial actions illustrating the most important risks and uncertainties.

In the majority of foreseen circumstances, a screening quantitative analysis of remedial risks should be completed to provide the comprehensive risk information needed to make an informed decision. The quantitative screening remedial risk evaluation in Phase 2D (Figure 1) will follow the basic outline in Phase 2C. Site-specific information will be utilized when available to estimate health risks and uncertainties for both exposure and accident hazards. If a decision can be made based upon the screening quantitative results, then it is documented for review and comment as shown. Otherwise, a more detailed and accurate risk analysis is warranted as illustrated in Figure 1.

Phase 3: Detailed Quantitative Baseline and Remedial Action Risk Analysis

The most critical aspect of Phase 3 is to reexamine the remedial goals and decision criteria to see if a decision could be made in light of the original requirements and uncertainties as well as what can be gained by additional site characterization. Available information including the models used and the data needed to analyze risks and uncertainties should be reevaluated for those parameters that most likely drive the risks for baseline conditions and remedial actions. Additional site characterization and more accurate models may be required to provide the information needed by decision makers. Otherwise, the Phase 3 analysis generally follows that for Phase 2.

APPLICATION OF THE RISK ANALYSIS FRAMEWORK

The framework was first applied using expert judgment to the Subsurface Disposal Area (SDA) and Calcined Bin Sets located on the Idaho Site. The SDA represents a shallow land burial of mixed wastes whereas the Bin Sets are partially buried stainless steel bins containing calcined high-level waste. The expert evaluation identified the critical components needed to guide further analysis of life-cycle risks for these sites. The results were presented to the Idaho Site Citizen's Advisory Board. The Board endorsed the clarity of the approach and strongly recommended to the USDOE that the provisions of the reports be followed[4]. The evaluation illustrated the effectiveness, flexibility, and value of the approach in providing risk information needed to make an informed remedial decision. For the sake of brevity and because the focus here is on buried wastes, the results from the SDA evaluation will be described.

The Idaho Site Subsurface Disposal Area (SDA)

The Subsurface Disposal Area (SDA) comprises a 3.9×10^5 m^2 (97-acre) area in the Radioactive Waste Management Complex (RWMC) on the Idaho Site. Transuranic (TRU) and mixed wastes primarily from the Rocky Flats Plant near Denver, Colorado were buried in the SDA before 1970. TRU wastes were stored retrievably in the RWMC after that. Other wastes including small amounts of TRU-contaminated materials and large amounts of fission products and organic solvents from other USDOE sites or generated on the Idaho Site were buried in the SDA.

The wastes buried in the SDA were diverse in their contaminants, sizes, and forms. Some wastes were buried in drums, cans, and boxes. Highly radioactive materials were buried in shielded casks to reduce radiation exposure. Low-level, but high-activity liquid wastes containing fission products were poured into augur holes. Waste zone monitoring indicates that volatile organic compounds (VOCs), plutonium isotopes, Am-241, and uranium isotopes have migrated some distance from the original burial sites. Additional monitoring indicates that, in addition to VOCs, radionuclides including Tc-99, Am-241, Pu-239, Pu-240, Sr-90, and Pu-238 have migrated into the vadose zone. VOCs and nitrates have migrated more than 170 m to the sole-source aquifer underlying the SDA.

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[3] A management flow diagram illustrates the general process steps that must be completed—and the order in which they are undertaken—to provide a protective final state for the wastes [3].

[4] The information described in this paper was presented to the Idaho Site Citizen's Advisory Board (CAB) in July 2005. CAB recommendations (#123 and #124) are available at http://www.cresp.org/ (accessed December 2008).

To support the Idaho Site CERCLA process, site personnel performed remedial investigations [7, 8] and a feasibility study for proposed remedial actions [9]. These assessments provide guidance on the risks posed by the SDA contaminants. However, these assessments have not fully considered the range of populations potentially at risk, time frames of specific risks, or land use remaining under government control in perpetuity. Consideration of these issues is important to determine who is at risk and when under the range of future land use scenarios.

Subsurface Disposal Area (SDA) Risk Analysis

According to the risk analysis framework, the first step in evaluating life-cycle risks for a site is to complete an initial characterization of site conditions. The information available in the Idaho Site CERCLA Administrative Record (located at ar.inel.gov) and that provided by Idaho Site personnel was used as the basis of the initial SDA risk evaluation. This information includes the aforementioned remedial investigations and feasibility study.

The next step in assessing risks posed by a contaminated site is to develop a baseline conceptual site model (CSM) linking sources of contamination to potentially impacted receptors. The CSM provides a basis for identifying and communicating the risks posed by contaminated sites. Development of the baseline CSM for the SDA entails scenario development. In essence, a scenario for potential exposure and risk to receptors is represented by a complete transport pathway from contaminant source to receptor. A gross indication of the consequences of a complete transport pathway is conveyed by the CSM in that a complete pathway indicates a possible exposure of a receptor to contaminants although the actual impact is not described. A reasonable rule-of-thumb is that potential exposure (via a complete transport pathway) is an undesired consequence. This rule-of-thumb drives the desired final state for remedial actions to block pathways from sources to receptors.

