**Safety Assessment Tool Developed for Nuclear Fuel Handling Facilities**

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**ABSTRACT**

The PCSA Tool software has been developed to aid the U.S. Nuclear Regulatory Commission in reviewing a preclosure safety analysis of a potential high-level waste geologic repository. During the preclosure period (i.e., the period before permanent closure), the nuclear waste may be handled at the surface and subsurface facilities for receiving, repackaging, transporting, and emplacing. To ensure public and worker safety, the Yucca Mountain site-specific regulation 10 CFR Part 63 requires that the U.S. Department of Energy perform a preclosure safety analysis to demonstrate that a geologic repository can be designed and operated in compliance with the performance objectives. The PCSA Tool allows staff to perform independent confirmatory analyses to support the review of preclosure safety analysis and make a determination that a geologic repository can be designed and operated in accordance with regulatory requirements. This paper discusses the review methodology and the PCSA Tool modules to support a risk-informed performance-based review. This paper also provides an example demonstrating the capabilities of the PCSA Tool. The PCSA Tool framework is general enough to allow its use in risk assessments for other nuclear facilities (e.g., power plants, fuel cycle facilities) that are not subjected to 10 CFR Part 63 requirements.

## INTRODUCTION

Several nations are investigating deep geologic repositories for permanent disposal of their nuclear waste. The potential geologic repository at Yucca Mountain, Nevada, USA, will be designed for permanent disposal of about 70,000 metric tons of spent nuclear fuel and high-level waste. The performance of a potential repository is evaluated for two periods: preclosure and postclosure. The preclosure period of geologic repository operations is the period before such a repository is permanently sealed. During the preclosure period, waste is transferred from transportation casks to waste packages, prepared for disposal, and moved to emplacement locations. Facility operations during the preclosure period present potential risks to workers and the public. This paper presents a risk-informed, performance-based approach for evaluating risks that may be present in waste-handling operations during the preclosure period. This approach has been implemented in computer software referred to as the PCSA Tool [1]. This tool can be used to conduct independent confirmatory analyses and perform regulatory reviews involving nuclear waste-handling operations at a potential repository.

## REVIEW METHODOLOGY

The risk-informed, performance-based regulation 10 CFR Part 63 provides the general scope, requirements, and objectives of the preclosure safety analysis to ensure the safety of the public and workers during the period before permanent closure. As part of any license application to receive and possess nuclear waste at the potential geologic repository, this regulation requires the U.S. Department of Energy (DOE) to perform a preclosure safety analysis for the period before permanent closure and demonstrate compliance with the performance objectives. As defined in the regulation, a preclosure safety analysis is (i) a systematic examination of the repository site and facility design and (ii) an evaluation of potential hazards, initiating events, event sequences, and dose consequences to workers and the public. The Yucca Mountain Review Plan (YMRP) [2] provides a risk-informed review guidance that enables the U.S. Nuclear Regulatory Commission (NRC) to assess the DOE preclosure safety analysis. NRC will determine whether DOE has demonstrated in the license application that the repository can be designed, constructed, and operated in compliance with the specified performance objectives throughout the preclosure period.

The information and data from the site; facility descriptions; and design of structures, systems, and components (SSCs) would be evaluated first to assess adequacy and sufficiency of the information provided to review a preclosure safety analysis. The review activity systematically addresses the risk triplets: “What can go wrong?”, “How likely is it?”, and “What are the consequences?” The risk-insight information generated from this review would be used to assess (i) the ability of the repository design to meet the regulatory performance objectives and (ii) the identification of SSCs important to safety that are required to comply with the performance objectives. In addition, risk-insight information would be used (i) to identify risk-significant event sequences and (ii) to focus the in-depth review to consider the sources of uncertainty and sensitivity of parameters used in event sequence and consequence analyses.

## PCSA TOOL

The PCSA Tool provides capabilities to allow the user to determine whether a preclosure safety analysis demonstrates compliance with the performance objectives in 10 CFR Part 63 and whether SSCs important to safety are appropriately identified. The PCSA Tool software combines attributes from the integrated safety analysis methodologies used in the chemical industry and probabilistic risk-assessment capabilities and tools used in the safety assessment of nuclear power reactors. Although the PCSA Tool software has been designed for the review of geologic repository operations, its framework is general enough to be applied to other nuclear facilities (e.g., power plants, fuel cycle facilities, interim fuel storage facilities, mixed-oxide fuel fabrication facilities, and transport operations) however, 10 CFR Part 63 does not apply to these facilities.

