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ACRONYMS

CA	construction authorization
LA	license application
NRC	U.S. Nuclear Regulatory Commission
PSA	preclosure safety analysis
R&P	receive and possess (i.e., LA amendment to R&P high-level radioactive waste)
SSCs	structures, systems, and components
TSPA	total system performance assessment

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1. INTRODUCTION AND OVERVIEW

A preclosure safety analysis (PSA) is a required element of the license application (LA) for a high-level radioactive waste repository. This document provides analysts and other Yucca Mountain Site Characterization Project personnel with standardized methods for developing and documenting a PSA.

A definition of the PSA is provided in 10 CFR 63.2, and more specific requirements for the PSA are provided in 10 CFR 63.112, as described in Sections 1.2 and 2.

The PSA requirements described in 10 CFR Part 63 were developed as risk-informed, performance-based regulations. These requirements must be met for the LA. The PSA addresses the safety of the geologic repository operations area for the preclosure period (i.e., the time up to permanent closure) in accordance with the radiological performance objectives of 10 CFR 63.111. Performance objectives for the repository, after permanent closure (described in 10 CFR 63.113), are not mentioned in the requirements for the PSA, and they are not considered in this guide. The methods described herein are expected to be in conformance with the review methods. The LA will be comprised of two phases: the LA for construction authorization (CA) and the LA amendment to receive and possess (R&P) waste. The PSA methods must support the safety analyses that will be based on the differing degrees of design detail in the two phases.

The methods described here combine elements of probabilistic risk assessment and deterministic analyses that comprise a risk-informed, performance-based safety analysis.

1.1 PURPOSE

The purpose of this desktop guide is to describe and standardize methods judged to be in conformance with NRC regulations and guidance for developing and documenting a PSA as part of the LA for a repository. In addition, this document provides approaches for obtaining:

- Uniformity in analyses
- Auditable analyses and databases
- A basis for training safety analysts
- Improved communications among the design and licensing groups and the U.S. Department of Energy
- A distinction in the analysis scope and approaches for the CA and R&P phases
- Preferred methods for analyzing and documenting preclosure safety.

The format of this desktop guide is flexible and sectioned to facilitate modifications. Changes may be motivated by requirements of the forthcoming NRC Yucca Mountain Review Plan, requests from the operating contractor, the U.S. Department of Energy, or the NRC.

1.2 SCOPE

This desktop guide is intended to be a complete guide for the preparation of a PSA for a repository in support of the LA. This guide provides analysts with relevant regulations, regulatory guidance, and licensing precedents, as well as instructions for performing each of the required analyses.

The document provides reference links for details and background information concerning methods and regulatory matters. The methods described are recommended for use on the Yucca Mountain Site Characterization Project. The methods generally are applicable to varying levels of design detail. Where important differences exist between analyses suitable for CA and those required for R&P, the initial issue of this document favors support of CA and may defer preparation of R&P-specific sections until needed.

The PSA is an iterative process that continues throughout the design and operational evolution of the repository design. The contents of the PSA are defined in 10 CFR 63.112(a) through (f). The analyses initially identify instances in which functions are required to prevent or to mitigate potential hazards and radiological releases. Prevention and mitigation functions are provided by SSCs important to safety that are identified and evaluated for reliability as part of the PSA process. The analyses also provide the risk-informed design bases (per 10 CFR 63.2) for developing design criteria (as described in 10 CFR 63.112(f)) that are incorporated in the project design criteria documents. The PSA supports the repository safety strategy (see Section 3) by identifying the event sequences and natural phenomena that define the design bases. In addition, the PSA demonstrates how the performance requirements of 10 CFR 63.111, the design criteria of 10 CFR 63.112(f), and the system reliability considerations of 10 CFR 63.112(e) are satisfied.

The PSA is independent and separate from the total system performance assessment (TSPA), which addresses postclosure safety. The PSA is concerned with events involving natural phenomena, active systems, and human actions that could occur within a time scale of 1 to several 100 years. The TSPA addresses events involving passive elements and natural processes that could occur over tens of thousands of years following permanent closure of the repository. Two areas of analysis have some similarity between PSA and TSPA: identifying natural phenomena hazards and calculating radiological consequences. Identifying and screening credible hazards from natural phenomena is performed in an External Events Hazards Analysis that provides input to the PSA. The TSPA has a separate procedure for identifying and screening features, events, and processes. The PSA will include a review of these features, events, and processes for their relevance as potential preclosure hazards. The PSA includes calculations of potential radiological consequences to workers and the public. Some of the methodology and biological dose conversion factors used in the PSA are similar to, or the same as, those used in the TSPA.

This guide is organized into modules; each module covers a limited range of subject matter.

- Section 1–Overview of the PSA process and the organization of this guide.

- Sections 2 through 4–Background information on regulatory requirements, the safety strategy used to define the goals of the safety analysis, and an overview of the PSA process to accomplish these goals.

- Section 5–Definition of the types of site and facility design information required as input to the PSA.

- Sections 6 through 9–Methods for performing hazards analyses, event sequence analyses, consequence analyses, and uncertainty analyses.

- Section 10–Methods for analyzing external events such as fires, earthquakes, and the loss of off-site power.

- Sections 11–Preclosure criticality.

- Sections 12 and 13–Definition of the processes for using PSA results to identify and classify SSCs important to safety in accordance with quality assurance classification methodology and to select 10 CFR 63.2 design bases for the SSCs important to safety.

- Section 14–Guidance on documenting PSA results and output of the processes described in Sections 2 through 13. This guidance includes comprehensive documentation of the analyses required to support a repository LA in accordance with the Yucca Mountain Review Plan.

- Appendix–Glossary.

1.3 REFERENCES

1.3.1 Documents Cited

None

1.3.2 Codes, Standards, Regulations, and Procedures

10 CFR 63. 2002. Energy: Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, Nevada. Readily available.

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2. REGULATORY REQUIREMENTS

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ACRONYMS

LA	license application
PSA	preclosure safety analysis
SNF	spent nuclear fuel
SSCs	structures, systems, and components

3. PRECLOSURE SAFETY STRATEGY

3.1 INTRODUCTION

This section describes the strategy that will be used to prevent or mitigate unacceptable preclosure radiological consequences for the high-level radioactive waste repository. The strategy focused on the offsite dose performance objectives presented in 10 CFR 63.111 and considered the preclosure activities that occur prior to the postclosure period. The strategy is a general plan that does not provide requirements for the repository.

3.2 GENERAL PRINCIPLES

When the license application (LA) is submitted, the safety case for the repository will be presented in a Safety Analysis Report. The safety case will address the logic, analyses, and calculations that describe how the repository systems, structures, and components (SSCs) meet performance objectives, and will include material incorporated by reference and other docketed material. This report will provide the basis for a U.S. Nuclear Regulatory Commission decision to authorize construction and eventually to license the repository. The preclosure safety case will be based on 10 CFR 63.2 SSC design bases (i.e., functions and controlling parameters) and the results of analyses and calculations presented in the preclosure safety analysis (PSA). The preclosure safety strategy is an approach that describes how a risk-informed design should be considered to facilitate compliance with 10 CFR Part 63 preclosure performance objectives.

3.3 PRECLOSURE SAFETY CASE

The preclosure period for evaluating event sequences will be consistent with the anticipated life of the repository. For simplicity, a 100-year preclosure period will be used in the PSA. A preclosure period of 100 years equates to a 1×10^{-2} per year event sequence probability cutoff for Category 1 event sequences, and it equates to a 1×10^{-6} per year event sequence probability cutoff for Category 2 event sequences. Using the 100-year period provides margin in evaluating event sequences for preclosure operations SSCs because the expected duration for emplacement activities is expected to be less than 50 years. The preclosure period must encompass the phases of preclosure operations preceding the time of permanent closure of the repository.

The *Design Basis Event Frequency and Dose Calculation for Site Recommendation* (BSC 2001b) assumed a 100-year operational phase for a higher-temperature operating mode. This operational period is valid for lower-temperature operating modes that have longer preclosure operational phases (BSC 2001a). However, if an operating mode is selected that extends the preclosure period of subsurface drift ventilation beyond 100 years, the effects on the event sequence probability cutoffs for subsurface events must be assessed. For ease of analysis, the preclosure period could be divided into two phases. Phase 1 would encompass the activities associated with emplacing waste in the subsurface facilities. This phase would include phased construction of the subsurface and potentially the surface facilities. Phase 2 would begin after emplacement activities are completed. If the flexible thermal design focuses on a lower-temperature operating mode, then cooling of the waste package could extend the Phase 2 preclosure period to 275 years after emplacement operations end. Because there is no expected movement of waste packages during the cooling period, the hazards to the waste package are

reduced. Furthermore, the resulting likelihood of Category 1 or Category 2 event sequences is reduced. Phase 2 may start when emplacement is completed (e.g., after 50 years of emplacement activities) and extend until permanent closure (the next 275 years for a total precolsure period of 325 years).

3.3.1 Preclosure Safety Analysis

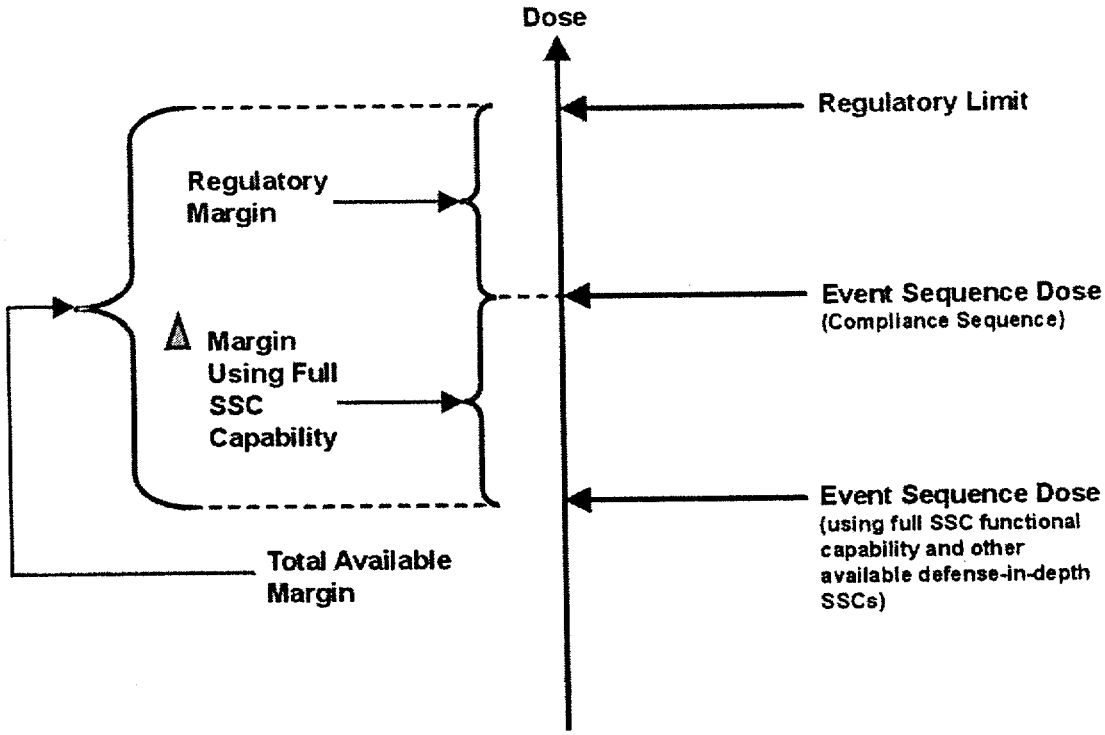
The purpose of the PSA will be to ensure that relevant internal and external hazards that could result in unacceptable consequences have been evaluated, and to ensure that preventive or mitigative features are included in the repository design such that the limits on radiation exposures specified in 10 CFR 63.111 will not be exceeded. The PSA will provide a framework for applying risk-informed, performance-based decision making to identifying SSCs important-to-safety, measures for providing defense-in-depth, license specifications, and surveillance intervals. The PSA will identify potential natural and operational hazards during the preclosure period, assess potential events and event sequences and their consequences, and identify SSCs and personnel activities that are intended to prevent or mitigate each accident sequence. Event sequence identification and analysis comprises an iterative process integrally tied to repository design. Consequently, the PSA and event sequence identification and analysis will continue to evolve with design maturation. Preliminary analyses based on the conceptual design should show large margins between expected performance and the regulatory limits. As the design matures, these margins will be reduced.

3.3.2 Margin and Defense-in-Depth

Margin, as used in this section, refers to the difference between calculated event sequence consequences and regulatory compliance limits (Figure 3-1). Margin is included in safety analyses for reasons that include analysis uncertainties, operational flexibility, and additional safety confidence.

The specific margin credited in the PSA will be the amount needed for defensibility of analyses and compliance with regulations. In specific cases, license specifications may be established to ensure that sufficient margin is maintained relating to the bounds of values related to the safety analyses. To accommodate potential changes to the design, data, or analyses that are in effect when the LA for construction authorization is submitted, one-half of the limits prescribed by the regulations will be used as a guideline for evaluating performance. The purpose of this guideline is to indicate the need for consideration of alternative features for prevention or mitigation of consequences resulting from potential design basis events. At the time of submittal of the LA amendment to receive and possess high-level radioactive waste, the acceptance criteria will be the regulatory dose limits with consideration of defendable uncertainties (see Section 9).

Defense-in-depth is the application of redundant or diverse physical and administrative barriers (or other protective measures) to mitigate unanticipated conditions, processes, and events such that failure of any one barrier or SSC does not result in failure of the entire system. Defense-in-depth ensures that safety is not wholly dependent on any single element of the design, construction, operation, or maintenance of the facility. The application of defense-in-depth will be risk-informed and will not be arbitrarily assigned. Facilities that include defense-in-depth should be more tolerant of failures and external challenges.



NOTE: Illustration of typical margin calculations for an event sequence. This event sequence takes credit for the 10 CFR 63.2 design bases functions. The dose calculation for the compliance event sequence is compared to the regulatory limit to provide a regulatory margin. Also shown is the dose calculation for the event sequence that credits the full design bases functional capabilities of the SSCs along with any additional defense-in-depth SSCs. The application of this SSC functional capability would provide additional margin to the regulatory limit that is under control of the Department of Energy.

Figure 3-1. Margin For Dose Compliance

3.3.3 Consequence Analysis of Very Low Probability Events and Event Sequences

The regulatory limit for event sequences that must be analyzed is greater than one chance in 10,000 for the preclosure period. Exceeding this threshold for the potential event sequences may be precluded by the design of SSCs. For example, the preclosure design bases for the repository will preclude a breach of a high-level radioactive waste or spent nuclear fuel (SNF) shipping cask, canister, or waste package resulting from a drop event (or other credible impacts) because that event sequence will have been demonstrated to have a frequency of less than 1×10^{-6} per year (see Section 3.5). If the event sequence has a frequency greater than 1×10^{-6} per year, the safety analysis must demonstrate that releases from a breached container will not result in site boundary doses above the regulatory limits.