Analyses of contaminated environmental media may prompt remedial action; however, these results do not suffice to evaluate future risks. These risks must be predicted using models. Characterization of uncertainties in input data and parameters and the models (from simplification and assumptions) used to predict future exposures is essential to understanding risks. An explicit declaration of the value judgments and simplifying assumptions made by the risk assessor is needed as well as the likely impact of significant uncertainties on the risk estimates.

SDA Qualitative Baseline Risk Evaluation

The baseline risks from Idaho Site remedial investigations were initially used by experts to evaluate risk drivers for SDA wastes [7, 8]. VOCs and nitrates, most of which originated in Rocky Flats Plant wastes, pose the most imminent risk to human health [7]. Carbon tetrachloride has been detected in the sole source aquifer underlying the SDA. VOCs are being removed using vapor vacuum extraction to reduce the source. Extraction will continue, and if risks are not sufficiently reduced, VOCs will continue to pose the most imminent risk to human health.

Mobile, long-lived fission and activation products posed the next most immediate concern to human health. Most of the mobile fission and activation products were generated by Idaho Site reactor operations [8]. Many of these contaminants have been detected sporadically in the subsurface and work is underway to better understand and model their transport through the environment [7]. Long-term risks result primarily from uranium and long-lived actinides. The immediacy, magnitude, and source of risks must be considered to determine the best path forward.

SDA Qualitative Remedial Actions Risk Evaluation

Because the SDA poses unacceptable risks, remedial actions must be considered. The method employed to screen unacceptable alternatives used three CERCLA evaluation criteria (i.e., effectiveness, implementability, and cost) [10]. The resulting alternatives fell into two categories: 1) manage the wastes in-place or 2) retrieve the wastes for treatment and disposal elsewhere. Despite differences in approaches, the overarching issue was whether or not the site would have to be excavated and wastes retrieved for treatment and disposal. Because USDOE shallow land burial sites are often large and complex, it is possible (and likely recommended) that retrieval actions be targeted to specific waste areas that are either high-risk or high-profile.

To summarize, risks and uncertainties for a proposed remedial action were evaluated using the following steps [3]:

- A *task list* was developed in conjunction with a *management flow diagram* which described the primary subtasks and sequence required to implement the remedial actions.
- A *risk flow diagram* was developed based on the *management flow diagram* that indicated those activities that have the potential to pose significant health risks to workers or the general public.
- *Conceptual remedial models* (patterned after *conceptual site models)* were developed for remedial actions and final protective states.
- A *detailed hazard analysis* was developed[5]. For each subtask, the following were determined: 1) task frequency, 2) what can go wrong, 3) how likely is the adverse event, 4) severity of the consequences, 5) impacted population, 6) basis for characterizing the risk, and 7) contribution of the subtask to overall risk.
- A *detailed gap analysis* describing key knowledge barriers, missing information gaps, and uncertainties was performed. For each subtask, knowledge gaps were identified and then characterized by: 1) what information is missing, 2) how important the missing information is, and 3) how large the knowledge gaps.
- An *integrated hazard and gap analysis* was performed and the most important potential risks and information gaps were provided in a summary table.

Based on the detailed analysis, the most significant hazards for the proposed SDA remedial actions involved *in situ* grouting (ISG). *In situ* grouting, which can be used to immobilize contaminants and/or stabilize the subsurface against subsidence, presents events that appear to be both *probable* and *severe* (for consequences) [3]. The intent of process design and implementation is to mitigate hazards and minimize risks to the extent practical. However, all possible hazards cannot be completely mitigated, and, as a result, adverse outcomes may still occur. Therefore, the identification of risks is important not only for process selection, but also to carry out the intended remedial actions as safely as possible. The hazards most likely to be problematic for the SDA remedial action are described below.

Grout System Failure Resulting in Projectiles &/or Grout Release (*In Situ* Grouting). A failure of the high-pressure grout system is *anticipated* during grouting operations and would result in projectiles or grout release and possible worker injury or fatality [11]. A system similar to that planned for the SDA failed during tests and generated a projectile that injured a worker. No radioactive or hazardous material is used in the grouting system; however, it is possible that contaminated grout under pressure could be transported to the surface.

Injuries and Exposure due to Excavation and Related Material-Handling Activities (Retrieve, Treat, and Dispose Actions). Steps used in the retrieve, treat, and dispose (RTD) actions have at least one hazard considered to be *high-risk*[6]. The consequences from these hazards tend to be either traumatic injuries from excavation-related or tote-bin handling activities or exposure due to containment system failure or disturbance of contaminated soil.