The PCSA Tool structure is based on the risk-informed performance based review methodology of the YMRP, and has been discussed previosuly. [3,4]. The primary modules in the PCSA Tool are system description, operational hazards analysis, event sequence analysis, consequence analysis, safety assessment, and identification of potential SSCs important to safety. The tool is designed to perform a systematic preclosure safety analysis for the entire facility or focused areas within a facility. The tool provides flexibility to conduct confirmatory analyses for selected or all aspects of preclosure safety analysis, as well as wide ranges of sensitivity and uncertainty analyses.

The analysis can be structured by segmenting the facility into different functional areas that can be defined in terms of physical boundaries, type of operations, or systems. In each functional area, the tool allows storage of input and output data, model analysis, display of graphical results, and generation of reports. The results from all functional areas can be combined for an assessment of preclosure safety. The tool also includes a database for component failure rates obtained from historical data and literature, including a human error probability generator.

In the system description module, the tool allows the entry of information required for the analysis. The information on facility design, operations, process description, human activities, design bases and criteria for SSCs, and waste stream can be stored in an organized manner, as determined necessary by the reviewer.

The operational hazard analysis module of the tool uses several standard qualitative hazard analysis methodologies, such as Failure Modes and Effects Analysis and What-If analysis. In addition, qualitative Human Reliability Analysis capability can be used to identify potential human errors. The tool provides a list for generic naturally occurring hazards (e.g., seismic, flood, fire, etc.) and human-induced hazards (e.g., aircraft crash, nearby industrial hazards, etc.). Justification for inclusion or exclusion of any of these hazards for further analysis is required. The hazard analysis module forms the basis for postulating initiating events and event sequences that have the potential to cause radiological consequences to the public and facility workers.

In the frequency analysis module, the PCSA Tool provides the capability to conduct event sequence analysis. An event scenario is first developed by postulating the initiating event and progression of system or component failures as a sequence of events. The tool invokes the system analysis software SAPHIRE [5] to model event trees for each scenario and calculate event sequence frequencies. SAPHIRE is also used to evaluate system reliability using fault tree analysis. Each event sequence is categorized as Category 1 or Category 2 based on the likelihood of occurrence. The regulation at 10 CFR 63.2 defines Category 1 as those event sequences that are expected to occur one or more times before permanent closure of the geologic repository operational area. Category 2 event sequences are those that have a probability of occurrence of at least one in ten thousand during the preclosure period. The regulation requires demonstration of compliance with performance objectives for Category 1 and Category 2 event sequences. Performance assessments are not required for other event sequences below Category 2 limits.

The consequence module provides capabilities to calculate radiological consequences that may result from facility operations to the public and onsite workers. The types of consequence assessments that may be performed depend on facility design and event sequences. The source term for airborne release calculations may be damaged spent nuclear fuel from either pressurized water reactor (PWR) boiling water reactor (BWR), or a user-specified radionuclide inventory. The PCSA Tool uses the RSAC code [6] to calculate radiological consequences to an offsite member of the public from an atmospheric release of radioactive material. The tool allows the user to select either a deterministic calculation, in which all inputs and outputs are single valued, or a probabilistic calculation. The tool also uses the MELCOR code [7] to estimate the building discharge fraction, which serves as an input to atmospheric release calculations. Inhalation, ingestion, ground surface, and submersion doses are calculated and combined to estimate the total effective dose equivalent to the whole body and total dose equivalent to individual organs. A probabilistic approach is incorporated to assess the uncertainty and variability in the consequence analysis. The input parameters for the probabilistic calculations in RSAC are generated via Latin Hypercube Sampling. RSAC is executed once for each sampled set of input parameters to determine the dose from that realization. Results from dose calculations are processed and displayed in this module.

The worker dose option in the consequence module provides the capability to address dose to workers located outside or inside the buildings. For consequence to the outside workers, the tool calculates dose from the atmospheric release of radioactive material that includes building wake effects. The dose to downwind workers depends on three aerodynamic zones: (i) cavity zone, (ii) wake zone, and (iii) displacement zone. Wind flow around the building depends on a number of physical factors, including the horizontal distance of the worker from the source, the height of the release, and the building dimensions. For these calculations, the Gaussian plume dispersion models are modified to account for the highly modified aerodynamic conditions downwind of the building. The indoor worker dose option performs an analysis for workers exposed to releases of radionuclide inside buildings for events resulting in releases from dry handling of fuel. Worker dose is modeled as leakage of airborne radioactive material from a hot cell into an adjoining room during potential loss of negative pressure between ventilation zones. Several physical parameters, such as room volume, ventilation rate in the worker's room, leakage rate, and time spent by worker in the adjacent room, serve as input for the calculation. The tool also provides the capability to calculate releases of radioactive material resulting from underwater events. The worker dose can be modeled for the release of gases from a spent nuclear fuel pool directly to the room where the worker is located. This scenario-specific calculation is limited to underwater-handling events, with workers present above the pool without respiratory protection equipment.