The PSA will include evaluations of the consequences of selected sequences that are below the Category 2 threshold, using the best estimate of expected conditions, to provide confidence in the repository preclosure design. The purpose of this evaluation will be to ensure that an event sequence with high consequence levels is not arbitrarily excluded based on the low frequency of the event. Selected design features that maintain the event sequence frequency below 1×10^{-6} per year will be candidates for designation as important to safety. Features added to mitigate the consequences of such events would not be considered to be important-to-safety. These

consequence analyses will not be part of the safety case, but may provide additional confidence in the repository performance.

3.3.4 Nuclear Industry Precedent and Experience

The strategy for the preclosure operational period includes maximizing the use of proven technology and concepts that have been used for years in the commercial nuclear industry and in Department of Energy activities for safely handling radioactive wastes.

Precedents and experience from the commercial nuclear industry (and other nuclear fuel cycle facilities) will be used where appropriate in the design and analysis of the repository operational facilities. The use of precedent provides confidence in the PSA approach, and it provides data and lessons learned for incorporation into the hazards and consequence analyses.

The PSA will incorporate industry precedents that are appropriate for the repository. The use of precedent provides additional assurance that the processes used in the PSA are acceptable to the U.S. Nuclear Regulatory Commission, and it will allow them to focus on the application of processes. The use of precedents should also facilitate the review process. Industry precedent should be used (or adapted) when it results in compliance with regulatory requirements and it does not result in significant over-conservatism in the design development.

Regulation 10 CFR Part 63 is risk-informed and performance-based, and it requires identifying SSCs that are important to safety. This approach is a broader recognition of radiological risk than the traditional safety-related definition. Many industry and licensing precedents are based on traditional safety-related concepts with a more deterministic approach to safety analysis. The use of industry and licensing precedents should form the building blocks for the development of the PSA; however, in many cases, the intent and philosophy of the precedents should be used. For example, using regulatory guides that are based on the safety-related concept may be appropriate for the application to SSCs important-to-safety that have been classified as Quality Level-1, but they may be overly conservative for important-to-safety SSCs that are classified as Quality Level-2 or Quality Level-3 (quality assurance classifications are described in Section 12). However, for natural phenomena, the direct application of industry and licensing precedents may be appropriate (e.g., protection against floods or tornadoes).

When evaluating the applicability of industry and licensing precedents, the following will be considered:

- Differences in the regulatory basis or philosophy
- Regulatory definitions (e.g., event sequences, important to safety, safety-related)
- Performance objectives
- Licensing period.

Recent precedents related to risk-informed regulation will be used whenever appropriate. Using recent precedents will help to achieve the appropriate balance between using traditional industry and licensing precedents and using the current risk-informed regulatory philosophy.

3.3.5 Evaluation Approach

3.3.5.1 Risk-Informed Approach

A risk-informed approach, as discussed in this guide, is used to evaluate preclosure repository safety. As a result, deterministic precedents are not applied a priori. The risk-informed regulation results in balancing deterministic and probabilistic approaches. For example, the design of the preclosure facility to protect against external floods, extreme winds, tornado winds, and tornado missiles will primarily be deterministic and precedent-influenced. However, probabilistic analyses may provide insight into the appropriate intensity of site-specific hazards that the facility should withstand (e.g., magnitude of seismic events or tornadoes). In addition, selection of tornado missiles using a site-specific probabilistic method rather than through the use of a prescribed list may result in a more robust risk-informed design. Using probabilistic techniques to evaluate potential hazards is expected to be more appropriate for evaluating internal events. No arbitrary single-failures will be considered in the safety evaluation of event sequences. Failures will be based on a risk-informed approach as described in Section 4.

3.3.5.2 Mechanistic Evaluation

Mechanistic evaluations of the facility represent the preferred approach for evaluating event sequences. Mechanistic evaluations represent potential causes and effects of failures and actions. A non-mechanistic failure would be an arbitrary assumed failure of a component that is not linked to a cause (e.g., a breach of a transportation cask without a cause for the breach). In general, nonmechanistic failures are not assumed in the safety evaluation.

3.3.6 Conservative or Bounding Approaches

Reasonable values (e.g., mean frequencies and consequences; see Sections 7 and 8) and approaches will be used in evaluating the preclosure safety aspects of repository facilities. Simple bounding evaluations will be used when they do not overly constrain the design or the operations of the facility. For example, if a simple, conservative evaluation of an event sequence meets regulatory limits with existing SSCs and does not result in unusual quality assurance classification of an SSC (see Section 12) or the addition of SSCs to prevent or mitigate the event sequence, then the analysis is complete. However, if the bounding treatment of an event sequence results in the need for additional SSCs or the need for non-typical design and quality requirements to meet regulatory limits, then a more rigorous, less deterministic analysis may be warranted.

3.3.7 Preferred Approach

Many options are available for ensuring that event sequences are adequately prevented or mitigated. While the approaches to addressing event sequences may differ, a preferred strategy will govern how the repository event sequences are addressed:

- Design features are preferable to administrative features
- Passive features are preferable to active features

- Automatic features are preferable to manual features
- Separation is preferable to co-location.

Additionally, a risk informed approach should be used to determine acceptable preclosure 10 CFR 63.2 design bases (see Section 13). Protection will progress from a single component or system to redundant components and systems. Diverse components and systems will be included in the design if potentially important common-mode failures are identified. Developing a design that maximizes the implementation of these elements can result in a simple and transparent safety case, a facility with passive safety features, and less overall risk and minimal operational complexity.

3.3.8 Retrievability

Consistent with regulatory requirements, full retrieval of waste packages is not part of the LA acceptance criteria. However, waste package retrieval capability must be demonstrated in the design of the facility. The assessment of retrieval capability will demonstrate that the consequences of Category 1 and Category 2 event sequence will be within the performance objectives of 10 CFR Part 63 and that there are no Category 1 or Category 2 event sequences that could occur during retrieval that would preclude the capability to retrieve the waste packages.

An explicit analysis of full retrieval will not be included as part of the LA submittal. If full retrieval becomes necessary, an amendment to the Safety Analysis Report (with the design and operational modifications) will be submitted prior to commencing retrieval operations.

3.3.9 License Specifications and Surveillances

License specifications–License specifications are rules that establish when repository SSCs important-to-safety must be operable (including allowed outage times). They establish the limiting parameters for the operation of SSCs important-to-safety and the limits on the types and forms of waste to be received. These specifications provide additional assurance that the repository preclosure operations will be performed safely.

Licensing specifications will be derived from the PSA. Licensing conditions may include restrictions on the maximum annual throughput of transportation casks and waste packages; restrictions on the chemical form of radioactive waste; restrictions on waste package characteristics; requirements on testing, calibration, or inspection to ensure license conditions are observed; controls to restrict access to the site; preventative maintenance activities; and administrative controls related to management, procedures, record keeping, review, and audit. The licensing specifications will be developed to provide confidence that the facility will operate within the preclosure safety licensing conditions. Factors to consider in developing licensing specifications include the type and number of risks identified in the PSA, industry and regulatory precedents, and manufacturer specifications.

Surveillances are periodic (e.g., monthly, quarterly, or annually) operational tests of SSCs to demonstrate the ability of the SSCs to perform required safety functions. The frequency of surveillance and time constraints of action statements will be risk-informed.

Regulation 10 CFR 63.21(18) requires that license specifications, including the identification and justification for the selection of those variables, conditions, or other items that are determined to be probable subjects of license specifications, are included in the repository LA submittal.

3.3.10 Preclosure Testing

Testing activities that occur during the preclosure period will be evaluated in the PSA. Tests that need to be performed to demonstrate the operational readiness of the facility will be performed before startup and during the operating phase of the repository. These tests will demonstrate the adequacy of the facility to operate within the preclosure licensing basis.

3.4 STRATEGY FOR PREVENTING OR MITIGATING PRECLOSURE OFFSITE RADIATION EXPOSURE

3.4.1 Identification of Important-to-Safety Features and Controls

To ensure that radiation doses associated with Category 1 and Category 2 event sequences do not exceed the limits in 10 CFR 63.111(a)(2) and 63.111(b)(2), the repository design will incorporate a combination of prevention and mitigation features and controls. Prevention is the use of design features to reduce the postulated frequency of events that result in radiological release from the repository operations area to less than one chance in 10,000 of occurring before permanent closure. Mitigation is the use of design features and barriers to ensure that the consequences of a postulated radiological release event sequence are within the regulatory limits for doses to workers and the public. Mitigation includes features intended to reduce releases from the routine operations that are included in the Category 1 event sequence annual dose summation. The PSA is used to identify the preventive features, mitigative features, and operational controls that are required to demonstrate compliance with radiation dose limits.

This preclosure safety strategy requires using prevention features in the repository design wherever reasonable. Eliminating or minimizing the potential for radiological release events provides design and operational benefits. From an operations perspective, surveillance and maintenance of active safety features for mitigating the consequences of events have been demonstrated to add to nuclear facility operational complexity, and recovery from events has proved to be more challenging than anticipated. This strategy is implemented by performing the PSA as an integral part of the design process in a manner consistent with a performance-based, risk-informed philosophy. A risk-informed approach uses risk insights, engineering analysis and judgement, and equipment performance history to demonstrate the importance of the repository preclosure operational functions that have the most safety significance and to establish design criteria and management controls based upon these risk insights. This integral design approach ensures that the design features and operational controls important to safety are selected in a manner that assures safety while minimizing design and operational complexity through the use of proven technology.

3.4.2 Design Bases for Facilities and Limits on Operations

The preclosure safety strategy requires that SSCs important-to-safety must be designed, constructed, and operated in such a manner that they will survive credible external events and natural phenomena and that Category 1 and Category 2 event sequence dose limits will not be exceeded.

3.4.3 Safety Strategy for Repository Preclosure Operational Functions

The safety strategy for repository preclosure operational functions is based on the receiving waste, transferring waste into disposal containers, sealing disposal containers, transferring waste packages to emplacement drifts, and emplacing waste packages. These functions are based on site recommendation design features and illustrate the application of the preclosure safety strategy discussed in previous sections. The safety strategy for each of these functions is either prevention augmented by mitigation or mitigation augmented by prevention. Summary descriptions of the safety strategy for each of the five repository preclosure operations functions, and a potential list of safety strategies for each are summarized in Table 3-1.

Table 3-1. Preclosure Safety Strategy

Example Basic Operations	Canistered Fuel Safety Strategy	Uncanistered Fuel Safety Strategy
Receipt of Waste		
Survey Remove impact limiters Remove personal barriers Remove hold downs Upright cask Transfer cask to cart	Prevent events that could exceed shipping cask design basis (preclude breach)	Prevent events that could exceed shipping cask design basis (preclude breach)
Vent and Sample cask Unbolt cask cover Remove cover Remove materials from cask Install cover Bolt cask cover Store canistered waste Store SNF assemblies Decontaminate cask Remove DC cover Load DC Install DC cover Decontaminate DC	Prevent events that could exceed canister design basis (preclude breach)	Minimize the number of events that could result in uncanistered fuel drops; minimize radiation releases from drop events
Sealing the Disposal Container		
Weld DC Inspect DC welds Stress relieve DC welds	Prevent events that could exceed canister design basis (preclude breach)	Minimize the number of events that could result in disposal container drops; minimize radiation releases from drop events

Table 3-1. Repository Preclosure Safety Strategy (Continued)

Example Basic Operations	Canistered Fuel Safety Strategy	Uncanistered Fuel Safety Strategy
Transfer of the Waste Package (WP) to the Emplacement Drift		
Move WP and pallet to tunnel entrance Descent to drift entrance Park at drift entrance	Prevent events that could exceed WP design basis (preclude breach)	Prevent events that could exceed WP design basis (preclude breach)
Move WP and pallet to tunnel entrance Descent to drift entrance Park at drift entrance	Prevent events that could exceed WP design basis (preclude breach)	Prevent events that could exceed WP design basis (preclude breach)
Emplacement		
Move WP and pallet from tunnel entrance to permanent drift position	Prevent events that could exceed WP design basis (preclude breach)	Prevent events that could exceed WP design basis (preclude breach)

NOTE: DC = disposal container; WP = waste package

3.5 REFERENCES

3.5.1 Documents Cited

BSC (Bechtel SAIC Company) 2001a. *Preliminary Preclosure Safety Assessment for Monitored Geologic Repository Site Recommendation.* TDR-MGR-SE-000009 REV 00 ICN 03. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010705.0172.

BSC 2001b. *Design Basis Event Frequency and Dose Calculation for Site Recommendation.* CAL-WHS-SE-000001 REV 01 ICN 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20011211.0094.

3.5.2 Codes, Standards, Regulations, and Procedures

10 CFR 63. 2002. Energy: Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, Nevada. Readily available.

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ACRONYMS

ALARA	as low as is reasonably achievable
CA	construction authorization
HEPA	high-efficiency particulate air
HVAC	heating, ventilation, and air-conditioning
LA	license application
LA-CA	license application for construction authorization
LA-R&P	license application to receive and possess
NRC	U.S. Nuclear Regulatory Commission
PSA	preclosure safety analysis
QA	quality assurance
R&P	receive and possess (i.e., LA amendment to R&P high-level radioactive waste)
SSCs	structures, systems, and components
YMP	Yucca Mountain Site Characterization Project

4. OVERVIEW OF PRECLOSURE SAFETY ANALYSIS ELEMENTS AND APPROACHES

4.1 INTRODUCTION

A high-level overview of how the preclosure safety analysis (PSA) will be performed for a repository at Yucca Mountain is presented in this section. The PSA comprises several kinds of analyses that must be integrated into a cohesive evaluation and documented. Further, the PSA process supports developing 10 CFR 63.2 design bases, design criteria, design requirements, structures, systems, and components (SSCs) classification, design evaluation, Q-List development, and the preclosure safety strategy in license application (LA) documentation.

The PSA process must support the LA for construction authorization (CA) as well as the LA amendment to receive and possess (R&P) high-level radioactive waste. The process must be sufficiently flexible and robust to support the LA given the level of design detail available for the SSCs of the geologic repository operations area at the time of the license application for construction authorization (LA-CA).

4.2 BACKGROUND

The requirements for performing and documenting a PSA for a repository, per the definition of 10 CFR 63.2 and the content defined in 10 CFR 63.112, are described in Section 2. The methods described are responsive to the U.S. Nuclear Regulatory Commission's (NRC's) methods and review acceptance criteria. The repository licensing process for waste emplacement consists of two steps: a CA and a license to R&P. A PSA is required to be provided in support of both licensing steps. Each of the licensing steps requires an NRC safety determination that is based on, respectively, the initial PSA for the CA, and the updated PSA for the license application to receive and possess (LA-R&P). The licensing plan is to submit the amount of design information in the LA that provides sufficient information for the NRC safety evaluation.