Failure of Long-Term Stewardship (Manage-in-Place Actions). Risks to the public associated with managing wastes in-place depend largely on the effectiveness of long-term stewardship (LTS) activities. Failure of LTS activities may result in site intrusion, inappropriate land or natural resource use, population encroachment, or contamination of the underlying aquifer. LTS activities will have three primary components: maintaining performance of the engineered systems, maintaining institutional controls (ICs), and monitoring effectively. Public acceptance of these measures will largely depend on the credibility of DOE and the financial and legal mechanisms established for insuring LTS.

Qualitative Uncertainty and Gap Analysis for the SDA

The nature of the baseline and short-term risk assessments for the SDA indicated that there are uncertainties and gaps in knowledge that must be addressed prior to completing a comprehensive risk analysis [7, 9, 12]. A detailed analysis of the gaps in knowledge for modeling tasks as well as the LTS and IC activities was completed [3]. The significant uncertainties and information gaps that impact the SDA baseline assessment and remedial action

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[5] A set of *uniform terminologies and categories* were developed by the experts involved to characterize hazards and knowledge gaps in a meaningful fashion [3].

[6] *High-risk* hazards are defined as those from events with likelihood/consequence combinations deemed as 1) *probable* and either *critical* or *severe* or 2) *possible* and *severe* (using the definitions provided by Brown [3]).

selection are summarized in this section. Key information gaps included those that were both *critical* (from a safety standpoint) and *large* (indicating little or no information was available) based on definitions provided by Brown [3].

Geospatial Distribution of Wastes and Waste Forms (All Actions). The inventories and geospatial distributions of contaminants of potential concern are highly uncertain, and these drive both the evaluation of risk and remedial alternatives. Knowledge of the locations of the risk driving contaminants is needed to evaluate the effectiveness of proposed remedial actions. For example, if contaminants originally present in the waste are now widely dispersed, waste retrieval actions would be ineffective in reducing risk.

Presence and Location of High-Level Waste, Spent Fuel, or Similar High-Activity Material (All Remedial Actions). There is uncertainty concerning the presence, type, and amount of high-level waste (HLW) and spent nuclear fuel (SNF) or similar material in the SDA [3, 10, 12]. If HLW or SNF was buried in the SDA, then this waste must be retrieved and disposed of as such. For example, the Nuclear Waste Policy Act specifies that HLW must be disposed of in a deep geologic repository. The 1995 Settlement Agreement stated that "DOE shall treat all high-level waste currently at [the Idaho Site] so that it is ready to be moved out of Idaho for disposal by a target date of 2035."

Potential for Facilitated Plutonium Transport (All Actions). More than a metric ton of plutonium was buried in the SDA[7]. Under oxidizing and consolidated conditions, plutonium is fairly immobile. However, plutonium can move large distances if present as fine particulates, chelated, or under reducing conditions or if it is present as, transformed into, or attached to a colloid [16]. Up to 75 kg of plutonium may be of a size that could form colloids [3]. Plutonium can also form aqueous complexes with organic materials such as EDTA and versenes, which were also buried in the SDA [17]. Colloid concentrations in natural subsurface systems tend to be low which limits facilitated transport. Colloids may not be stable over the long distances necessary to reach the aquifer. There are insufficient data to test or calibrate colloid transport models for the SDA [3, 18]. Thus facilitated transport cannot be ruled out and may pose a significant information gap that must be addressed to adequately assess SDA risks.

Possible Future Legal Decisions and Resulting Actions (Retrieve, Treat, and Dispose). These options involve retrieving, segregating and treating wastes, and then disposing non-TRU wastes on-site and TRU wastes at the Waste Isolation Pilot Plant (WIPP). The extent to which wastes must be retrieved is controversial and may ultimately be based on pending legal decisions concerning the disposition of Rocky Flats Plant (RFP) waste buried in the SDA before 1970. Because legal actions may dictate the remedial actions that must be taken, these actions also directly influence the risks associated with the SDA remediation.

Integrated Gap and Hazard Analysis Summary for the SDA

From discussions with Idaho Site stakeholders and especially the Citizens Advisory Board (CAB), one of the most important sources of information for decision-making was the integrated gap and hazard analysis summary. An example of the summary for the SDA is provided in Table 1. The summary table was derived from the results of the detailed hazard and gap analyses also used to define risk flow diagrams for the proposed remedial actions [3].

Significant hazards were identified for *in situ* grouting (ISG). ISG may be needed to immobilize contaminants or to stabilize the subsurface against subsidence. This step poses significant hazards because it includes a task that was both *probable* and *severe* (in terms of consequences) [3]. The ISG risks were compounded by a *high-priority* information gap associated with knowing where grouting would be needed to immobilize contaminants.

PRELIMINARY COMPARISON OF REMEDIAL ALTERNATIVES FOR THE SDA

Integrating the hazard and gap analyses allows for a qualitative ranking of proposed remedial alternatives in terms of risk, human health, environmental, and programmatic factors as dictated in the risk analysis framework. When assessed for these factors and in the context of the numerous assumptions and value judgments made by the experts when evaluating risks and uncertainties, the proposed remedial actions for the SDA can be ranked.