In the safety assessment module, the frequencies and consequences of event sequences are combined to assess compliance with the risk-informed performance-based regulatory objectives defined in 10 CFR Part 63.111 (a) and (b). For determining compliance with the performance requirements for public and worker doses from normal operations and Category 1 event sequences, the PCSA Tool calculates three quantities: (i) annual dose from each Category 1 event sequence, (ii) sum of frequency-weighted annual doses from Category 1 event sequences, and (iii) summation of doses from credible combinations of multiple event sequences within a single year of operation. Each of these three quantities should be added to the normal operational dose for comparison with the numerical performance objectives. For Category 2 event sequences, the PCSA Tool allows radiological consequences from each Category 2 event sequence to be compared with the regulatory limits specified in 10 CFR Part 63.111(b)(2) for individual members of the public located at or beyond the site boundary.

The PCSA Tool may be used to identify SSCs that are important to safety. SSCs are identified as important to safety based on their capabilities to prevent or mitigate event sequences that have the potential to exceed the regulatory dose limits for Category 1 and Category 2 event sequences. The tool provides a take-away analysis to identify SSCs important to safety. In this analysis, each SSC is individually assumed, one at a time, to not provide its credited safety function, and the event trees and fault trees are reanalyzed so that the performance of the facility can be reevaluated. If the SSC take-away results in a degraded facility performance and fails to meet any of the regulatory requirements, the SSC is considered to be important to safety.

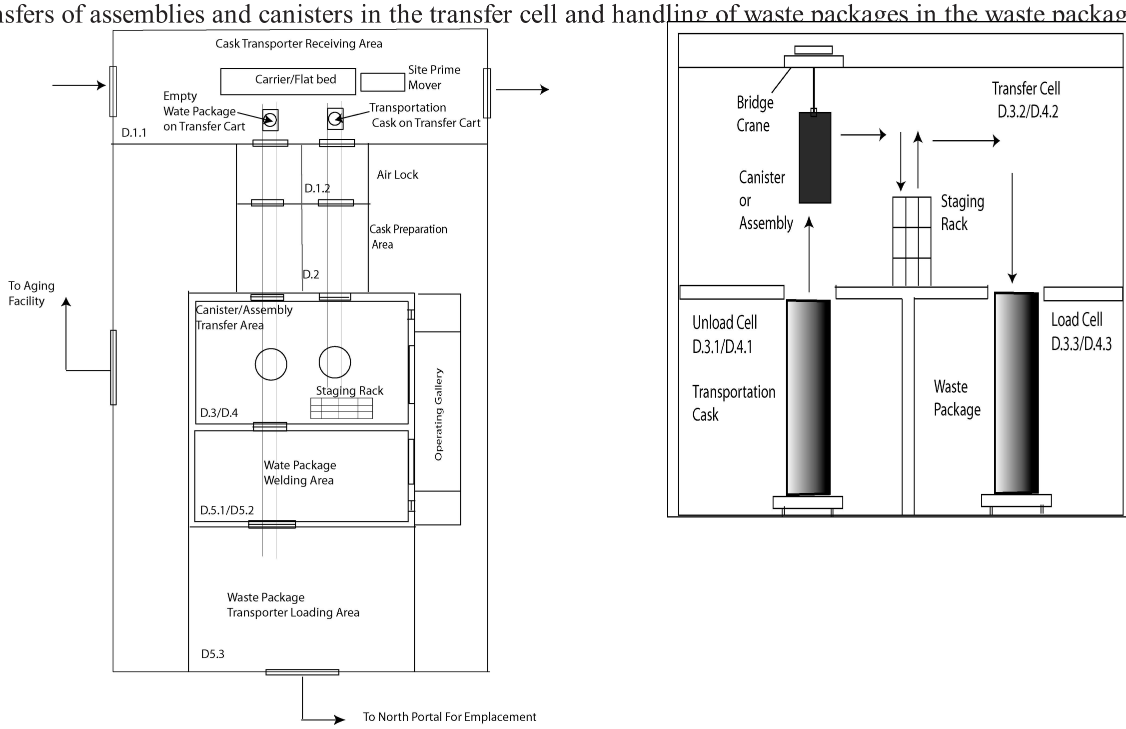
The risk-assessment module evaluates risk associated with all event sequences, regardless of their categorization. An estimation of aggregate risk is not required by the NRC regulation in 10 CFR Part 63 and will not be used directly in compliance determination. However, an estimation of aggregate risk is incorporated in the PCSA Tool to assist in gaining risk insights. Additionally, the risk assessment can also be used to evaluate the reliance of facility design on individual SSCs important to safety [8, 9].