Because 10 CFR Part 63 was developed as a risk-informed, performance-based rule, the PSA is adapting a risk-informed, performance-based approach. While parts of the safety strategy (see Section 3) are based on deterministic principles and regulatory principles, a large portion of the safety evaluation for the preclosure operations apply elements of risk analysis. The methods described in this guide are consistent with NRC regulations and guidance. The methods are compatible with NRC guidelines (Milstein 2000, NRC 1983) for performing an integrated safety analysis (which was the term ascribed to the PSA prior to the promulgation of the Final Rule (10 CFR Part 63). The NRC guidelines permit the licensee to apply appropriate methods to produce results and documentation that are deemed suitably comprehensive by the NRC.

4.3 OVERVIEW OF PROCESS FOR PERFORMING A PRECLOSURE SAFETY ANALYSIS

The PSA applies elements of risk analysis that are imbedded in the hazards and event sequence analyses. The PSA comprises a structured, multi-tiered evaluation of hazards and event sequences. The PSA applies the risk-analysis triplet that asks the three questions:

- What can happen? (hazard identification and scenario development)
- How likely is it? (frequency or likelihood analysis)
- What are the consequences? (radiological doses or physical harm to workers or public)

The questions can be answered qualitatively, as well as quantitatively, and therefore, can be applied to deterministic, as well as probabilistic analyses.

These same three questions are applied over and over as the PSA progresses through the hazards analysis phase, event sequence analyses, consideration of safety-specific analyses, and as the design detail evolves. The PSA also includes elements of risk management by identifying means for preventing, reducing the likelihood of, or mitigating hazards.

The performance of a comprehensive hazards analysis and event sequence analyses in the preliminary stages of design requires the application of the knowledge and experience of a multi-disciplinary team comprised of personnel who are cognizant of one or more areas related to safety and design:

- Hazards analysis and event sequence analysis for radiological safety
- Design of mechanical systems for handling, opening, sealing, loading, and transporting waste forms
- Design of structural, electrical, and instrumentation and control systems
- Design of pool water-treatment and cooling systems (if needed)
- Design of heating, ventilation, and air-conditioning (HVAC) and high-efficiency particulate air (HEPA) filter systems for radioactive areas
- Design of disposal container and waste package
- Radiological consequence analyses
- Criticality safety
- Fire hazards and fire protection
- Design for radiation protection, shielding, and as low as is reasonably achievable (ALARA)

- Systems reliability modeling, including fault tree, failure modes and effects analysis, human factors, and common-cause failures
- Processing, packaging, and disposal of site-generated radiological and hazardous waste
- Licensing and regulations.

As needs dictate, other disciplines should be addressed. In addition to engaging multiple disciplines in the development of the PSA, the formal review of PSA products should engage cognizant personnel (subject mater experts) to ensure that the PSA is complete.

PSA activities and documentation will be Yucca Mountain Site Characterization Project (YMP) procedures.

4.3.1 Flow Diagram of Preclosure Safety Analysis Process

Figure 4-1 illustrates the PSA process that will be documented in the Safety Analysis Report. Individual sections of this desktop guide describe how each of the specific elements are performed and documented. Section 4.4.3 describes the process for performing a preliminary PSA with a limited amount of design detail. The three risk-analysis questions are addressed through the PSA process.

The elements of the PSA process, for the stages of design maturity, are described in the following paragraphs. (The bolded paragraph lead-ins refer to PSA elements shown in Figure 4-1.)

4.3.1.1 Hazards Analyses

Internal and External Hazard Identification–Hazards analysis is a systematic identification and evaluation of naturally occurring and human-induced hazards (see Section 6). To ensure completeness, the analysis begins with checklists of generic categories of hazards to identify which are applicable to a repository. The preclosure hazards at a geologic respository are not like those at a complex facility such as a nuclear power plant or petroleum refinery that contains and controls large amounts of thermal and chemical energy that can contribute to the initiation and magnitude of consequences should an accident occur. The high-level radioactive waste forms are contained in a series of physical barriers, including fuel rod cladding, canisters, transport casks, and waste packages. Thus, some form of energy must be imparted, generally from an external source, to a waste form to initiate some undesired sequence of events. Natural phenomena, such as earthquakes and tornadoes, are sources of energy, as well as the processes for lifting, moving, transporting, and welding that are inherent in repository operations. The role of the hazard analysis is to identify sources of energy that can have the potential to harmfully interact with a waste form. In the structured internal event hazards analysis, the forms of energy are categorized as Collision/Crushing, Chemical Contamination/Flooding, Explosion/Implosion, Fire, Radiation/Magnetic/Electrical/Fissile (i.e., potential criticality), or Thermal. The external events hazards analysis identifies credible natural phenomena such as earthquakes that could impart sufficient energy to the facilities to pose a hazard to a waste form.

The evaluation of hazards provides the technical bases for either including or excluding specific hazards from the PSA. Initially, qualitative evaluations are applied to screen out inapplicable or

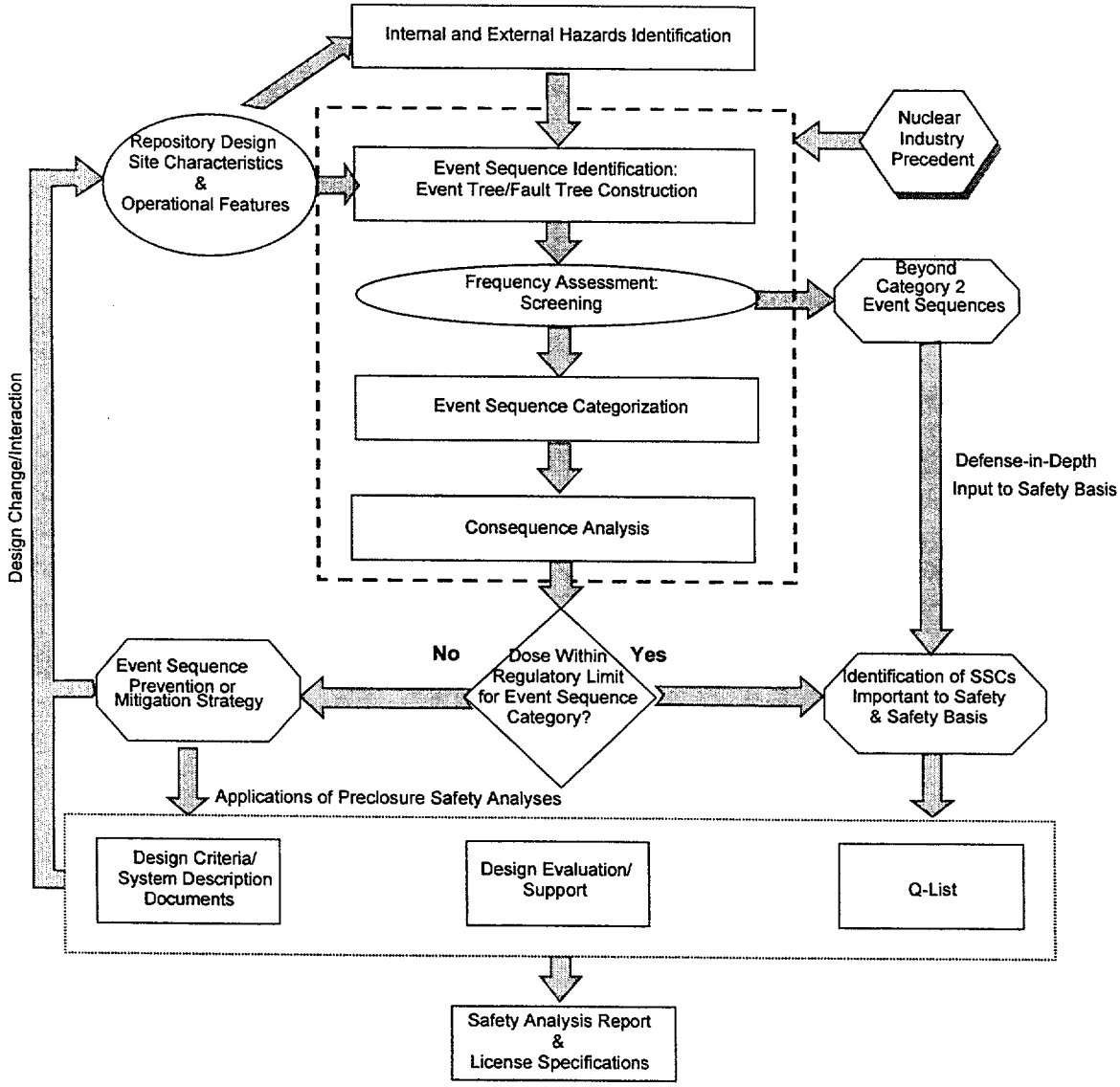

Figure 4-1. Preclosure Safety Analysis

incredible hazards, from hazards either internal or external to the repository facilities. External hazards include natural phenomena and human-induced events. Each credible hazard is considered as a potential initiator of event sequences that could lead to releases of radioactivity or radiological exposure of workers.

4.3.1.2 Event Sequence Analysis

The central box in Figure 4-1 contains several steps that comprise the PSA process. The analytic elements are described below, as they are applied in event sequence analysis for internal initiating events. The process applies several of the methods familiar to probabilistic risk

assessment. (Section 4.3.1.3 describes a variation on the process that is applied to external initiating event and natural phenomena, and which may invoke deterministic analysis or regulatory precedents.)

The qualitative screening of the internal events hazards analysis identifies credible events in each operational area that could potentially initiate an accident sequence. The internal event analysis identifies in more detail what events have to occur to result in a radiological accident and evaluates their credibility and potential consequences. The event sequence analysis incorporates analyses and design strategies from safety-specific disciplines (e.g., criticality and fire-protection) and across disciplines (e.g., criticality, fire, and radiological exposure).

Sequence Identification: Event Tree and Fault Tree Construction–The internal hazards are classified by potential energy sources, associated with each operation in the facility, that could directly or indirectly impact various radioactive waste forms. Energy sources include drops, collisions, tipovers and slapdowns, fires, explosions, flooding, criticality, chemical, radiation, thermal, and human interactions. Potential accident scenarios (or event sequences) may be displayed in the form of event trees that include an initiating event (from an identified hazard) and one or more enabling events that must occur to result in a release of radioactivity, a criticality, or an abnormal worker exposure. The event tree format provides a framework for estimating the likelihood of event sequences by displaying the frequency of the initiating event and the conditional probabilities of contributing (enabling) events.

Potential criticality event sequences are subjected to specialized analyses to demonstrate that sufficient design and operational controls are in place to ensure the probability of a criticality is below the threshold for credibility.

Frequency Assessment: Screening–The frequency (or annual probability of occurrence) is estimated with quantitative analyses for each event sequence that potentially results in a release of radioactivity or abnormal worker exposure. The framework of the event tree is used to display the frequency of the initiator and the conditional probabilities of each enabling event in a sequence. The frequency of each event sequence is calculated as the product of the initiator frequency and the probabilities of the enabling events.

The frequencies of initiating events for internal hazards are estimated from the annual frequency of each operation multiplied by the conditional probability of the initiating event per operation. For example, the frequency of a canister drop is estimated by the product of the frequency of canister lifts (i.e., the number per year) and the conditional probability of dropping the canister per lift. The annual frequencies of each operational step are determined from programmatic information that specifies the maximum number of transport casks, spent fuel assemblies, spent fuel canisters, high-level radioactive waste canisters, and waste packages that are expected to be processed each year during the preclosure operations. The conditional probability of each enabling event (usually a failure of some preventive or mitigative feature), such as a drop of a waste form, is estimated from generic data for similar operations. In many cases for the preliminary event sequence screening analyses, conservative probabilities are assumed for the conditional events (e.g., assuming a probability of 1.0 that all fuel rods breach in a drop sequence). This conservatism is warranted in most cases in the early screening because design criteria or design details are not in place. As noted below, one objective of the internal event

analysis is to define where prevention or mitigation controls are needed. Nevertheless, the event tree framework helps to display and keep track of the assumed probabilities and their bases.

The quantitative screening applies the 10 CFR 63.2 definition of event sequence to screen out event sequences whose estimated frequency results in a probability of less than one chance in 10,000 of occurring during the preclosure operations. Such event sequences are termed beyond Category 2 event sequences and are screened out as noted by the octagonal box in Figure 4-1. Because of uncertainties, the frequency screening is conservatively applied initially so that event sequences within a factor of 10 of the threshold are retained in a list of event sequences until they may be shown to be less than 10^{-6} per year.

Event Sequence Categorization–In this step of the analyses, the frequency of each event sequence that survived the frequency screening is categorized as Category 1 or Category 2 as defined by 10 CFR 63.2. This categorization is important because it establishes which portion of the performance objectives of 10 CFR 63.111 govern each sequence.

Consequence Analysis–In this portion of the analysis, the potential consequences of releases or exposures are calculated for Category 1 and Category 2 event sequences. In some cases, the release or exposure characteristics are similar for two or more event sequences permitting sequences to be grouped. For Category 1 event sequences, consequences are evaluated as potential contributors to chronic exposures and are aggregated for Category 1 event sequences. For Category 2 event sequences, consequences are evaluated for each Category 2 event sequence, individually, as an acute exposure. Consequence analyses are also performed to support prevention or mitigation strategies for external events, as described in Section 4.3.1.3.

The assessment of doses to the public and to workers for each event sequence is evaluated for credible exposure pathways.

Section 8 describes the dose pathways considered in more detail.

The output of the event sequence analysis is a tabulation of the event sequences by category and the consequences associated with each. Where appropriate, a bounding event sequence for each category is identified for each operational area. The characteristics of the bounding event sequence define the 10 CFR 63.2 design bases requirements for SSCs important to safety associated with that operational area.

Dose Within Regulatory Limit for Event Sequence Category?–This evaluation determines whether a specific repository design is licensable. If any deficiencies are noted wherein the respective performance objectives for Category 1 or Category 2 event sequences are not met (i.e., resulting in a "No"), the YMP develops an event prevention or mitigation solution to correct the deficiency. The solution may result in a design change or additional administrative control.

Ultimately, the answer must be "Yes" to be licensable. The SSCs that are to ensure that credible event sequences are in compliance with 10 CFR Part 63 are termed "important to safety." This step is shown in Figure 4-1 as Identification of SSCs Important to Safety and Safety Basis. Section 4.5 describes the requirements for ensuring the performance of SSCs important to safety. Section 12 presents the approach of the quality level classification process.

As necessary through design evolutions, portions or all of the PSA steps are iterated until the performance objectives of 10 CFR 63.111 are met with the proposed design.