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[7] Large quantities of fissionable material were buried in the SDA; thus the potential for a criticality accident might be considered possible. The safety analyses showed that any conceivable criticality accident would have a frequency less than once in 10,000 years [11, 13], a conclusion supported by SDA criticality analyses [14, 15].

Table 1. Summary of Important Human Health Risks and Knowledge Gaps for Selected SDA Remedial Actions [3]

Process Step	**MIP**	**RTD**	**What can go wrong?**[a]	**How likely is it?**[b]	**What are the consequences?**	**High Priority Information Gaps**	**Overall Risk Contribution**[c] **(H,S,L,N/C)**
Burial site characterization	√	√	• No *high-risk* hazards	• Not applicable	• Not applicable	▫ Potential for facilitated transport ▫ Presence/ location of high-rad waste ▫ Geospatial dist. of wastes & forms	Significant (0,3,2,2)
In Situ Grouting (ISG) for stabilization	√	√	• Grout system failure resulting in projectiles &/or grout release	• Probable	• Severe to worker	▫ No *high-priority* gaps	**High** (1,4,13,1)
ISG for stabilization & immobilization	√	√	• Grout system failure resulting in projectiles &/or grout release	• Probable	• Severe to worker	▫ Geospatial dist. of wastes & forms	**High** (2,4,22,1)
Excavate, retrieve, & segregate wastes		√	• Contaminated soil removal with exposure • Tote-bin dropped releasing radiation • Traumatic injury (e.g., cave-in during excavation)	• Probable • Probable • Possible	• Critical to worker • Critical to worker • Severe to worker	▫ Future legal decisions & resulting actions ▫ Geospatial dist. of wastes & forms	*Significant*[d] (0,11,37,3)
Long-term Stewardship (LTS)	√	√	• Failure of MIP LTS • Failure of RTD LTS	• Possible • Possible	• Severe to public • Critical to public	▫ Geospatial dist. of wastes & forms	**High** (1,7,8,1)

[a] *High-risk* hazards are 1) *probable* with either *critical* or *severe* consequences or 2) *possible* with *severe* consequences based on the definitions provided by Brown [3].

[b] *High-priority* gaps are *critical* (in terms of safety) and *large* (meaning little or no information is available) [3].

[c] The contribution is based on the detailed hazard information using the process described by Brown [3] for "rolling up" hazard contributions to a single metric. Most importantly, if a task is *high-risk* so is the overall contribution to risk. The numbers in parentheses indicate the number of events that are (*High*, *Significant*, *Low*, *Not Considered*).

[d] The fact that there are three *high-risk* hazards associated with this process step makes it significant from a risk perspective so much so that it may need to be considered a *high-risk* step.

For the manage-in-place (MIP) alternative[8], there were no remedial options that would be considered *low-risk* because of the hazards associated with failure of long-term stewardship (LTS). LTS activities are required for any proposed option. However, a surface barrier would be installed and thus risks would be reduced unless a catastrophic barrier failure occurs. Furthermore, all remedial alternatives would be classified as *high-risk* because they employed one or more of the *high-risk* process steps (i.e., *in situ* grouting and LTS) as illustrated in Table 1. This fact does not preclude a rank-ordering amongst the various possible remedial alternatives.

Significant risks were associated with both the MIP and retrieve, treat, and dispose (RTD) alternatives. One possible rank-ordering of the SDA remedial options in terms of risk (highest to lowest) would produce the following:[9]

No Action >> Maximum RTD > Targeted RTD > *In Situ* Grouting (MIP) > Surface Barrier (MIP)

Results of this evaluation indicated that the lowest risk option for the SDA would be containment using a surface barrier. Containment would reduce the flux of water to the contaminants and reduce their ability to migrate to the environment. However, the efficacy of this option strongly depends on the effectiveness of long-term stewardship activities—failure of which has the potential to impact a large number of people in the (possibly distant) future.

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[8] The manage-in-place (MIP) options considered included 1) No Action, 2) Surface Barrier installation (with ISG for subsurface stabilization), and 3) ISG for contaminant immobilization and surface barrier installation [3].

[9] The ordering uses the assumptions: 1) risk increases with increased retrieval, 2) risks are larger when using ISG for stabilization and immobilization than when ISG is used for only stabilization, and 3) not containing the wastes would have the potential to impact by far the greatest number the public overwhelming reduced worker risks.

However, the above rank-ordering and designation of the surface barrier option as *least-risk* are subjective; thus no clear choice can be identified for the SDA. Additional programmatic and regulatory information or analysis of risks and uncertainties would likely be needed to select an acceptable remedial option. A quantitative assessment of risks, different remedial requirements, or non-risk information may produce a different rank-ordering than that above.