## EXAMPLE ANALYSIS

An example analysis for a simplified hypothetical dry transfer facility is presented to demonstrate the capabilities of the PCSA Tool. This analysis is illustrative in nature and does not intend to represent the staff position on appropriate methods for preclosure safety analyses. The hypothetical dry transfer facility is based in part on previous design concepts, and does not necessarily represent a current design approach. The facility layout and design for dry transfer operations have been conceptualized, as shown in Figure 1a. This figure shows nuclear waste arriving in transportation casks being transferred from a conveyance onto a trolley cart that is remotely driven to the waste transfer cell through areas indicated in Figure 1a. Inside the transfer area, the waste is transferred from the transportation cask to waste packages or aging casks. After the transfer operations, the waste package is seal-welded remotely in the welding area and then transported to the underground facility for permanent emplacement. The aging casks are closed, moved to an aging facility (potentially to cool the waste in a natural environment), and after temporary aging, brought back to the dry transfer facility for final transfer to the waste packages.

For the purpose of this analysis, assembly and canister transfer operations are assumed to take place within a transfer cell. The transportation cask arrives on a trolley in the unload cell, and an empty waste package arrives on a trolley in the load cell (see Figure 1). These three cells are shown in Figure 1b. In the transfer cell, a bridge crane is remotely controlled and is used to transfer assemblies and canisters out of a transportation cask and into a waste package. The waste package is then moved onto a trolley to the waste package welding area, and a bridge crane is used to transfer the waste package from the trolley to the welding cell and back onto the trolley after the inner- and outer-lid weld are completed. A primary Heating Ventilation and Air Conditioning (HVAC) system maintains a negative differential pressure in the transfer cell with respect to the adjoining areas, which are assumed to operate under an independent secondary ventilation system. Worker access is assumed to be restricted in the transfer and welding area; however, workers may be present in the operating gallery and other areas inside the building.

To illustrate specific features of the PCSA Tool, a focused preclosure safety analysis was performed involving transfers of assemblies and canisters in the transfer cell and handling of waste packages in the waste package




(a) (b)

Figure 1. (a) Hypothetical Dry Transfer Facility and (b) Hypothetical Transfer Area. Functional Areas D.3.1, D.3.2, and D.3.3 are for the Assembly Transfer system and D.4.1, D.4.2, and D.4.3 are for the Canister Transfer System.

welding area. Functional areas were assigned for focused systematic analysis and organization of the information. In this case, the transfer cell was separated into a functional area for assembly transfers (D.3) and another one for canister transfers (D.4). The third functional area is the waste package welding area (D.5). The functional areas and sub-functional areas are shown in Figure 1. Hazard analysis, event sequence analysis, consequence analysis, and compliance analysis were performed in each of the functional areas and are discussed in the following sections.

**Hazard Analysis**

Table 1 shows the hazards that were identified in this hypothetical dry transfer facility for the transfer cell and the waste package welding area following a What-if analysis. For the transfer cell, the hazards involve the drop of an assembly, canister, or handling equipment (e.g., yoke) from a bridge crane caused by failure of mechanical, electrical, and control systems, including human errors. For the waste package welding area, the hazard is a drop and tipover of an unsealed waste package while it is being transferred to a turntable for welding.

**Event Sequence Analysis**

Event sequences were developed from postulated event scenarios in which an initiating event occurs and then one or more events (i.e., subsequent events) follow. The failure probability data and the number of transfers used in the calculations of event sequence frequencies are shown in Table 2. The fuel-handling operation period and preclosure period were assumed to be 50 and 100 years, respectively.

**Table 1. Hazards and Initiating Events**

| Functional Area | Hazards | Initiating Events |
|---|---|---|
| D.3.2: Transfer Cell (Assemblies) | Assembly Drop | Failure of the bridge crane while transferring an assembly |
| D.4.2: Transfer Cell (Canisters) | Canister Drop | Failure of the bridge crane while transferring a canister |
| | Handling Equipment Drop Onto Canister | Lifting yoke detaches from the bridge crane and falls onto a canister |
| D.5.2: Waste Package Welding Area | Drop and Tipover of an Unsealed Waste Package | Failure of the bridge crane while transferring a waste package to a turntable for welding |