4.3.1.3 External Event Preclosure Safety Analysis

The event sequence analysis of external events involves some variations on the process used to evaluate internal hazards (see Section 10). In most instances, the safety strategy for external event initiators is prevention of sequence initiation or SSC survivability through design. Consequently, sequences that could result in releases or exposures would be expected to be beyond the Category 2 cutoff. As appropriate, however, potential event sequences are defined and their potential consequences are calculated and evaluated against the dose limits of 10 CFR 63.111. If prevention or mitigation is necessary to meet the regulations, the SSC(s) involved will be designed to withstand the effects of external events of prescribed intensity, either using NRC precedents or site-specific events. The following are portions of the external event analyses that are not illustrated explicitly in Figure 4-1.

External Event Hazards and Screening Analysis–Potentially credible hazards that survive the initial qualitative and quantitative screening of the external events hazards analysis, such as earthquakes, winds, tornado missiles, lightning, external fires, loss of offsite power, aircraft crashes, and industrial-military activities, are subjected to further analyses. Such analyses may include quantitative evaluation of their likelihood to determine if they can credibly occur during the preclosure operations, or credibly cause a radiological release.

Selection of Design Basis External Events–This is the outcome of the external events hazards and screening analysis, including the specification of the frequency and intensity of design basis earthquakes, tornadoes, loss of offsite power, and similar events. The external event sequences are considered in light of how undesired consequences (i.e., radiological, criticality, or fire and explosion) might be generated by interaction of the external event with operations or storage areas within the facility.

Event Sequence Prevention and Mitigation Strategy–This step produces design requirements such that event sequences initiated by external events cannot credibly result in an unacceptable release of or exposure to radioactivity. For example, cranes and similar devices may need to be designed to halt in a safe condition without dropping a waste form upon loss of offsite power. The buildings housing handling, packaging, and lag-storage of waste forms may need to be designed to withstand design basis earthquakes and other natural phenomena without initiating or failing to mitigate a release of or exposure to radioactivity and without initiating a criticality. This step is part of the activity, Identification of SSCs Important to Safety and Safety Basis, shown in Figure 4-1.

4.3.1.4 Applications of Preclosure Safety Analyses

Insights from the event tree analysis and associated consequence analysis help to define requirements for SSCs to prevent, or mitigate effects of, initiating events and contributing events. A given SSC may be significant to preventing an initiating event, preventing progression of an event sequence, or preventing or mitigating the release of radioactivity. Those SSCs that are necessary to prevent, reduce the likelihood, or mitigate consequences such that the Category 1

and 2 event sequences meet the performance requirements of 10 CFR 63.111 are designated as SSCs important to safety. The ultimate application of the PSA is support of the preclosure safety basis in the LA.

The following areas use results from the PSA:

- **Q-List**–Those SSCs designated as SSCs important to safety are included in the *Q-List* (YMP 2001). The classification is developed from results of safety analyses and classified as QL-1, QL-2, or QL-3 and placed on the Q-List (see Section 12).

- **10 CFR 63.2 Design Bases and YMP Design Criteria Documents**–Nuclear safety 10 CFR 63.2 design bases are developed for those SSCs designated as important to safety. The design bases ensure that the necessary preventive and mitigative functions identified for the SSC are included in the final design. The nuclear design bases are stated in the system description documents.

- **Design Evaluation and Support**–As the level of design detail evolves and design concepts are put forth, concurrent supplemental safety analyses are performed to evaluate whether or not the design basis are met, or to help the designers evaluate a proposed design. These analyses may be qualitative or quantitative. A qualitative evaluation, for example, might be used to demonstrate that the transportation cask handling operations can not result in a drop of a transport cask from a height greater than the cask design basis. A quantitative analysis might apply a fault tree model to demonstrate that the reliability of an SSC meets the probability criteria (e.g., to demonstrate that the HVAC system of the Waste Handling Building remains operational for a given time with a specified probability). Should the qualitative or quantitative analyses identify a deficiency or vulnerability in the proposed design, the designers would revise the design, operations, or both, accordingly.

  In some instances, alternative design concepts for certain handling, packaging, or storage of waste may be under consideration by the design engineers. For example, alternatives for unloading a transportation cask may include dry (in air) or wet (under water) conditions. Similarly, design alternatives may include: remote vs. local control of operations; robotic vs. human control; handling only canistered spent nuclear fuel vs. a mixture of canistered and uncanistered spent nuclear fuel. Where decisions on such alternatives are pending at the time of submittal of LA-CA, the PSA explores the safety significance of each alternative (e.g., rates and concepts of handling, or characteristics of the waste forms). The PSA either presents the event sequence frequency and consequences for the bounding alternative of each operation, or the results for the baseline design with a discussion of the sensitivity of results to each of the alternatives.

As illustrated in Figure 4-1, the performance of the PSA is an iterative process incorporating site characteristics, design information, and safety strategies. The PSA process is performed and documented under YMP procedures. Excerpts and results of the respective analyses are incorporated into the Safety Analysis Report.

4.4 DEVELOPING AND DOCUMENTING THE PRECLOSURE SAFETY ANALYSIS IN THE LICENSE APPLICATION

In support of the LA-CA, the PSA process begins with information on conceptual design and operations, including application of a preclosure safety strategy, application of good practices from similar operations, industry codes and standards, and NRC regulatory precedents. A structured hazards analysis is performed to identify potential hazards, external and internal to the repository facilities, that initiate event sequences that could result in releases of radioactivity. Information on the natural phenomena and man-made hazards at the site and region should be well characterized. SSCs important to safety are identified from the analyses of hazards and event sequences. Design requirements derived from 10 CFR 63.2, design bases, that prevent or mitigate potential accidents are defined for the SSCs important to safety and are incorporated into the YMP design criteria document. As the 10 CFR 63.2 design bases are incorporated into the design, the PSA is updated to reflect the design commitments. For example, if a design feature eliminates a hazard or reduces the likelihood of an accident sequence, the PSA is revised.

4.4.1 Level of Design Detail in the License Application for Construction Authorization

The purpose of the LA is to present the safety case for a repository, and it must demonstrate that a repository will meet the postclosure and preclosure performance objectives. To demonstrate that a repository can meet postclosure performance objectives, a total system performance analysis is performed that is independent of the PSA. To demonstrate that a repository can meet the preclosure safety objectives, a PSA is performed. The PSA for the LA-CA must be at sufficient depth, commensurate with the available design detail, that provides sufficient assurance that the preclosure performance objectives of 10 CFR 63.111 will be met in the final design of a repository. A principal role of the preliminary PSA is defining the design bases that ensure that preclosure performance objectives can be met in the final design, in accordance with 10 CFR 63.112.

The LA should include a description of the systems that are required to protect the health and safety of the public and workers from Category 1 and Category 2 event sequences as defined in 10 CFR 63.2 for the preclosure period. The SSCs important to safety are identified as those required to meet preclosure performance objectives of 10 CFR 63.111. The LA should also include a description of systems that process radioactive waste and protect important to safety SSCs from interactions from other SSCs. In addition, the LA should identify design features that protect the health and safety of the worker during normal operations, including the proposed program for ensuring ALARA in a repository design. Further, the LA should define the design and operational strategies for addressing the safety-specific disciplines of criticality and fire-protection. The strategies, criteria, standards, and associated analyses for criticality and fire protection should be incorporated into the PSA.

4.4.2 Information Base for Preclosure Safety Analysis in Support of License Application for Construction Authorization

The premise of the PSA process is that sufficient information exists to (1) define the kinds of event sequences (scenarios) that can credibly occur in the kinds of operations that are known or expected to be necessary for receiving, handling, processing, packaging, transporting, and storing

waste forms, (2) estimate their frequency (likelihood), and (3) estimate their consequences. Section 5 states the requirements for descriptions of operating facilities and the site. At the time of the LA-CA, the hazards and event sequence analyses should be based on the information available that will consist of the following:

- Regulatory requirements per 10 CFR Part 63
- Site information (location, geography, geology, seismicity, and meteorology) that is well characterized by Exploratory Studies Facility, Nevada Test Site, and generally available information
- Industry codes and standards
- Regulatory and industry precedents for similar facilities
- Knowledge of good practices employed in similar operations that will be, or expected to be, adopted in a repository
- Experience and knowledge of members of multi-disciplinary PSA team
- Conceptual designs and principals of construction and operation.

Information on conceptual designs, construction, and operation should be derived from the general system descriptions provided in the project description document and system description documents. The information listed below provides a large portion of the bases for hazards analysis and event sequence development, such as:

1. Characterization of waste forms (age, thermal output, enrichment, burnup, radionuclide inventories) and their vulnerabilities to damage (e.g., physical form, cladding, allowable drop height)
2. Rate of waste receipt for each year of operation
3. Subsurface layout of drifts, positions of waste packages within the emplacement drifts, and installation of drip shields as defined by post-closure performance assessment considerations
4. Ground support, ventilation, and fire-protection systems of the subsurface facilities
5. Concepts for rescue, recovery, and decontamination of disabled transport and emplacement equipment
6. Concepts for waste package transport and emplacement in subsurface, including control, instrumentation, communication, and power supply system
7. Waste package design bases for potential accidental conditions (i.e., allowable drop heights, impacts, thermal or fire loading); criticality control features

8. Waste package sealing (welding or other); process for waste package remediation

9. Waste package radionuclide source terms for spent fuel assemblies, high-level defense waste

10. Preliminary surface facility layout, functional descriptions of operations for receiving, handling, packaging, staging, and transporting waste forms, including the rate of throughput

11. Surface facility construction concepts and commitments to NRC regulations, industrial codes and standards, including design for ventilation or filtration of radiological areas, seismic, tornadoes and winds, floods, and fire protection

12. Nuclear or radiological design bases and requirements (commitments) for surface and subsurface SSCs

13. Plan and schedule for concurrent construction (development) of the surface and subsurface facilities.

The documented basis for description of functions, operations, and features to be incorporated into the facility design should be derived from project documents.

4.4.3 Preclosure Safety Analysis Based on Level of Design Detail Available at Time of License Application

Figure 4-1 illustrates the overall PSA process. Figure 4-2 provides additional explanation for applying the PSA process as the design evolves. In the figure, the shaded boxes represent design processes and the open boxes represent portions of the PSA process.

The basic functional requirements of a repository are clearly defined and the basic operations required to carry out those functions can be defined, although design alternatives may exist to perform those functions. Design engineers initially focus on success and devise means to carry out each operation. The role of the hazards and safety analysts is to postulate potential failures and accident scenarios that could be associated with each functional area, including scenarios involving mechanical or hardware failures, software failures, human errors, and common-cause failures.

Various alternatives may be devised by designers for one or more operations to improve throughput (e.g., to achieve better reliability or improved maintainability), ensure licensability (e.g., a design meeting NRC guidelines), or reducing cost (e.g., a simpler design). Designers may also consider alternative designs that reduce the likelihood of accidents, either radiological or industrial, e.g., to implement the preclosure safety strategy. (Based on the results of the hazards and event sequence analyses of the PSA, design alternatives may be proposed to better meet regulatory requirements.)

Each of the functional operations requires suitable control and instrumentation systems, supporting systems such as AC and DC electrical power or fuel pool water supply, filtration, and cooling systems, and decontamination systems. Further, each of the functional operations

requires appropriate housing having an HVAC system, including HEPA filtration where necessary, and fire protection systems. The housing of the operations involving radioactive wastes will be designed, as appropriate, to withstand credible natural hazards such as earthquakes, tornadoes, and winds to preclude the initiation of event sequences.

Thus, even with limited design detail, the kinds of hazards and potential event sequences associated with the surface and subsurface operations can be identified and evaluated for their relative risk, and SSCs important to safety can be identified.

4.5 ENSURING PERFORMANCE OF STRUCTURES, SYSTEMS, AND COMPONENTS IMPORTANT TO SAFETY

The process described above results in the identification of SSCs important to safety based on function and provides insights into requirements for reliability of the SSCs and their support systems such as power supplies and associated instrumentation and controls. For other SSCs, the degree of mitigation may be identified, such as required filter efficiency for a HEPA filter. In some cases, the process identifies the need for a safety function that may not be in the evolving design drawings and facility descriptions within the design available at the time of LA CA. In these instances, only the 10 CFR 63.2 design bases and design requirements for those safety functions which will be included in the system description documents.

Regulation 10 CFR 63.112(e) requires an analysis of the performance of the SSCs to identify those that are important to safety. This analysis should identify and describe the controls that are relied on to limit or prevent potential event sequences or mitigate their consequences. This analysis should also identify measures taken to ensure the availability of safety systems.

As stated in 10 CFR 63.112(e), the areas to be discussed include, but are not necessarily limited to, consideration of thirteen areas listed in Table 4-1. For each area, the table provides examples of programmatic strategies or controls that will be in place at the time of LA-CA.

Further, 10 CFR 63.112(f) requires a description and discussion of the design, both surface and subsurface, of the operations area, including the relationship between design criteria and the requirements specified by preclosure performance objectives (see 10 CFR 63.111(a) and (b)) and the design bases and their relationship to the design criteria.

As noted in Section 4.3, the LA-CA includes a description of the functions and operations of surface and subsurface facilities as the bases for the PSA. The PSA identifies the event sequences that could result in radiological exposures of the public or workers. In accordance with 10 CFR 63.112(f)(1), the design criteria of the SSCs important to safety are derived to ensure that the performance objectives of 10 CFR 63.111(a) and (b) are met, either as requirements to prevent or limit the likelihood of, or to mitigate the consequences of, the event sequences. The design requirements and criteria are incorporated into the system description documents of important to safety SSCs and which include the associated design bases. In accordance with 10 CFR 63.112(f)(2), the descriptions of a repository design and design bases provided in the LA-CA either demonstrate how the design bases are met or will be met at the time of the LA-R&P (Section 13 describes the process).