THE RISK SCREENING TOOL FOR USDOE SHALLOW LAND BURIAL SITES

A screening risk tool was implemented in the GoldSim simulation software [19] to evaluate important elements of the risk analysis framework (Figure 1) for a *screening-type* analysis. The primary drivers for exposure risks are the release and transport of contaminants from sources to receptors. Transport in GoldSim is represented as mass fluxes among exposure media (e.g., air, water, soil, etc.) over time. GoldSim allows the important features and processes to be modeled deterministically or stochastically to analyze the impact of uncertainty on predicted exposures and risks.

The screening risk tool used the generic performance assessment (PA) model by Tauxe as a starting point [20]. The Tauxe model provides an excellent example for estimating doses related to radioactive waste disposal. The Tauxe model was expanded to include new radionuclides, chemicals, fractured and surface water media, new transport pathways and receptors, and accident risks [3]. The screening risk tool describes both arid and humid conditions and can be used to estimate exposure and accident risks for baseline, remedial, and post-closure conditions.

Exposure Media

At a basic level, the burial model and risk tool can be defined by the media through which contaminants migrate and receptors may be exposed. These are the media that must be managed or excavated so wastes and contaminants can be retrieved for treatment and disposal elsewhere. Media are defined in the model so that arid or humid conditions can be modeled. Another way to visualize the media and transport pathways is provided in Table 2.

Waste Areas, Inventories, and Source Terms

USDOE buried waste sites are often large and complex areas containing diverse types of wastes and contaminants buried in a variety of forms over decades. A total of 237 isotopes and 45 nonradioactive compounds are included in the screening risk tool to identify contaminants of concern based on selected USDOE sites. In the screening risk tool, sources are grouped into Waste Areas based on retrieval potential. The aggregation to Waste Areas simplifies modeling considerably without introducing significant inaccuracy in the resulting predictions [3].

From a release perspective, whether a contaminant is in a container and/or bound in a matrix are critical issues. Contaminants are partitioned based on source area, containment, and waste form. Two waste areas are defined: one containing the wastes to be managed in-place and the other with wastes targeted for retrieval. Inventories are allocated by waste form among *Source* elements representing containerization. The surface wash, dissolution, and diffusion release mechanisms are used to control contaminant fluxes from *Source* elements to the environment.

Transport Pathways

As shown in Table 2, various transport pathways are modeled to represent migration of contaminants from the burial site through exposure media to potential receptors. The contaminant transport pathways modeled include advection, diffusion, and animal- and plant-induced transport. For the atmospheric pathway, advection, dispersion, and barometric pumping are important transport mechanisms. For water-borne contaminants, flooding and inundation may play an important part in migration; whereas, colloidal transport may be significant for some high-profile radionuclides (e.g., plutonium isotopes). Contaminants may also be transported via the bulk movement of soil either via the atmospheric pathway (i.e., resuspension) or the surface water pathway (i.e., runoff).

Potential Receptor Scenarios and Exposure

Representative receptors were used (i.e., on- and off-site resident, transient, recreational, and workers) to describe exposures, doses, and risks. These receptors were meant to represent reasonable and not worst-case exposure cases. If receptors are present, then reasonable maximum or expected exposures and risks are estimated for either a single desired point-value estimate (e.g., best, 95%-percentile, etc.) or a probabilistic case.

Table 2. Media and Pathways for Two Performance Assessment Models in GoldSim [3]

	Screening Risk Tool [3][a]	Tauxe Generic PA Model [20]	Diffusion (Air)[b]	Diffusion (Water)[b]	Advection (Air)	Advection and Dispersion (Air)	Barometric Pumping (Advection, Air)	Advection (Water)	Colloidal (Advection, Water)	Flooding (Advection, Water)	Inundation (Advection, Water)	Resuspension (Advection, Soil)	Runoff (Advection, Soil)	Plant-Induced Transport (Soil)	Animal-Induced Transport (Soil)
Off-Site Atmosphere	fx				▨ ↑	▨ ↑									
Atmospheric Layer	▤	▤	↓		†	▨ ↑	▨ ↑					▨ ↑			
Surface Soil/Cap Layers[c]	▤	▤	↕				▨ ↑	↓		▨ ↓		▨ ↑	▨ ↓	↑	↓
Accessible Waste Area	▤	▤	↕				▨ ↑	↓	▨ ↓	▨ ↓	▨ ↓			↑	↑
Inaccessible Waste Area	▤	▤	↕				▨ ↑	↓	▨ ↓	▨ ↓	▨ ↓				
Bottom Soil	▤	▬	↑				▨ ↑	↓	▨ ↓	▨ ↓	▨ ↓				
Upper Vadose Zone	≋							↓	▨ ↓						
InterBed Region	≋							↓	▨ ↓						
Lower Vadose Zone	≋	▬						↓							
Local Saturated Zone	▬	▬						↓		▨ ↓	▨ ↓				
Off-Site Saturated Zone	▬							†							
Local Surface Water	N							↓		▨ ↓	▨ ↓		▨ ↓		
Off-Site Surface Water	N							†							

[a] The GoldSim implementation includes: fx *Expression*, ▤ *Cell Pathway* element, ≋ *Fracture Network*, ▬ *Pipe Pathway* element, and N multiple *Cell Pathway* elements in series [19].