**Table 2. Data Used in the Analyses**

| Parameter | Data Values | Data Source |
|---|---|---|
| Bridge Crane Drop Rate | 5.6H10$^{-5}$ drops/lift | Assumed value based on information in NUREG-1774 [10] |
| Handling Equipment Drop Rate | 1.9H10$^{-6}$ drops/lift | Fault tree analysis |
| Probability of Weld Defect in Canister | 1H10$^{-3}$ | Assumed |
| Probability of Primary Heating Ventilation and Air Conditioning (HVAC) Failure | 8.0H10$^{-5}$ | Fault tree analysis |
| Probability of Secondary HVAC Failure | 8.0H10$^{-4}$ | Fault tree analysis |
| High-Efficiency Particulate Air Filtration Failure | 1.2H10$^{-5}$ | Fault tree analysis |
| Number of Assemblies Transferred | 12,000 per year | Assumed |
| Number of Canisters Transferred | 1000 per year | Assumed |
| Number of Waste Packages Transferred | 500 per year | Assumed |
| Airborne Release Fractions for Consequence Analysis | — | Point-estimate calculation: NUREG/CR-6672 [11]; Probabilistic calculation: PCSA tool default Distributions and values |
| Atmospheric Transport Parameters for Consequence Analysis | — | Point-estimate and probabilistic calculations: PCSA tool default distributions and values |
| Biosphere Dose-Pathway Parameters for Consequence Analysis | — | Point-estimate and probabilistic calculations: PCSA tool default distributions and values |
| Room Volume, Ventilation Rate, Leakage Rate, Breathing Rate for Worker Dose Calculation | — | PCSA tool default values |
| Occupancy Factor for Worker Dose Calculation | 0.233 | Scaling factor for normal operation source term |

Event scenarios were developed by considering the hazards and initiating events from Table 1 and potential equipment failures subsequent to the initiating event. These event scenarios with initiating event frequencies are shown in Table 3. The highest initiating event frequencies occur with the drop of an assembly into a transportation cask and the drop of an assembly onto another assembly. This is due to the relatively large number of assembly transfers (i.e., 12,000) compared to canister transfers and waste package movements (i.e., 1,000 and 500, respectively).

**Table 3. Event Scenarios**

| Functional Area | Initiating Event | Event Scenario Breach of Assemblies, Canisters, and Waste Packages Followed by HVAC Failure and/or HEPA Failure | Event Scenario Identifier | Initiating Event Frequency (per year) | Fuel Assembly Involved |
|---|---|---|---|---|---|
| D.3.2 Transfer Cell (Assemblies) | Failure of Bridge Crane | Drop Assembly Into Transportation Cask | ADTC | 0.672 | 2 PWR |
| | | Drop Assembly Onto the Dry Transfer Cell Floor | ADFL | 0.084 | 1 PWR |
| | | Drop Assembly Into Empty Waste Package | ADEWP | 0.134 | 1 PWR |
| | | Drop Assembly Onto Another Assembly in Waste Package | ADAWP | 0.538 | 2 PWR |
| | HVAC Failure | Radioactive Material Leakage to an Adjacent Room | HVFL | 0.024 | 1 PWR |
| D.4.2 Transfer Cell (Canisters) | Failure of Bridge Crane | Drop Canister Into Transportation Cask | CDTC | 0.056 | 21 PWR |
| | | Drop Canister Into Staging Rack | CDFL | 0.112 | 21 PWR |
| | | Drop Canister Into Empty Waste Package | CDEWP | 0.014 | 21 PWR |
| | | Drop Canister Onto Another Canister in Waste Package | CDAWP | 0.042 | 21 PWR |
| | Handling Equipment Failure | Handling Equipment Drop Onto Canister in Staging Rack | EQCSR | 0.004 | 21 PWR |
| | | Handing Equipment Drop Onto Canister in Waste Package or Transportation Cask | EQDCC | 0.002 | 21 PWR |
| D.5.2 Waste Package | Failure of Bridge Crane | Drop and Tipover of an Unsealed Waste Package | WPDFL | 0.028 | 44 BWR |

| **Functional Area** | **Initiating Event** | **Event Scenario**<br>Breach of Assemblies, Canisters, and Waste Packages Followed by HVAC Failure and/or HEPA Failure | **Event Scenario Identifier** | **Initiating Event Frequency (per year)** | **Fuel Assembly Involved** |
|---|---|---|---|---|---|
| Welding Area | | | | | |