Table 4-1. Sample Approach for Demonstrating Compliance with 10 CFR 63.112(e)

Item	10 CFR 63.112(e) Requirement	Potential Approach for LA-CA
(1)	Means to limit concentration of radioactive material in air;	Radiation Protection Program strategy; Radiation confinement areas; Design criteria/bases for HVAC
(2)	Means to limit the time required to perform work in the vicinity of radioactive materials;	Radiation Protection Program strategy; Use of remote handling and maintenance equipment
(3)	Suitable shielding;	Radiation Protection Program strategy; Design bases for shielding; Preliminary shielding analysis of principal operations areas
(4)	Means to monitor and control the dispersal of radioactive contamination;	Radiation Protection Program strategy; Radiation confinement areas; Design bases for HVAC; Design criteria for Radiation Monitoring System
(5)	Means to control access to high radiation areas or airborne radioactivity area;	Radiation Protection Program strategy; Radiation confinement areas; Design bases for Radiation Monitoring System ; Design bases for interlocks and administrative controls
(6)	Means to prevent and control criticality;	Criticality safety strategy; Design bases for criticality controls of operational areas and waste packages
(7)	Radiation alarm system to warn of significant increases of radiation levels, concentrations of radioactive material in air, and increased radioactivity in effluents;	Radiation Protection Program strategy; Design bases for Radiation Monitoring System; Preliminary analyses of performance of Radiation Monitoring System
(8)	Ability of structures, systems, and components to perform their intended safety functions, assuming the occurrence of event sequences;	Design bases for SSCs including performance requirements derived from hazards and event sequence analyses, operating environments, and ability to withstand natural phenomena
(9)	Explosion and fire detection systems and appropriate suppression systems;	Fire Protection strategy; Preliminary fire hazards analyses
(10)	Means to control radioactive waste and radioactive effluents, and permit prompt termination of operations and evacuation of personnel during an emergency;	Radiation Protection Program strategy; Design bases for waste treatment building and systems; Design bases for Radiation Monitoring System including alarms; Preliminary emergency plans
(11)	Means to provide reliable and timely emergency power to instruments, utility service systems, and operating systems important to safety if there is a loss of primary electric power;	Design bases for primary and backup power sources for SSCs important to safety as appropriate to their safety function and need for continuing power or other support (e.g., radiation monitoring and continuation of cooling or air circulation) on loss of primary power source
(12)	Means to provide redundant systems necessary to maintain, with adequate capacity, the ability of utility services important to safety; and	Design bases for primary and redundant subsystems and power sources for SSCs important to safety as appropriate to their safety function and reliability requirements (e.g., to ensure sufficient small likelihood of an event sequence, or to ensure availability of mitigation function); Process flow, piping and instrumentation diagrams, and electrical one-line diagrams, as appropriate, to demonstrate the capability
(13)	Means to inspect, test, and maintain structures, systems, and components important to safety, as necessary, to ensure their continued functioning and readiness.	Design requirements to ensure that inspections, tests, and maintenance can be carried out; Preliminary commitments to administrative controls (e.g., preliminary licensing specifications) for carrying out periodic surveillance and tests to ensure availability of SSCs important to safety

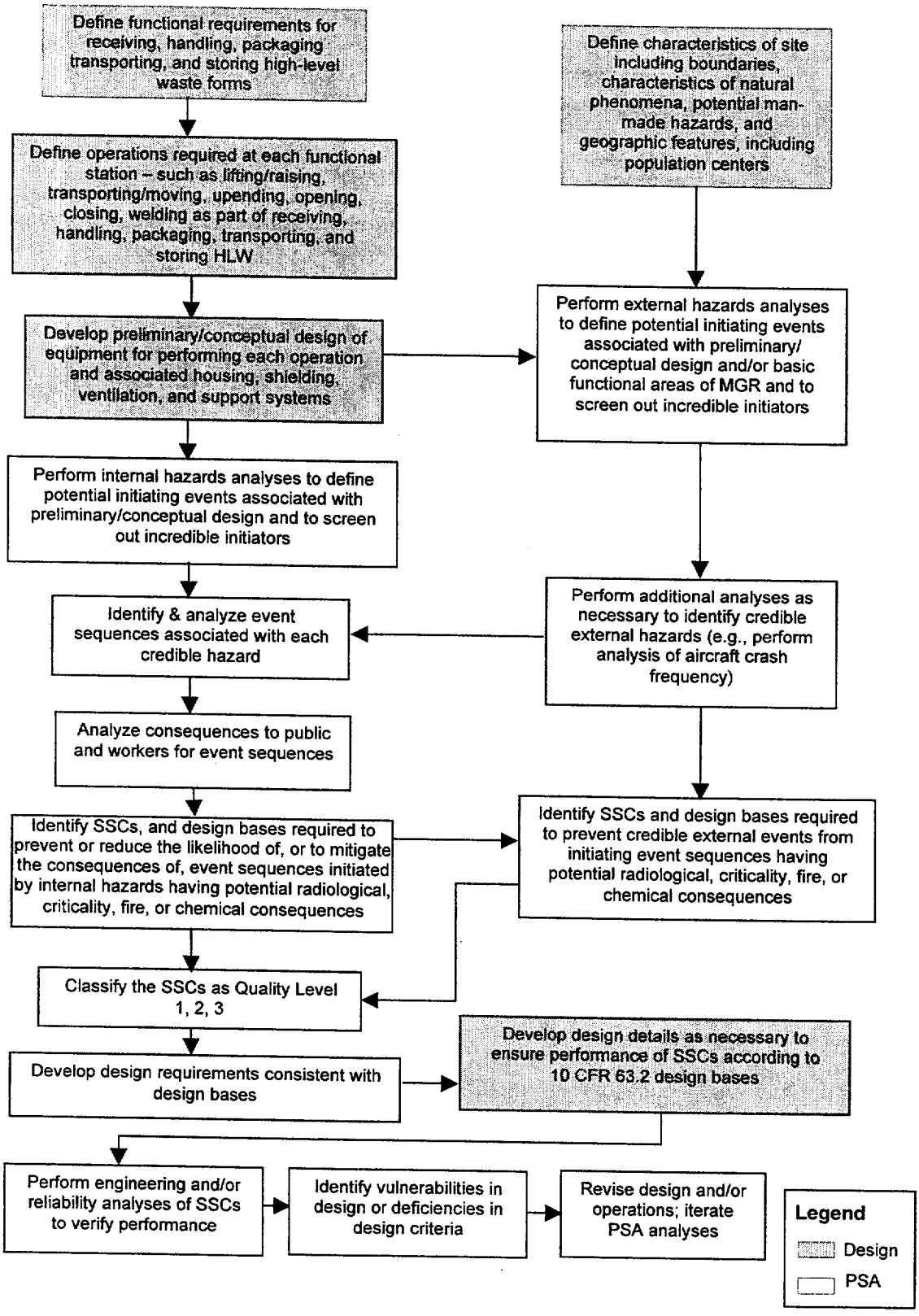

Figure 4-2. Process for Preclosure Safety Analysis Using Available Level of Design Detail

Even where the level of design detail is preliminary, the analyses included in the PSA processes identify the required safety functions, the design criteria for SSCs to achieve these safety functions, and commitments to ensure that the safety functions will be realized in the LA-R&P design. The PSA process will be updated as the design evolves to LA-R&P and the requirements of 10 CFR 63.112 (a) – (f) will be completely satisfied and documented.

4.6 REFERENCES

4.6.1 Documents Cited

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4.6.2 Codes, Standards, Regulations, and Procedures

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ACRONYMS

PSA	preclosure safety analysis

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5. DESCRIPTION OF SITE, FACILITIES, AND OPERATIONS

5.1 INTRODUCTION

The preclosure safety analysis (PSA) must include a general description of the structures, systems, and components, equipment, and process activities in the repository operations area. In addition, the PSA must provide a description of data pertaining to the repository site and surrounding region with sufficient detail to identify naturally occurring and human-induced hazards in the repository area (10 CFR 63.112).

Guidance for developing a description of the site characteristics, surface and subsurface facilities, and operations sufficient to support the hazards and event sequence analyses for preclosure radiological safety is presented in this section. A discussion of the applicable natural phenomena, external man-made hazards, and nearby facilities that could potentially affect the repository area is included. Site and facility characteristics applicable to repository postclosure safety are not discussed in this section.

5.2 OVERVIEW OF APPROACH

Material to be provided in support of the PSA will be contained in a brief summary section. Site and design features that are used in the hazards or event sequence analyses will be summarized with pointers to detailed sections of the license application submittal. No analytic methodology is required.

[Information for this section is under development and will be provided later.]

Information will be included that is relevant to performing preclosure hazards analyses, event sequence analyses, and consequence analyses. References will be provided to information sources and detailed descriptions found elsewhere in the license application submittal. A general description of the structures, systems, components, equipment, process (i.e., operational), and activities in the repository area will be provided (10 CFR 63.112(a), 10 CFR 63.112(f)).

As the basis of the safety analysis, brief descriptions of the site factors that could affect preclosure safety before permanent closure will be provided in the PSA, including:

- Site geography (location relative to prominent natural and man-made features such as mountains, rivers, airports, population centers, hazardous commercial facilities, and hazardous manufacturing facilities)
- Human populations (information based on recent census data)
- Natural phenomena and other external events sufficient to assess the likelihood of occurrence and to assess the impact on preclosure safety; discussion of relationship to features, events, and processes used in postclosure radiological analyses
- Meteorology (prevailing wind directions and speeds; discussion of data used in analyses of airborne releases for normal and postulated event sequences)

- Site boundaries (including a description and a map) and a description of methods for access control at the boundary.

- Operational and design factors that could affect radiological safety before permanent closure (i.e., the preclosure safety strategy, discussed in Section 3, and precedents from licensing of 10 CFR Part 50, 71, or 72 facilities).

5.3 REFERENCES

5.3.1 Documents Cited

None

5.3.2 Codes, Standards, Regulations, and Procedures

10 CFR 50. 1999. Energy: Domestic Licensing of Production and Utilization Facilities. Readily available.

10 CFR 63. 2002. Energy: Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, Nevada. Readily available.

10 CFR 71. 1999. Energy: Packaging and Transportation of Radioactive Material. Readily available.

10 CFR 72. Energy: Licensing Requirements for the Independent Storage of Spent Nuclear Fuel and High-Level Radioactive Waste. Readily available.

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ACRONYMS

CPB	Carrier Preparation Building
DC	disposal container
DPC	dual purpose canisters
EEHA	external events hazards analysis
EEHL	external events hazards list
HLW	high-level radioactive waste
LA	license application
LLW	low-level radioactive waste
PSA	preclosure safety analysis
SNF	spent nuclear fuel
SSCs	structures, systems, and components
WHB	Waste Handing Building
WP	waste package

6. HAZARDS ANALYSIS

6.1 EXTERNAL EVENTS HAZARDS ANALYSIS

This section presents details of the methodology for the external event hazards analysis (EEHA) and the internal event hazards analysis portions of the Preclosure Safety Analysis (PSA).

6.1.1 Introduction

This section describes a method for performing an EEHA as part of the PSA to support the license application (LA) submittal. The EEHA provides a systematic method to identify and screen hazards stemming from natural phenomena and man-made activities that have the potential for initiating repository preclosure event sequences. A generic and comprehensive list of potential hazards is compiled in the EEHA. Qualitative and quantitative screening analyses are applied to reduce the number of potential hazards. The output of the screening process is a list of potential external hazards that must be evaluated as part of the repository design process or subjected to further evaluation to determine the credibility of the hazard and its potential radiological consequences. This list is called the external events hazards list (EEHL).

This section presents the methodology for performing an EEHA. External hazards include natural phenomena and man-made activities and facilities that are beyond the direct control of repository operations. Such hazards include onsite construction activities that may be concurrent with waste receipt, waste handling, and storage operations. Section 6.2 describes the approach for performing a counterpart analysis of hazards that are internal to the repository operations.

6.1.2 Overview of Approach

The PSA is a risk-informed, performance-based approach. As such, its purpose is to address these three questions:

1. What can happen? (What event sequences are possible?)
2. How likely is it? (What is the probability or frequency of the event sequence?)
3. What are the consequences? (What are the radiological releases and exposures? Intermediate consequences may be addressed to synthesize potential event sequences.)

This approach is similar to the methods used for Process Hazards Analysis, as described in *Guidelines for Hazard Evaluation Procedures* (AIChE 1992).

The first question is applied in the EEHA to hazards that are potential initiating events for radiological release event sequences. The "what" is defined at the first level by a list of generic events. The possibility of initiating an event sequence having radiological consequences (the third question) is implicit, but is not addressed initially. Instead, the EEHA addresses the second question (How likely is it?) to determine if a given hazard is a credible preclosure repository initiating event. A knowledge of the site characteristics is required to answer this question.

Potential intermediate consequence of the event sequences are considered to the extent that the direct consequences of an event sequence (e.g., landslide) could interact with the repository operational processes to induce a radiological release. A knowledge of the repository operations and the locations of radioactive material, as well as a conceptual layout of the facility, are required to determine the potential vulnerabilities to the respective external hazards. If a hazard category can be eliminated (screened out) it will not be necessary to consider potential event sequences, radiological consequences, or design solutions to withstand the hazard.

Screening Criteria–The question "How likely is it?" is addressed by performing the following series of qualitative and quantitative screening evaluations to determine whether or not:

1. The potential hazard exists at the repository site
2. The rate of the physical process of the hazard can produce sensible effects during the repository preclosure period (i.e., up to 325 years)
3. The consequences of the hazard are significant enough to affect operations or storage during the preclosure period
4. The event frequency is greater than 1×10^{-6} events per year.

The criteria are addressed sequentially so that when the answer to the query is negative, the analysis stops and the hazard is screened out and will not appear in the external events hazard list.

Documented rationale must be provided to support every response to the criteria. Such documentation must be in accordance with established procedures for documentation and categorization of data, if applicable.

Responses to the first, second, and fourth criteria are independent of the facility design. To the extent possible, the analysis should screen out those natural phenomena that are known to be impossible or non-existent in the region (e.g., ocean-front hazards such as a tsunami). The removal of these types of hazards may be accomplished through either a pre-screening to remove events from the (global) generic list of hazards or through the application of the same logic formally and repeatedly in the evaluation. In this guide, the latter method is used in the examples. Care must be taken to not screen out natural phenomena that may have site-specific applicability, such as flooding. Responses to the third criteria should be largely independent of the facility design. However, major changes in facility structures and operational concepts should be examined in light of the third screening criteria.

The product of this analysis is the EEHL, which contains the potentially credible external hazards that cannot be screened out. The hazards listed, however, will be categorized according to future actions and commitments. The hazards will be categorized according to the following criteria:

1. **Design Basis**–The hazard is included in the 10 CFR 63.2 design bases for preclosure safety (e.g., the requirements for items important to safety to withstand the specific natural phenomena).

2. **Analysis Required**–The hazard cannot be screened out without additional or corroborative analyses; the EEHL will be updated as such analyses are completed, with credible hazards re-categorized as initiating events for event sequences.

For ease of review, a companion table will list the hazards removed through the screening process and a summary statement detailing the basis for the removal.

6.1.3 Details of Basic Approach to Screening with Examples

This section illustrates the process for performing an EEHA through the application of the screening criteria previously discussed to a generic list of repository external hazards. The approach consists of the following steps:

1. Compile a comprehensive list of external hazards (natural phenomena and man-made) from generic sources (e.g., AIChE 1992).

2. Acquire information on the site and facility.

3. Apply the screening criteria, supported by analyses, where appropriate.

4. Produce a list of external hazards subject to design solutions (i.e., become event sequences) or to further analyses (e.g., event sequence modeling or consequence analysis).

The following subsections describe each of these steps.