[b] Arrows (i.e., ↑, ↓, or ↕) indicate direction. Shaded areas indicate new transport mechanisms. Diffusion in water is not implemented because transport is dominated by advection. An '†' indicates transport to a sink or from a source.

[c] The Generic PA model uses a cap comprised of four layers [20]. The screening risk tool uses 1) a soil layer for baseline conditions or 2) multiple layers representing either an evapotranspiration (ET) or RCRA Subtitle 'C' cap.

Receptors may experience exposure and accident risks. It is desired to compare potential impacts (e.g., morbidity risks from radionuclides, latent cancer incidence risks from chemicals, accident risks, etc.) for remedial actions. Whereas the possibility of comparing potential radionuclide impacts appears promising (e.g., mortality and dose are exposure-driven), the possibility of relating non-carcinogen effects to other risk metrics appears improbable. No common basis exists for comparing non-carcinogen and carcinogen effects for chemicals, and probabilistic interpretation of non-carcinogen effects is without foundation. Potential non-carcinogen effects should be presented with those for the cancer-related impacts to provide a comprehensive risk picture for decision-making purposes.

Standard Industrial or Accident Risks

A worker is exposed to various hazards. Depending on the workplace, hazards may involve potential exposure to hazardous chemicals or radiation, which can be evaluated using the methods described above. However, during site cleanup, exposure risks are often not the dominant sources of risk to the workers [6]. Most site cleanups, especially those involving excavation and waste retrieval, resemble heavy construction sites and the primary risk drivers are the same[10]. The relationship for estimating accident risk is that the annual risk of injury or fatality is proportional to the time worked per year. The proportionality is represented by a risk factor derived from the statistical analysis of historic accident data. Information is available for injuries, fatalities, total recordable cases, etc. for various types of workers; the focus for the screening risk analysis is injuries and fatalities to workers.

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[10] If wastes are transported off-site over long distances, then transportation accidents, even without radionuclide or hazardous chemical releases, may be a significant, if not the dominant, risk contributor.

COMPARISON OF SDA REMEDIAL ALTERNATIVES USING THE SCREENING RISK TOOL

The risk tool predicts contaminant releases and fluxes, concentrations in media, and impacts to selected receptors during the assessment period. Although contaminant fluxes are the primary results needed to characterize transport and resulting doses and risks, these latter values are often the focus of the decision-making process. For example, doses corresponding to different remedial options can be directly compared like risks or hazards. However, comparisons of doses to risks are problematic even though doses and risks are functions of exposure and are typically highly correlated. When this is the case, the focus can be placed on radiation risks instead of doses.

Figure 3 illustrates the predicted annual morbidity rates (representing exposure risks) to the on-site receptor for baseline and remedial options for the SDA. The RTD options did provide significant reductions in exposure risks over time to the receptors when compared to the MIP options. The most significant result in terms of exposure risks was that the retrieval cases appeared to present little benefit for the likely increased worker and general public risks associated with the increased excavation, retrieval, treatment, and off-site shipment activities.

Another important result shown in Figure 3 was that the remedial options considered would not provide a final state that could be released for *unrestricted* use. Because these results were based on best inventories and expected parameters, there was no need to perform stochastic simulations to determine the likelihood that an unrestricted final state could be produced. The nature of the contamination in and around the SDA (i.e., radioactive and volatile chemicals that have migrated into the vadose zone), site restoration would be difficult. However, remedial alternatives were predicted to provide final states protective for future *restricted* release of the SDA.

The results in Figure 3 were predicated on the idea that, if colloids were created and transported through the vadose zone, they would be "screened out" by the sedimentary interbeds between the SDA and aquifer. This "screening" has a profound impact on the predicted groundwater results. Assuming colloids are stable, the impact of not screening the colloids increases predicted risks for baseline and remedial options by more than two orders of magnitude [3]. Furthermore, no remedial option considered would be able to place the site in a state adequate for restricted use. However, there several interbed regions between the SDA and the aquifer that would have to be ineffective at screening colloids and colloids would have to be stable over the 170-m distance from the SDA to the aquifer. In this case, it is likely that more than sporadic indications of plutonium would be detected in the aquifer monitoring wells.