An example event tree for the drop of an assembly into a transportation cask (Event Scenario ADTC) is shown in Figure 2a. As shown in this event tree, a PWR assembly is dropped from the bridge crane onto another PWR assembly in the transportation cask. Subsequent to this initiating event, the assemblies may breach, the HVAC system may fail to exhaust air from the transfer cell, and the High Efficiency Particulate (HEPA) filtration may fail to operate. Data from Table 2 was used to calculate the event sequence frequencies displayed in Figure 2a. As shown in this figure, event sequence 1 (ADTC-1) results in no consequence for an assembly that does not breach. Event sequence 2 (ADTC-2) may result in a noble gas release to the public and outdoor workers. Event sequence 3 (ADTC-3) may result in noble gas and particulate releases to the public and outdoor workers. Finally, event sequence 4 (ADTC-4) may result in noble gas and particulate releases to the worker in an adjacent room to the transfer cell as a result of a loss of differential pressure caused by failure of the HVAC exhaust system. The fault tree shown in Figure 2b is used to develop the probability of failure of the primary HVAC exhaust system. The exhaust system is assumed to contain redundant fans and dampers. The probability obtained from the fault tree was used in the branch of the event tree identified as PR-HVAC-1.

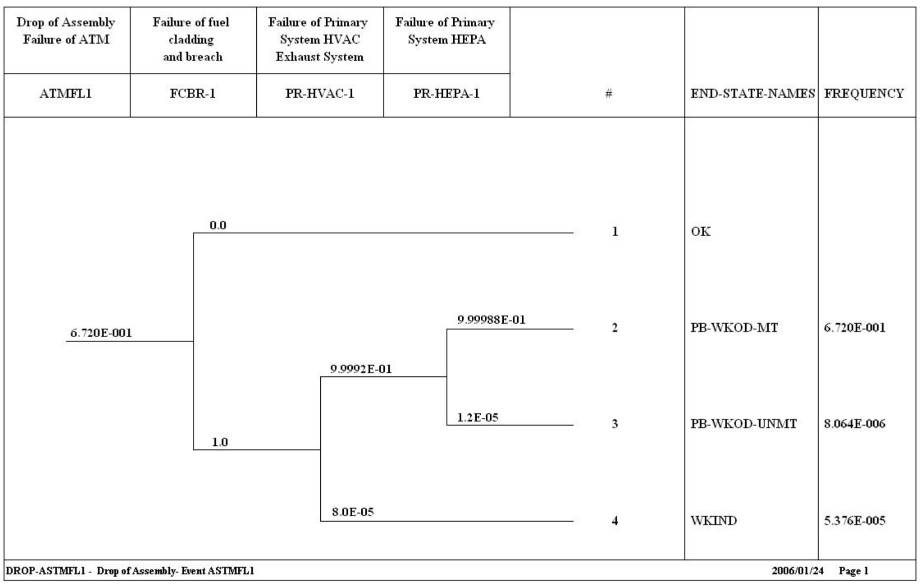



Figure 2(a): Event Tree Model for Event Scenario ADTC

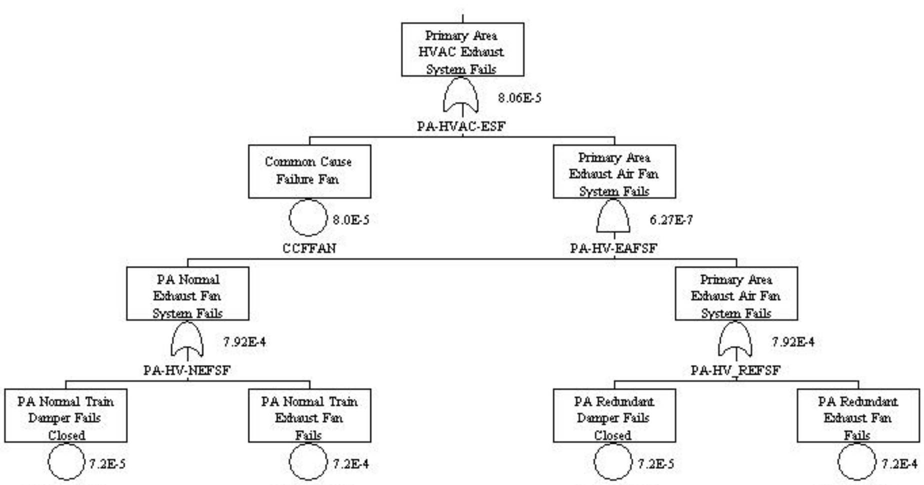
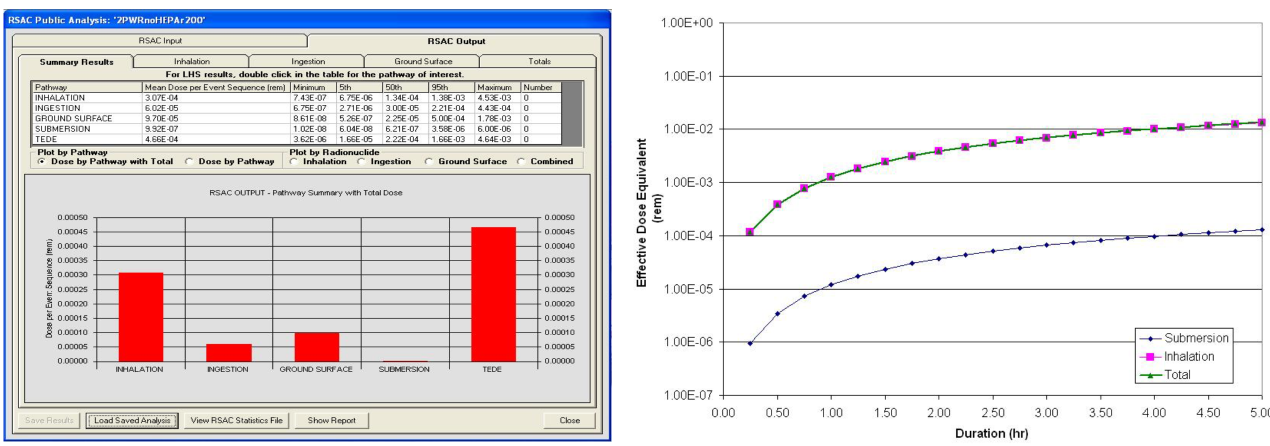