6.1.3.1 Generic Events Checklist

The analysis begins with the development of a comprehensive list of events that could impact the repository operations areas and initiate an event sequence that results in a radioactive material release. The generic list is not project-specific, but provides a starting point for the systematic approach that is intended to identify potentially hazardous external events. The generic hazards list (Table 6-1) was synthesized from lists of external hazards developed by others (AIChE 1992). Its intent is to provide the most comprehensive list to ensure a thorough treatment of possible hazards. Should other potential external hazards be identified in the course of supporting LA submittal, these hazards should be subjected to the same screening analysis methodology and criteria as the generic hazards.

An event is considered a potential initiator of a radiological event sequence if, and only if, all of the screening criteria presented in Section 6.1.2 are determined to be applicable.

Table 6-1. Generic External Events

External Category Hazard	Definition	Potential Concern for Preclosure Safety
1 Aircraft crash	Accidental impact of an aircraft on the site.	Penetration or loss of confinement of radioactivity; compounded by concurrent fire
2 Avalanche	A large mass of snow, ice, soil, or rock, or mixtures of these materials, falling, sliding, or flowing under the force of gravity.	Blockage of North Portal, burying of waste package transporter, collapse or distortion of structures housing radioactivity, disruption of electric power
3 Coastal erosion	The wearing away of soil and rock by waves and tidal action (see Erosion).	Not applicable
4 Dam failure	Failure of a large man-made barrier that creates and restrains a large body of water.	If possible, could invade surface structures, wash out bridges supporting waste transporter, disrupt power.
5 Debris avalanching	The sudden and rapid movement of debris (soil, vegetation and weathered rock) down steep slopes resulting from intensive rainfall.	Similar to Avalanche
6 Denudation	The sum of the processes that result in the wearing away or the progressive lowering of the surface of the earth by weathering, mass wasting, and transportation.	[And, so on ....analyst to identify issues related to Preclosure Safety]
7 Dissolution	A process of chemical weathering by which mineral and rock material passes into solution.	
8 Eperogenic displacement	Geomorphic processes of uplift and subsidence that have produced the broader features of the continents and oceans.	
9 Erosion	The slow wearing-away of soil and rock by weathering, mass wasting, and the action of streams (denudation), glaciers, waves, wind.	
10 Extreme wind	Wind is a meteorological term for air that moves parallel to the surface of the earth. Extreme wind conditions for nuclear plants are defined in NUREG-0800 (NRC 1987) and ASCE 7-98 (ASCE 2000).	
11 Extreme weather fluctuations	Various types of weather fluctuations that exceed expected operational ranges of repository processes.	
12 Range fire	The combustion of natural vegetation external to the repository that propagates to combustible materials within the repository operations area.	
13 Flooding (storm, river diversion)	The covering or causing to be covered with water.	

Table 6-1. Generic External Events (Continued)

External Category Hazard	Definition	Potential Concern for Preclosure Safety
14 Fungus, bacteria, and algae	Fungus and bacteria are part of a general class of microorganisms that may be present in the subsurface environment. Algae are aquatic plants that may be present in spent fuel storage and staging water-filled pools.	
15 Glacial erosion	Reduction of the surface of the earth as a result of grinding and scouring by glacier ice armed with rock fragments.	
16 Glaciation	The formation, movement, and recession of glaciers or ice sheets.	
17 High Lake Level	Any inland body of standing water occupying a depression in the surface of the earth, generally of appreciable size and too deep to permit vegetation to take root completely across the expanse of water with potential for overflow or flooding.	
18 High Tide	Tides are the rhythmic, alternate rise and fall of the surface of the ocean, and bodies of water connected with the ocean with the potential for flooding inland areas.	
19 High river stage	A river is a natural freshwater permanent or seasonal surface stream of considerable volume with a potential for flooding	
20 Hurricane	An intense cyclone that forms over the tropical oceans and ranges 100 to 1000 km in diameter.	
21 Inadvertent future intrusions (man-made)	Man-made inadvertent future intrusions with regard to the 100-year operational period involving undetected surface access into repository facilities.	
22 Industrial activity induced accident	An accident resulting from industrial or transportation activities unrelated to the repository.	
23 Intentional future intrusions (man-made)	Man-made intentional future intrusions with regard to preclosure involving undetected surface access or sabotage to repository facilities. Sabotage may also include events such as bombings and missile attacks.	
24 Landslides	A general term covering a wide variety of mass-movement land forms and processes involving the downslope transport, under gravitational influence, of soil and rock material.	
25 Lightning	The flashing of light produced by a discharge of atmospheric electricity between an electrically charged cloud and the earth.	
26 Loss of offsite or onsite power	The loss of electrical power either generated or controlled by persons outside of the repository site or a loss of power within the repository.	

Table 6-1. Generic External Events (Continued)

External Category Hazard	Definition	Potential Concern for Preclosure Safety
27 Low lake level	A lake is any inland body of standing water occupying a depression in the surface of the earth, generally of appreciable size and too deep to permit surface vegetation to take root completely across the expanse of water where the lake level must be maintained for cooling purposes.	
28 Low river level	A river is a natural freshwater permanent or seasonal surface stream of considerable volume where river level must be maintained for cooling purposes.	
29 Meteorite impact	The impact of any meteoroid that has reached the surface of the earth without being completely vaporized.	
30 Military activity induced accident	An accident resulting from military activities on the Nevada Test Site or Nellis Air Force Range.	
31 Orogenic Diastrophism	Movement of the crust of the earth produced by tectonic processes in which structures within fold-belt mountainous areas were formed, including thrusting, folding, and faulting.	
32 Pipeline accident	Industrial pipeline containing hazardous materials (e.g., oil and gas).	
33 Rainstorm	A rainstorm of concern is one that produces the 100-year or greater maximum rainfall rate occurring for one day.	
34 Sandstorm	Extreme wind capable of transporting sand and other unconsolidated surficial materials.	
35 Sedimentation	The process of forming or accumulating sediment (solid fragmental material that originates from weathering of rocks) in layers.	
36 Seiche	A free or standing-wave oscillation of the surface of water in an enclosed or semi-enclosed basin (as a lake, bay, or harbor).	
37 Seismic activity, uplifting (tectonic)	A structurally high area in the crust, produced by positive movements over a long period of time that result in faults giving rise to the upthrust of rocks.	
38 Seismic activity, earthquake	Pertaining to earthquake or earth vibrations, including those that are artificially induced.	
39 Seismic activity, surface fault displacement	A fracture or a zone of fractures along which there is potential for displacement of the sides relative to one another parallel to the fracture.	
40 Seismic activity, subsurface fault displacement	A fracture or a zone of fractures along which there is potential for displacement of the sides relative to one another parallel to the fracture.	

Table 6-1. Generic External Events (Continued)

External Category Hazard	Definition	Potential Concern for Preclosure Safety
41 Static Fracturing	Any break in a rock due to mechanical failure by stress (includes cracks, joints, and faults).	
42 Stream Erosion	The progressive removal, by a stream, of bedrock, overburden, soil, or other exposed matter, from the surface of its channel.	
43 Subsidence	The sudden sinking or gradual downward settling of the surface of the earth with little or no horizontal motion.	
44 Tornado	A small-scale cyclone generally less than 500 m in diameter and with very strong winds. Intense thunderstorms that are present in the desert southwest have the capability of producing tornadoes.	
45 Tsunami	A gravitational sea wave produced by a large-scale, short-duration disturbance on the ocean floor. Wave heights of up to 30 m may impact coastal regions.	
46 Undetected past intrusions (man-made)	Past intrusions involve mining activities where deep shafts, drill holes, or tunnels may have been excavated.	
47 Undetected Geologic features	Geologic features of concern to the 100-year operational period include natural event such as faults and volcanoes.	
48 Undetected Geologic processes	Geologic processes of concern to the 100-year operational period include natural events such as erosion, tectonic and seismic processes.	
49 Volcanic Eruption	The process by which magma and its associated gases rise into the crust and are extruded onto the surface of the earth and into the atmosphere.	
50 Volcanism, intrusive magmatic activity	The development and movement of magma and mobile rock material underground.	
51 Volcanism, ashflow (extrusive magmatic activity)	A highly heated mixture of volcanic gases, magma, mobile rock material, and ash traveling down the flank of a volcano or along the surface of the ground (silacic volcanism).	
52 Volcanism, ashfall	Airborne volcanic ash falling from an eruption cloud.	
53 Waves (aquatic)	An oscillatory movement of water manifested by alternating rise and fall of the water surface.	

6.1.3.2 General Description of the Repository Site

A site description should be prepared to establish a basis for screening natural phenomena. Section 5 of this guide provides guidance for gathering site-related information to support the EEHA (and the PSA). The EEHA analysts should advise the preparer of the PSA site description of the particular needs and degree of detail required to support the EEHA screening process. A summary of the relevant site description information should be provided in the EEHA documentation.

The site description should include summaries of pertinent information concerning site:

- Geography
- Demography
- Meteorology
- Hydrology
- Geology
- Nearby facilities (industrial and military)
- Transportation routes (public, industrial, and military).

An example of a site description summary is:

> Yucca Mountain is located in southern Nevada approximately 100 miles (160 km) northwest of Las Vegas. The mountain is an irregularly shaped volcanic upland varying in elevation at its crest from 1,500 m to 1,930 m (4,921 ft to 6,332 ft) and characterized by approximately 650 m (2,132 ft) of relief. The area surrounding the site includes Nye, Lincoln, Esmeralda, and Clark counties in Nevada and Inyo County in California. The site occupies land controlled by three federal agencies: the U.S. Air Force (Nellis Air Force Range), DOE (Nevada Test Site), and the U.S. Bureau of Land Management (BLM). Nearly all the area surrounding Yucca Mountain is federally owned, and very little is developed or urban land. A large percentage of the land around Yucca Mountain is anticipated to remain federally owned or withheld from public use in the future.

The description should be as complete as necessary to support the PSA and the EEHA. Similarly, the description might continue with a summary of climatological and meteorological characteristics of the region and site to establish perspective for the screening analysis descriptions.

6.1.3.3 General Description of the Repository Facilities

The EEHA should provide a brief summary of the repository operational areas that are potentially vulnerable to external event hazards. This summary can be simplistic in describing the types and locations of radioactive materials (and operations involving those materials) that could be potentially vulnerable to a credible external event. This summary and the associated assumptions establish a portion of the bases for the evaluation of external hazards.

6.1.3.4 Application of Screening Criteria

A generic list of external hazards is presented in Table 6-1 with definitions sufficient to establish the potential impact on the repository based on site and facility descriptions. The screening criteria previously discussed can be applied sequentially with supporting rationale. Whenever the response to any criterion is negative, the analysis of that hazard ceases. Therefore, the rationale for negative responses must be defensible. As appropriate, qualitative arguments or calculations are provided to support the negative response. If the rationale is affected by a design-specific or site-specific assumption or condition, the rationale must document the source of the assumption or condition according to the procedures for documenting quality-affecting work.

If a hazard cannot be screened out through the application of screening criteria, it is retained on the EEHL for further disposition, either by including the hazard in the facility design criteria or by recommending the initiation of additional analyses of frequency or potential impact (consequences).

For clarity of presentation and to ensure completeness, the EEHA should be documented in a standard format to indicate the response to each criterion and to provide the supporting rationale, even if the rationale seems obvious. The analysis will establish a definition, establish the required conditions, will perform an evaluation, and will determine the applicability of each generic external event. The following format is used in Section 6.1.3.5 to document the screening analysis of each external event:

Definition–Establishes the explanation of the event to be analyzed.

Required Condition–State what has to occur for the event or events to exist and result in a potential release of radioactive material or exposure to radioactivity.

Evaluation–States what must occur for the event to be considered a potential initiator of a radiological release or exposure during the preclosure period.

Applicability–States the conclusion of the screening (i.e., whether the hazard is or is not applicable to the repository preclosure period.

If all of the above statements are applicable for any external event, then the event is considered applicable to the hazards list for the repository. If any statement is indeterminate (its validity cannot be determined at this time) then the hazard is not eliminated through the screening process.

If, for any external event, any one of the above statements is not applicable, then the event is not considered applicable to the hazards list for the repository and all the statements that follow are not applicable.

The following subsection provides several examples of application of the EEHA screening process that include various types of hazards and applications of the criteria. An event is considered to be a potential initiator of a radiological release event sequence if, and only if, all of the screening criteria presented in Section 6.1.2 are determined to be applicable.

The following notes provide conditions to be considered for the consideration of the criteria.

1. The potential hazard exists and is applicable to the repository site.

   NOTE: If the event cannot exist in the Yucca Mountain region, e.g., because it pertains to an ocean or near-ocean phenomenon, then the statement is labeled as False. Similarly, if the event pertains to features that must exist in the immediate vicinity of the repository site to be considered a hazard, but do not actually exist at or near the repository, then the statement is also labeled as False.

2. The rate of the physical process of the hazard can produce sensible effects during the repository preclosure period (i.e., up to 325 years).

   NOTE: Long-term phenomena are defined as those that require thousands of years for perceptible changes to take place. Potential hazards including Erosion, Glaciation, Glacial Erosion, Orogenic Diastrophism, Sedimentation, Seismic Activity Uplifting [Tectonic], and Stream Erosion are such phenomena. These phenomena are not applicable to the repository during the preclosure period even if it is extended to 325 years. Although supporting information may be included, the information is not required for disposition of the phenomena.

3. The consequences of the hazard are significant enough to affect operations or storage during the preclosure period.

   NOTE: The response to this criterion must consider the characteristics of the repository operations that are potentially vulnerable to a release of, or exposure to, radioactivity as a consequence of the hazard interacting with the facility. This evaluation requires knowledge of the design of the facility, including the intended operations where radioactive material or potential fissile material are to be handled or stored. The facility information described in Section 5 of this guide is summarized in Section 6.1.3.3. This evaluation applies analysis elements similar to a "what if?" analysis or a Failure Modes and Effects Analysis to determine the manner in which direct or indirect consequences of the external hazards could potentially interact with the facility.

4. The event frequency is greater than 1×10^{-6} events per year.

   NOTE: The event cutoff frequency of 1×10^{-6} events per year is based on a 100-year operational period. This screening criterion is stated in 10 CFR Part 63 as a chance of one in 10,000 in the period before permanent closure. If a different time period is appropriate (e.g., 30 years for surface operations or 325 years for preclosure subsurface operations and storage), then the frequency screening criteria will be adjusted appropriately to the hazard and the potentially vulnerable operations area.

The following subsection provides examples of how the screening analysis is applied to a range of hazard types.

6.1.3.5 Examples of Application of Screening Criteria

The following subsections are presented in a format that can be used to document the external event hazards screening process. The formatted material may be presented in a table if preferred.

These examples were selected from a previous EEHA (CRWMS M&O 1999) to include several various types of hazards and to represent the application of each of the primary screening criteria. Table 6-2 summarizes the application of the screening process for these examples. Table 6-3 illustrates the EEHL, which is the principal product of the EEHA. Table 6-4 lists the hazards that have been eliminated through the screening process.