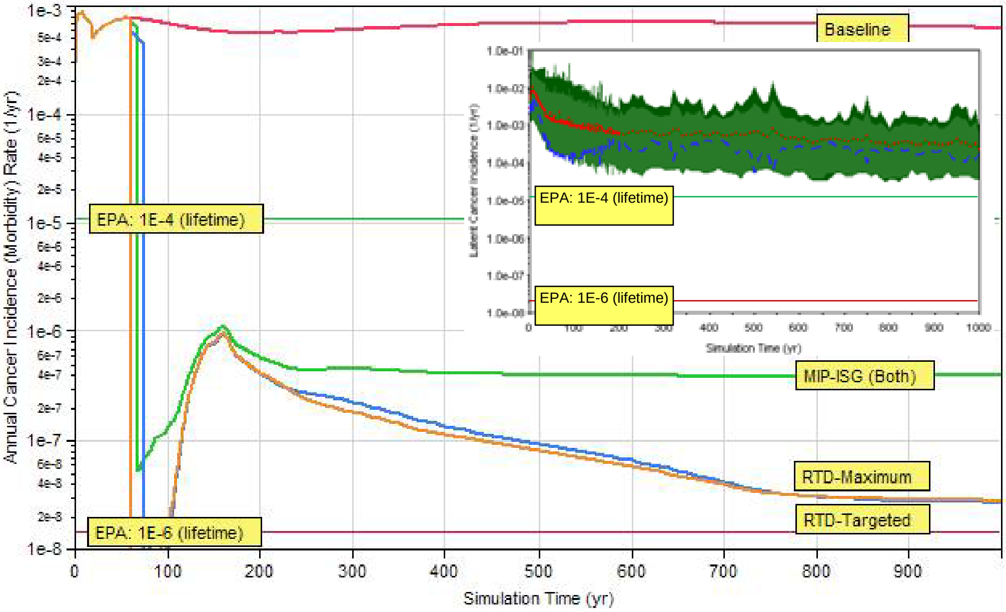

Figure 3. On-Site Resident Morbidity Rates for Baseline and Remedial Options. Results for Co-60 (which decays rapidly) were removed for clarification [3]. Wastes are emplaced at time zero and year 2008 corresponds to year 60 of simulation time. The inset illustrates the uncertainty in baseline results for all radionuclides.

The screening risk can also be used to predict expected accident risks for workers cleaning up the SDA. Legal decisions may force aggressive remedial actions (e.g., excavation and retrieval) without regard of the risks posed to the general public and workers [3]. The purpose here is not to critique either legal decisions or possible remedial actions but instead to identify the risks to the general public and workers so that an informed decision can be made. The SDA risks that were first evaluated using expert judgment are complemented using the screening risk tool.

Whether made explicitly or implicitly, a trade-off must be made between the risks posed by baseline conditions and the risks posed by remedial actions. Baseline risks tend to be long-term, exposure-based risks to the general public; whereas, remedial action risks are more likely to be short-term, exposure and accident risks to workers. Remedial actions may also place members of the public at risk from accidents from contaminant releases but more likely due to more mundane events like traffic accidents. Judgment is needed to assess whether or not the worker risks for a remedial action are unreasonable relative to the gains anticipated from its implementation.

The trade-off can be demonstrated graphically as illustrated in Figure 4 by showing the baseline exposure risks to the general public and the accident risks for remedial workers predicted using the screening risk tool. The primary message to take from this illustration is that accident risks for excavation and retrieval actions are significantly larger that the predicted impacts for exposure to radionuclides from the SDA. This trade-off diagram is intended to be controversial because the risks portrayed are fundamentally different. However, the comparison does indicate the nature of risk trade-off that would be made if wastes are retrieved instead of being managed in-place.

For clarification purposes, the results presented were based on point-value analyses using best inventories and expected parameters supplemented by evaluations to bracket exposure risks to the general public. The exposure results were complemented by exposure and accident risks for workers during both normal and remedial operations using the same screening risk tool. A number of important results are evident:

- It is likely that either manage-in-place or retrieval actions could produce a final state for restricted release.
- It is unlikely that the proposed actions could place the SDA in a final state for unrestricted release.
- The proposed remedial actions were likely to increase accident risks to workers and perhaps the public.
- The more aggressive the remedial action, the more worker risk likely to result.

These conclusions appear unlikely to change if the uncertainty evaluations were expanded. However, because there was no clear remedial alternative for the SDA on a risk basis, a screening quantitative uncertainty analysis seems warranted to help limit future evaluations to those remedial actions and parameters that are most likely to impact the remedial decision. This analysis can also be performed using the screening risk tool [3].

The proposed retrieval alternatives do not appear worthwhile in terms of the risks traded off, especially considering the potential benefit of installing a surface barrier on the SDA earlier than later. The primary drivers for reducing contaminant migration for the manage-in-place alternative are reducing biotic intrusion, barometric pumping, and water percolation primarily via installation of a surface barrier. The predicted lack of effectiveness of the *in situ* grouting (ISG) process, used in both the manage-in-place and retrieval alternatives, to immobilize contaminants and reduce risks is a function of the assumptions made and may be more effective in reality.