Figure 2(b): Fault Tree Model for the Primary HVAC Exhaust System PR-HVAC-1

**Consequence Analysis**

Radiological consequences from event scenario ADTC were calculated using the consequence module in the PCSA Tool. The data source for consequence analysis is shown in Table 2. Figure 3a shows the radiological consequences to a member of the public at a downwind offsite location from an unfiltered atmospheric release of radioactive material estimated for the drop of one PWR assembly onto another assembly (ADTC-3). This figure depicts the results from a probabilistic analysis and highlights mean doses from inhalation, ingestion, ground surface, and submersion pathways, which have been combined into a total effective dose equivalent. The PCSA Tool also was used to calculate consequences to indoor workers from event scenario HVFL initiated by failure of the primary HVAC exhaust system during normal handling of bare assemblies of spent nuclear fuel. Failure of the primary HVAC system was assumed to result in a loss of negative air pressure in the hot cell, relative to the adjacent occupied room with the subsequent leakage of airborne radioactive material from the hot cell into the occupied room over time. The failure of this system was based on the fault tree analysis (PR-HVAC-1) shown in Figure 2b. Ventilation in the occupied room was assumed to be unaffected and remained operational. The amount of airborne radioactive material present in the hot cell during one day of normal operation was estimated from a DOE report [12]. For this example, worker dose was calculated only for those radionuclides in gaseous or vapor phases (i.e., leakage of airborne particulates from the hot cell to the occupied room was not analyzed). Figure 3b shows the increase in worker dose from inhalation and submersion pathways due to the leakage of airborne radioactive gases over a period of 5 hours. The dose to the indoor worker initially increases rapidly and then levels out with increasing duration.




(a) (b)

Figure 3: (a) PCSA Tool Screen Shot of Public Dose Consequence for Event Sequence ADTC-3 and (b) Consequence to Indoor Workers is Plotted Against Duration of Time of Worker Presence for Event Scenario HVFL1 (Note: 1 rem = 0.01 sv)