Table 6-2. Example Summary of External Events Hazards Analysis Screening

External Hazard Name	Summary of Screening				
	1. Potential exists and the event is applicable to the repository site.	2. The rate of the hazard process is sufficient to affect the 100-year operational period.	3. Sensible consequences of the hazard are large enough to affect operations or storage during the preclosure period.	4. The event frequency is greater than 10^{-6} events per year.	Applicability (Included in EEHL?)
Aircraft crash	TRUE	TRUE	TRUE	TRUE	YES
Avalanche	FALSE	NA	NA	NA	NO
Coastal Erosion	FALSE	NA	NA	NA	NO
Dam Failure	FALSE	NA	NA	NA	NO
Eperogenic Displacement	TRUE	FALSE	NA	NA	NO
Extreme Wind	TRUE	TRUE	TRUE	TRUE	YES
Range Fire	TRUE	TRUE	TRUE	TRUE	YES
Inadvertent future intrusions (man-made)	TRUE	TRUE	TRUE	TRUE	YES
Loss of offsite or onsite power	TRUE	TRUE	TRUE	TRUE	YES
Meteorite Impact	TRUE	TRUE	TRUE	FALSE	NO
Seismic activity, earthquake	TRUE	TRUE	TRUE	TRUE	YES

NOTE: NA = Not applicable

Table 6-3. Example External Events Hazards List

External Hazard Name	Comments
Loss of offsite or onsite power	Design bases to mitigate release
Seismic activity, earthquake	Design bases to mitigate release
Aircraft crash	Probabilistic analysis required
Extreme Wind	Group with wind/tornado
Range Fire	Group with other fire analyses
Inadvertent future intrusions (man-made)	Additional analysis required

Table 6-4. Example External Events Hazards Screened Out

External Hazard Name	Principal Basis for Screening Out
Avalanche	1. Not present at site
Coastal Erosion	1. Not present at site
Dam Failure	1. Not present at site
Eperogenic Displacement	2. Process too slow to affect preclosure
Meteorite Impact	4. Frequency below 1×10^{-6} per year

External Hazard 1, Aircraft Crash

Definition–Accidental impact of an aircraft on the site.

Required Condition–Periodic presence of aircraft over or near the site.

Evaluation–

1. Potential exists and is applicable to the repository site. TRUE.

   Rationale–The statement is true because of the potential for commercial aircraft over-flights and the proximity of the repository site to the flight path of military aircraft flying from Nellis Air Force Base to their practice range (CRWMS M&O 1999).

2. The rate of the process of the hazard is sufficient to affect the 100-year operational period. TRUE.

   Rationale–The effect of an aircraft crash is immediate.

3. The consequences of the hazard are significant enough to affect operations or storage during the preclosure period. TRUE.

   Rationale–Potential effects of aircraft crash are readily identified as potential direct impact on radioactive waste and an indirect impact on safety-related structures, as well as a source of fire initiation. If deemed necessary, available evidence or analyses can be referenced. For example, a prior EEHA (CRWMS M&O 1999) referred to an analysis of the potential consequences that was performed in 1990.

4. The event frequency is greater than 1×10^{-6} events per year. TRUE.

   Rationale–Insufficient evidence exists to support a negative response without detailed analyses. Furthermore, the response to this criterion is subject to change if there are changes in site layout, site usage, or frequency and types of aircraft in the vicinity.

   Applicability–Yes. This event is applicable to the EEHL for the repository site.

External Hazard 2, Avalanche

Definition–A large mass of snow, ice, soil, or rock, or mixtures of these materials, falling, sliding, or flowing under the force of gravity.

Required Condition–Steeply sloped terrain found in high mountain ranges must exist.

Evaluation–

1. Potential exists and is applicable to the repository site. FALSE.

   Rationale–The required condition (high mountain ranges) does not exist. Therefore, it is not applicable on this basis alone.

   It is also noteworthy that temperature and precipitation levels at the repository site do not support the build-up of large masses of snow, ice, or soil required to produce an avalanche (except, potentially, a debris avalanche). If deemed necessary, references may be provided to justify that historical evidence for temperatures and precipitation preclude this event.

Criteria 2 through 4 are not applicable because the analysis stops with first not applicable evaluation.

Applicability–No. This event is not applicable to the EEHL for the repository site.

External Hazard 3, Coastal Erosion

Definition–The wearing away of soil and rock by waves and tidal action (see Erosion).

Required Condition–A coastline must exist at the site.

Evaluation–

1. Potential exists and is applicable to the repository site. FALSE.

   Rationale–This event requires a coastline, which does not exist at the repository; therefore, the event is eliminated from further consideration.

Criteria 2 through 4 are not applicable because the analysis stops with first negative evaluation.

Applicability–No. This event is not applicable to the EEHL for the Yucca Mountain site.

External Hazard 4, Dam Failure

Definition–Failure of a large man-made barrier that creates and restrains a large body of water.

Required Condition–A dam must exist in the vicinity of the site.

Evaluation–

1. Potential exists and is applicable to the repository site. FALSE.

   Rationale–This event requires a dam of sufficient size and proximity to the repository site. Since the required condition does not exist in the vicinity of the repository site, this event is eliminated from further consideration.

Criteria 2 through 4 are not applicable because the analysis stops with first negative evaluation.

Applicability–No. This event is not applicable to the EEHL for the repository site.

External Hazard 8, Eperogenic Displacement (see Subsidence)

Definition–Geomorphic processes of uplift and subsidence that have produced the broader features of the continents and oceans.

Required Condition–Geomorphic processes must exist at the site.

Evaluation–

1. Potential exists and is applicable to the repository site. TRUE.

   Rationale–Cannot exclude geomorphic processes that are ubiquitous (see 2, below).

2. The rate of the process is sufficient to affect the 100-year operational period. FALSE.

   Rationale–This event is defined as a long-term geologic process. Therefore, this phenomenon is not applicable to the repository during the preclosure operational period (approximately 325 years or less).

Criteria 3 and 4 are not applicable since analysis stops with first negative evaluation.

Applicability–No. This event is not applicable to the EEHL for the repository site.

External Hazard 10, Extreme Wind

Definition–Wind is a meteorological term for that component of air that moves parallel to the surface of the earth. In the *Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants* (NRC 1987, Sections 2.3.1, 3.3.1, and 4.3) it is stated that the 100-year return period "fastest mile of wind" including vertical velocity

distribution and gust factor should be used and be based on the standard published by the American National Standards Institute with suitable corrections for local conditions. The current standard published by the American National Standards Institute is ANSI/ASCE 7-98, *Minimum Design Loads for Buildings and other Structures* (ASCE 7-98 2000, Section 4.3). The basic wind speed is defined as a 3 second gust with annual probability of 0.02 of being equaled or exceeded (for a 50 year mean recurrence interval) (ASCE 7-98 2000, p. 13).

Required Condition–Meteorological conditions conducive to wind generation must exist at the site.

Evaluation–

1. Potential exists and is applicable to the repository site. TRUE.

   Rationale–Extreme winds do occasionally occur in southern Nevada (Eglinton and Dreicer 1984, Coats and Murray 1985), making this event applicable for consideration during the 100-year operational period.

2. The rate of the hazard process is sufficient to affect the 100-year operational period. TRUE.

   Rationale–The impact is immediate. Wind effects could initiate event sequences and cause collapse or failure of SSCs that house radioactive materials.

3. The consequences of the hazard are significant enough to affect the 100-year operational period. TRUE.

   Rationale–Wind effects could initiate event sequences and cause collapse or failure of SSCs that house radioactive materials. However, without engineering analyses, this statement is viewed as indeterminate. Since the response to this criterion is indeterminate (i.e., its validity cannot be determined at this time), it is treated as equivalent to TRUE.

4. The event frequency is greater than 1×10^{-6} events per year. TRUE.

   Rationale–Some credible extreme wind conditions exist for all sites. The design basis determination will establish the wind parameters for the repository facilities.

Applicability–Yes. This event is not applicable to the EEHL for the repository site.

External Hazard 12, Fire (Range)

Definition–The combustion of natural vegetation external to the repository that propagates to combustible materials within the repository operations area.

Required Condition–Combustible materials must exist on the site.

Evaluation–

1. Potential exists and is applicable to the repository site. TRUE.

   Rationale–Since vegetation is present and at least one source of range fires (see Lightning) then range fires are possible.

2. The rate of the hazard process is sufficient to affect the 100-year operational period. TRUE.

   Rationale–The impact is immediate. Range fire effects could initiate event sequences and cause failures of SSCs that house radioactive materials.

3. The consequences of the hazard are significant enough to affect the 100-year operational period. TRUE.

   Rationale–Range fire effects could initiate event sequences and cause failures of SSCs that house radioactive materials. However, without engineering analyses of range fire hazards and system vulnerabilities, the response to this criterion is indeterminate. Since the response is indeterminate (i.e., its validity cannot be determined at this time), it is treated as equivalent to TRUE.

4. The event frequency is greater than 1×10^{-6} events per year. TRUE.

   Rationale–Although it may be judged that the occurrence of range fires in the region is credible, additional engineering analyses are required to determine the credibility of range fires severe enough to impact the SSCs of the surface facilities. Since the response to this criterion is indeterminate (its validity cannot be determined at this time) it is treated as equivalent to true.

Applicability–Yes.

External Hazard 21, Inadvertent Future Intrusions (Man-Made)

Definition–Man-made inadvertent future intrusions (with regard to the 100-year operational period) involve undetected surface access into repository facilities.

Required Condition–Potential for human access to surface facilities must exist.

Evaluation–

1. Potential exists and is applicable to the repository site. TRUE.

   Rationale–The site borders the Nevada Test Site and highways exist in the area.

2. The rate of the hazard process is sufficient to affect the 100-year operational period. TRUE.

Rationale–The effects of an intrusion could be immediate with respect to initiating an event (e.g., loss of offsite power). This event may include intrusion into an area that contains radioactive material. However, engineering and safeguard analyses are required to identify specific vulnerabilities. Therefore, the response to this criterion is indeterminate (its validity cannot be determined at this time), so it is treated as equivalent to TRUE.

3. The consequences of the hazard are significant enough to affect the 100-year operational period. TRUE.

   Rationale–The effects of an intrusion could lead to an initiating event (e.g., loss of offsite power) or human exposure to radioactive material. However, engineering and safeguard analyses are required to identify specific vulnerabilities. Therefore, the response to this criterion is indeterminate (its validity cannot be determined at this time), and it is treated as equivalent to TRUE.

4. The event frequency is greater than 1×10^{-6} events per year. TRUE.

   Rationale–Without a supporting safeguards analysis to state the contrary, the response to this criterion is indeterminate (its validity cannot be determined at this time), and it is treated as equivalent to TRUE.

Applicability–Yes. This event is applicable to the EEHL for the repository site.

External Hazard 26, Loss of Offsite or Onsite Power

Definition–This event includes the loss of electrical power either generated or controlled by persons outside the repository site as well as a loss of power within the repository.

Required Condition–The need and provision for electrical power at the site.

Evaluation–

1. Potential exists and is applicable to the repository site. TRUE.

   Rationale–The repository operations will rely primarily on offsite power from a commercial grid. Such grids are vulnerable to outages from many causes. As appropriate to sustain required safety functions, onsite power supplies will be provided for selected SSCs important to safety.

2. The rate of the hazard process is sufficient to affect the 100-year operational period. TRUE.

   Rationale–The impact is immediate. Loss of power effects could initiate event sequences.

3. The consequences of the hazard are significant enough to affect the 100-year operational period. TRUE.

Rationale–Loss of power effects could initiate event sequences. Design bases and event sequence analyses are required to evaluate this event. Because this statement is indeterminate (its validity cannot be determined at this time), the statement is treated as equivalent to true.

4. The event frequency is greater than 1×10^{-6} events per year. TRUE.

   Rationale–The rate of occurrence of a loss of offsite power is known to be on the order of 0.1 per year for nuclear plants. Site-specific analysis is required for the repository offsite power supply reliability and design-specific reliability analysis of onsite safety-related power supplies are required as well. Because the response to this criterion is indeterminate (its validity cannot be determined at this time), it is treated as equivalent to TRUE.

Applicability–Yes. This event is applicable to the EEHL for the repository site.

External Hazard 29, Meteorite Impact

Definition–The impact of any meteoroid that has reached the surface of the earth without being completely vaporized.

Required Condition–Potential meteorite impact at the site.

Evaluation–

1. Potential exists and is applicable to the repository site. TRUE.

   Rationale–Meteorites fall randomly throughout the surface of the earth (Solomon et al. 1975, p. 69).

2. The rate of the hazard process is sufficient to affect the 100-year operational period. TRUE.

   Rationale–Because this statement is indeterminate (its validity cannot be determined at this time) then the statement is treated as equivalent to TRUE.

3. The consequences of the hazard are significant enough to affect the 100-year operational period. TRUE.

   Rationale–Because this statement is indeterminate (its validity cannot be determined at this time) then the statement is treated as equivalent to TRUE.

4. The event frequency is greater than 1×10^{-6} events per year. FALSE.

   Rationale–A screening analysis has been performed. Areal strike frequency data was obtained (Solomon et al. 1975, Table 1, Column 5): the sum of the probabilities greater than one pound (> 0.001 ton) is approximately 1.5×10^{-8} per year per 105 ft^2 area. The facility footprint was conservatively estimated to be 624,235 ft^2 and

assumed to be vulnerable to release of radioactivity given a meteorite greater than one pound. The probability of impact on the repository footprint area is estimated to be 9.36×10^{-8} per year ($6.24 \times 1.5 \times 10^{-8}$). The 624,235-ft^2 footprint-area is conservative because all of the area is not completely filled with waste forms. The area would have to be ten times larger to increase the frequency to greater than 1×10^{-6} per year. Even during peak years, only a fraction of the area will be occupied by waste forms. Therefore, meteorite impact is not considered credible for consideration during the 100-year operational period. Other supporting rationale may be provided, such as noting that the American Nuclear Society guidelines for external hazards at nuclear plants also states that the probability of meteorite impact is less than 1×10^{-6} per year (ANSI/ANS-2.12-1978).

The bases for such quantitative screening analyses, such as meteorite areal strike frequency and site vulnerable area, must be documented as inputs or assumptions.

Applicability–No. This event is not applicable to the EEHL for the repository site.

External Hazard 38, Seismic Activity, Earthquake

Definition–This event pertains to earthquake or earth vibrations, including those that are artificially induced.

Required Condition–Natural seismic activity or man-induced events such as weapons testing on Nevada Test Site.