The results from the screening risk tool are used to examine the original classifications in Table 1 and rank-ordering of remedial options. The ISG and LTS steps have lower contributions to overall risk than estimated using expert opinion. On the other hand, installation of a surface barrier and off-site disposal appear to have higher contributions to overall risk. In fact, none of the steps are classified as *low-risk* based on *quantitative* results. The rank-ordering of remedial actions made using expert judgment (i.e., manage-in-place options are less risky than retrieval actions) did not change substantively except that retrieval actions appear much more risky than manage-in-place actions.

A risk-informed decision includes non-risk factors (e.g., social values, past legal agreements, etc.) deemed important by the decision-maker. If waste retrieval is selected based on non-risk information, it is hoped that the information provided can help focus or target the retrieval process to the minimum footprint possible based on risks, timing, and receptors. Furthermore, the results from this research can be used to identify those process steps most likely to be harmful to remedial workers so steps can be taken during the planning stage.

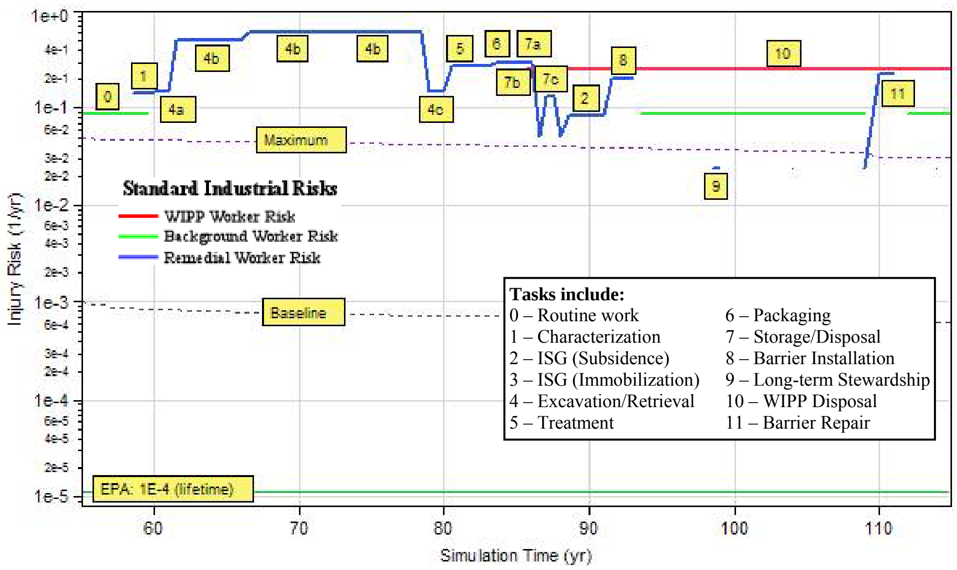

Figure 4. Solid Lines: Expected Annual Accident Risks for the SDA Maximum Retrieval Alternative.
Dotted Lines: Expected and Maximum Annual Morbidity Rates for All Pathways and Radionuclides. [3]

For a contaminated site, the screening tool can be used to assess whether the risks posed are unacceptable and, if so, identify contaminants of potential concern. Proposed actions can be assessed for potential effectiveness including remedial endpoints and residual risks. The accident risks to remedial workers can be estimated. The predictions are made in an integrated platform using a consistent set of models, assumptions, parameters, etc. to provide consistency and transparency to the analyses required to provide the risk information needed for a remedial decision.

CONCLUSIONS

To provide a foundation for risk-informed decision-making for USDOE shallow land burial sites, a framework was developed for the evaluation of the life-cycle risk trade-offs to the general public and workers associated with site disposition and remediation. A screening risk tool was developed in GoldSim as an integrated platform for estimating the risks needed for decision-making. Risk is one of the inputs (along with costs, technical feasibility, cultural impacts, etc.) needed to make a risk-informed decision. Use of the framework and risk tool to provide the necessary risk information differs from existing approaches by providing a basis for evaluating relevant risk tradeoffs involving the general public and workers over time in a consistent and transparent manner.

The framework was first applied to the Idaho Site SDA using expert judgment. The evaluation identified critical elements needed to guide further analysis of life-cycle risks for the site and further suggested that a *targeted* retrieval alternative based on those areas posing highest risks should be considered for site disposition. The results were presented to the Idaho Site Citizen's Advisory Board, who strongly endorsed the clarity of the approach and the results including targeted retrieval. In fact, targeted retrieval options are included in the most recent SDA feasibility study. The screening risk tool was also applied to the SDA to evaluate quantitatively baseline and remedial risks. The quantitative results generally supported the expert evaluation; however, the retrieval actions studied appeared unwarranted on strictly a risk basis suggesting that managing the waste in place might be preferable.

No risk analysis framework or software tool can decide whether a contaminated site poses unacceptable risk or, if so, what should be done with a contaminated site. However, the life-cycle risk analysis framework and the results from applying the risk screening tool can effectively organize the evaluation process and assure that the evaluation is performed in a consistent and transparent manner. The risk and uncertainty results obtained from the evaluation can be used as the risk input to the risk-informed decision-making process for the contaminated site.

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