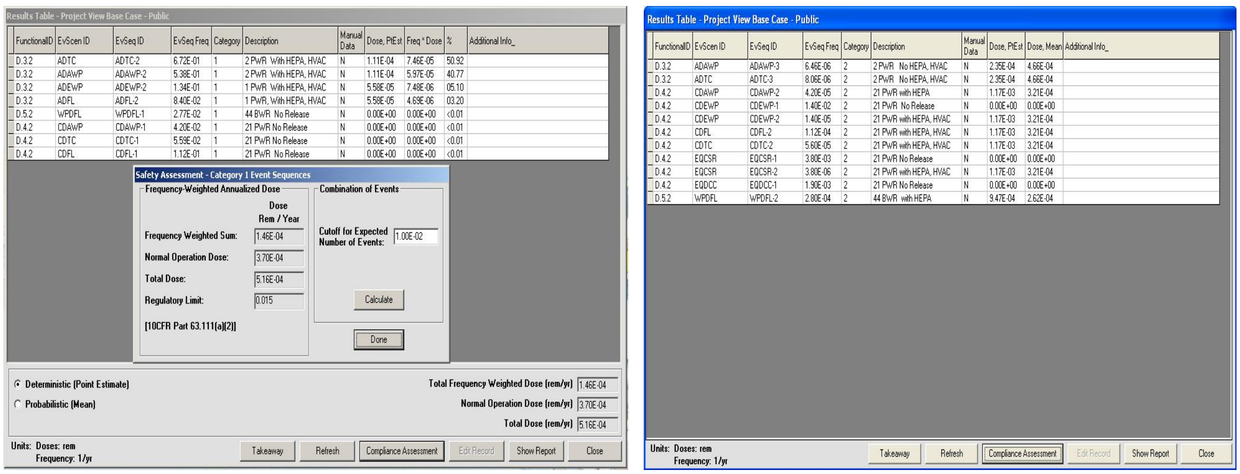
**Compliance Assessment**

The PCSA Tool has the capability to assess compliance with Category 1 and Category 2 performance objectives. The tool compiles frequency and consequence information from all the functional areas and determines the category for each event sequence. Once the categories are determined, the event sequences are then grouped by these categories as shown in Figures 4a and b. Category 1 event sequences for offsite dose are shown in Figure 4a. The tool evaluates compliance for each event sequence and calculates the frequency weighted sum as shown in a separate window in Figure 4a. The tool takes this frequency weighted sum and adds it to the normal release to get the total dose, which is then compared to the regulatory dose limit. Category 1 event sequences are considered for indoor and outdoor workers, but are not shown in Figure 4a. Category 2 event sequences are shown in Figure 4b. For Category 2 event sequences, each sequence is evaluated individually for compliance to the regulatory dose limit. As noted earlier, performance assessments are not required for event sequences below Category 2 frequency limit.

**SSCs Important to Safety**

The process of identifying SSCs important to safety in the PCSA Tool is demonstrated in Figure 5. The figure schematically shows how a take-away analysis is performed in the tool using a hypothetical event tree consisting of an initiating event and two SSCs credited to provide safety functions. Figure 5 shows the reevaluated event trees and degraded facility performance for the take-away of the two SSCs, one at a time.




(a) (b)

Figure 4: (a) Compliance Analysis for Category 1 and (b) Category 2

**CONCLUSION**

The PCSA Tool has been developed in preparation for conducting a risk-informed regulatory review of the preclosure safety analysis in the potential license application for a Yucca Mountain repository. The PCSA Tool provides capabilities for conducting confirmatory analysis for evaluating preclosure safety analyses to assess compliance with regulatory performance objectives and the identification of risk-significant SSCs required to ensure public and worker safety and gain risk insight during the regulatory review. The paper describes the structure and the modules of the tool to support a risk-informed performance based review. The capabilities of the tool are discussed using an illustrative example for a conceptualized facility and operations addressing several components of the preclosure safety analysis.

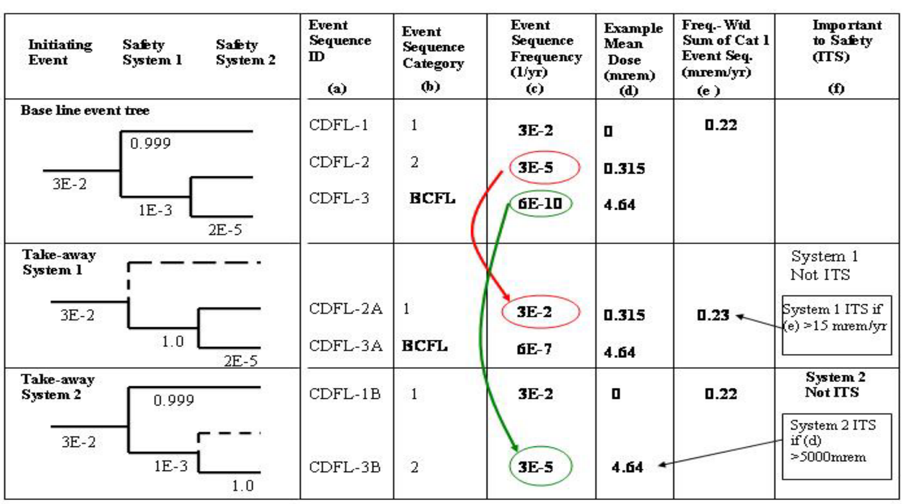



Figure 5: Analysis for Structures, Systems, and Components Important to Safety (Note: 1 mrem = 0.01 msv,

BCFL – Beyond Category 2 Frequency Limit)

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