Evaluation–

1. Potential exists and is applicable to the repository site. TRUE.

   Rationale–Earthquakes have occurred as recently as 1993 in the region (National Research Council 1995, p. 92), making this event applicable for consideration during the 100-year operational period. The *Preclosure Seismic Design Methodology for a Geologic Repository at Yucca Mountain* (YMP 1997) describes the strategy for the 100-year operational period seismic design methodology. Note that nuclear weapon testing is no longer performed at the Nevada Test Site.

2. The rate of the hazard process is sufficient to affect the 100-year operational period. TRUE.

   Rationale–The impact is immediate. Earthquake effects could initiate event sequences and cause collapse or failures of SSCs that house radioactive materials.

3. The consequences of the hazard are significant enough to affect the 100-year operational period. TRUE.

   Rationale–Earthquake effects could initiate event sequences and cause collapse or failures of SSCs that house radioactive materials. Design criteria for selected SSCs will have to be defined to prevent adverse consequences. Without engineering

analyses, the response to this criterion is viewed as indeterminate and is treated as equivalent to TRUE.

4. The event frequency is greater than 1×10^{-6} events per year. TRUE.

   Rationale–The repository will use mean annual probabilities of 1×10^{-3} and 1×10^{-4} as reference values in determining the frequency category 1 and frequency category 2 design basis vibratory ground motions (YMP 1997, p. iii). The SSCs important to safety will be designed to withstand a design basis earthquake (frequency category 1 or frequency category 2), as appropriate.

Applicability–Yes. This event is applicable to the EEHL for the repository site.

6.1.3.6 External Events Hazards List

The EEHA will summarize the process and the results. The EEHA process results in the EEHL. The EEHL is a listing of external hazards that will be addressed either as initiating events for event sequences, or otherwise dealt with. The EEHL will be accompanied by a summary table listing those events that have been eliminated for consideration through the screening process and a brief description of the principal basis for the elimination of the event.

Table 6-3 is an example of an EEHL using the examples presented in Section 6.1.3.5. The EEHL includes those events external to the control of repository operations that are potential candidates for initiating radiological event sequences during the preclosure (100-year) operational period.

In addition, the EEHA will provide a summary table of those hazards that were eliminated through the screening process, including a statement of the primary rationale for the elimination of the hazard. Table 6-4 illustrates these hazards, based on the examples in Section 6.1.3.5.

6.2 INTERNAL EVENTS HAZARDS ANALYSIS

6.2.1 Introduction

The purpose of this analysis is to identify and document the internal hazards and preliminary events as part of the PSA. Internal hazards are those hazards presented by operation of the facility and its associated processes. These hazards are in contrast to external hazards, which involve natural phenomena and external man-made hazards. The hazard analysis methodology used in this analysis provides a systematic means to identify facility hazards and associated event sequences that may result in adverse radiological consequences to the public and facility workers during the repository preclosure period. The events are documented in a preliminary internal event hazards list and are intended to be used as input to the repository initiating event selection process. It is expected that the results from this analysis will undergo further screening and analysis based on the criteria that apply to the performance of event sequence analyses for the preclosure period of repository operation. As the repository design progresses, this analysis will be reviewed to ensure that no new hazards are introduced and previously evaluated hazards have not increased in severity.

6.2.2 Overview of Basic Approach

This analysis is performed utilizing the hazard analysis methodologies described in the *System Safety Analysis Handbook* (Stephans and Talso, eds. 1997) and addresses the repository internal hazards and associated events that could result in radiological consequences to the public or facility workers during the preclosure period. The list of preliminary events is generated by applying a checklist of potential generic events (see Section 6.2.3.3) to each functional area within the repository. A description of the process steps is provided in the following sections.

6.2.2.1 Define Repository Functional Areas

To facilitate identification of repository hazards, the repository is divided into functional areas. These functional areas are defined by a specific function, physical boundaries of the facility, or both. Repository functional areas are listed in Section 6.2.3.1 and described in Section 6.2.4.

6.2.2.2 Define Repository Design Configuration and Operations

Following the definition of functional areas, facility design configuration and operations within those areas are established and documented prior to hazard identification activities. Functional area design configuration and operations are discussed in Sections 6.2.3.2 and 6.2.4.

6.2.2.3 Develop Generic Event Checklist

Once the repository functional areas, design configuration, and facility operations are defined, a list of generic internal events is developed that, if determined to be applicable, could result in adverse radiological consequences to the public or facility workers. This generic list is not project-specific and attempts to identify all potentially hazardous event sequences. A comprehensive list will ensure a thorough treatment of all possible events. The development of generic events will make maximum use of existing repository documents where similar work has been performed. A list of generic events is provided in Section 6.2.3.3.

6.2.2.4 Determine the Repository Applicability of Internal Events

This portion of the analysis includes a review of the repository functional areas, including facility design and operations, to determine the applicability of generic events that could potentially result in adverse radiological consequences.

Specific criteria will be developed for each of the generic events to support the applicability determination. If the criteria are satisfied, the generic event has the potential for adverse radiological consequence and specific preliminary events will then be identified. It should be noted that potential events producing adverse radiological consequences will not be identified in all functional areas.

A general review of previously performed safety evaluations of repository operations has been conducted to determine the preliminary events applicable to the repository. These evaluations included:

- *Preliminary Worst-Case Accident Analysis to Support the Conceptual Design of a Potential Repository in Tuff* (Jackson et al. 1984)
- *Site Characterization Plan Conceptual Design Report - Volume 4 Appendices F - O* (MacDougall et al. 1987)
- *Yucca Mountain Site Characterization Project Identification of Structures, Systems, and Components Important to Safety at the Potential Repository at Yucca Mountain* (Hartman and Miller 1991)
- *Preclosure Radiological Safety Analysis for Accident Conditions of the Potential Yucca Mountain Repository: Underground Facilities* (Ma et al. 1992)
- *Preclosure Radiological Safety Evaluation: Exploratory Studies Facility* (Schelling and Smith 1993).

The following approach should be used to document the analysis of preliminary events presented in Section 6.2.4.

- **Area Description**–Establishes the baseline description of the repository functional area. Information will be used to gain an understanding of the expected use of the area.
- **Generic Event Category Applicability**–Summarizes results from the applicability assessment for each of the following generic events:
  - Collision/Crushing
  - Chemical Contamination/Flooding
  - Explosion/Implosion
  - Fire
  - Radiation/Magnetic/Electrical/Fissile
  - Thermal.
- **Reference**–Identifies the source of the preliminary design data used to conduct the analysis.
- **Preliminary Events**–Identifies specific events based on the potential for interaction.

6.2.3 Approach for Evaluating Applicability of Generic Internal Events to Repository Functional Areas

The basic input used in the performance of this analysis consists of repository process and design information and includes system description documents, process flow diagrams, mechanical flow diagrams, and a conceptual description of repository operations. Additional design input to this analysis is described in the following sections.

6.2.3.1 Repository Functional Areas

The following functional areas have been defined to facilitate the identification of the repository hazards and events associated with preclosure operations. A description of each functional area is provided in Section 6.2.4.

- Waste Receipt and Carrier or Cask Transport
- Carrier Preparation
- Waste Handling - Carrier Bay
- Waste Handling - Canister Transfer
- Waste Handling - Assembly Transfer
- Waste Handling - Disposal Container Handling and Waste Package (WP) Remediation
- Subsurface Transport, Emplacement, and Monitoring
- Site-Generated Waste Treatment - Liquid LLW
- Site-Generated Waste Treatment - Solid LLW

6.2.3.2 Repository Design Configuration and Facility Operation

Prior to performing repository hazards analysis, facility design configuration and operations as well as the function of facility SSCs are established. This analysis is based upon the repository design and functions. A brief description of operations for each functional area is provided in Section 6.2.4.

6.2.3.3 Generic Internal Event Checklist

The development of the generic internal event checklist is based on the following hazard evaluation techniques:

- Energy Analysis (Stephans and Talso, eds. 1997, p. 3-77)
- Energy Trace Barrier Analysis (Stephans and Talso, eds. 1997, p. 3-79)
- Energy Trace Checklist (Stephans and Talso, eds. 1997, p. 3-85).

The generic list is based upon the lists provided in these three approaches that have been reorganized for convenience and applicability to repository preclosure operations. The resulting comprehensive checklist contains a series of questions for each generic hazard. Applicability to a functional area of design is determined by a positive response to all questions.

6.2.3.3.1 Collision/Crushing

A. **Categories–**

1. **Uncontrolled Mass/Force**–Examples include: excessive velocity or acceleration of mass, inadvertent operation of appendage, failure of primary or secondary structure, tumbling (or tipped-over) mass, uncontrolled robot, or uncontrolled fixed rotating equipment, falls, drops.

2. **Protrusions into Pathways**–Examples include: extended appendages, protruding structural elements, or improperly placed equipment.

B. **Applicability to Functional Area of Design**–

1. Is kinetic or potential energy present?

2. Can the kinetic or potential energy be released in an unplanned way?

3. Can the release of kinetic or potential energy interact with the waste form?

6.2.3.3.2 **Chemical Contamination/Flooding** (not normally a direct potential threat to the waste form—usually a contributing cause of another threat category)

A. **Categories**–

1. **Reactions**–Examples include: release of chemicals or materials that react with system materials causing system deterioration. The released materials could foster electrolytic, galvanic, or stress corrosion, or oxidation.

2. **Off-Gassing**–Example: release of volatile or condensable materials.

3. **Venting**–Examples include: leaking or venting of materials, gases, or liquids.

4. **Debris/Leaks**–Examples include: small loose or free parts, flaking, leaking fluids or flooding, or dirt and dust, oxidized materials (e.g., metal rust).

5. **Flooding**–Examples include: water, water leading to the potential for criticality.

B. **Applicability to Functional Area of Design**–

Category 1–Reactions:

1. Are corrosive or reactive chemicals or materials present?
2. Can these chemicals or materials be released?
3. Can the chemicals or materials interact with the waste form?

Category 2–Off-Gassing:

1. Are volatile or condensable materials present?
2. Can these materials be released?
3. Can these materials interact with the waste form?

Category 3–Venting:

1. Is there potential for venting materials in the area?
2. Can the materials interact with the waste form?

Category 4–Debris and Leaks:

1. Is there potential for debris or leaks in the area?
2. Can the debris or fluids interact with the waste form?

Category 5–Flooding:

1. Are sources of water present in the area?
2. Is there a potential to release the water?
3. Can the released water interact with the waste form with potential for criticality?

6.2.3.3.3 Explosion/Implosion (This event is normally accompanied by shrapnel or other high velocity debris.)

A. **Categories**–

1. **Pressure Energy Release**–Examples include: damage, failure, and rupture of pressurized containers or components and release of gases, or implosion of containers, vessels, or enclosed structural volume.
2. **Electrical Energy Release**–Examples include: faults, arcs, static charge, electrical component failure, battery overcharge or overdischarge, or out of phase source connection.
3. **Chemical Energy Release**–Examples include: chemical dissociation or reactions, fire internal to confined volumes, adiabatic detonation, or ignition of confined flammable gases.
4. **Mechanical Equipment**–For example: rotating equipment disintegration due to overspeed.

B. **Applicability to Functional Area of Design**–

1. Are pressure, electrical, chemical, or mechanical energy present?
2. Can an event occur that results in an explosion or implosion energy release?
3. Can the released energy impact the waste form directly?

6.2.3.3.4 Fire

Must have ignition, fuel, and oxidizer sources.

Ignition Sources–Examples include: electrical faults, shorts, arcs, chemical reactions, hot surfaces, small flames, or catalytic reaction (see Explosion/Implosion).

Fuel and Oxidizer Sources–Examples include: flammable materials (solids and liquids) and flammable atmospheres (gases), in addition to the presence of an oxidizing environment from ambient atmosphere or other chemical agents (see Contamination).

A. **Categories**–Not Applicable

B. **Applicability to Functional Area of Design**–

1. Are fuel, oxidizers, and ignition sources present?
2. Is there sufficient fuel and oxidizer to sustain fire?
3. Can fire interact with the waste form?

6.2.3.3.5 Radiation/Magnetic/Electrical/Fissile

A. **Categories**–

1. **Ionizing**–Examples include radioactive materials, x-rays, or high voltage radio frequency equipment.

2. **Non-Ionizing**–Examples include electromagnetic interference, radio frequency, or corona.

3. **Magnetic**–Examples include permanent magnets and electromagnetic devices.

4. **Nuclear Particles**–Examples include ion and electron beams or radioactive materials.

5. **Laser Light**–For example high energy laser beams and accompanying energy forms such as heat.

6. **Fissile Material**–Examples include uranium-233, uranium-235, and plutonium-239.

B. **Applicability to Functional Area of Design**–

1. Are radiation, magnetic, or electrical energy sources present external to the waste form? Is fissile material present?

2. Is a mechanism present to release radiation, magnetic, or electrical energy?

3. Can the release of radiation, magnetic, or electrical energy interact with the waste form?

4. Can fissile material be arranged in such a manner as to result in criticality?

6.2.3.3.6 Thermal (also see Fire)

A. **Categories–**

Heat–This category accommodates any thermal energy source with sufficient energy to have an impact on the waste form.

B. **Applicability to Functional Area of Design–**

1. Are external thermal energy sources present?
2. Can thermal energy be released?
3. Can the thermal energy affect the waste form?

6.2.4 Examples of Evaluating the Applicability of Generic Events to Repository Function Areas

6.2.4.1 Example 1: Waste Receipt and Carrier or Cask Transport

Area Description–Transportation casks containing spent nuclear fuel (SNF) and high-level radioactive waste (HLW) and associated carriers are received at the repository waste entry point or security gate. The SNF and HLW are contained in casks equipped with impact limiters and personnel barriers. At the security gate, the cask carrier and offsite prime mover are inspected for contraband, sabotage, and radioactive contamination. Following inspection, the offsite prime mover is decoupled and an onsite diesel-driven prime mover is used to transport the carrier or cask to the Carrier Preparation Building (CPB). Following preparation of the carrier or cask in the CPB, the system moves the carrier or cask to the carrier bay of the Waste Handing Building (WHB) for cask unloading.

This functional area is located on the surface at the north portal and consists of security inspection and radiation monitoring equipment, required road and rail systems, and onsite prime movers. The system also transports empty transportation casks and associated carriers from the WHB to the CPB for preparation and on to the repository security gate for dispatch from the site.

Generic Events Applicability–

Collision/Crushing–Yes
Chemical Contamination/Flooding– None identified
Explosion/Implosion–None identified
Fire–Yes - diesel fuel fire

Radiation/Magnetic/Electrical/Fissile–Yes - Radiation, Fissile
Thermal–Yes (see Fire)

Reference–Jackson et al. 1984, MacDougall et al. 1987, Hartman and Miller 1991, and applicable system description and design documents.

Preliminary Events–

Collision/Crushing–Cask collision, railcar derailment involving transportation cask, overturning of truck trailer involving transportation cask

Fire, Thermal–Diesel fuel fire

Radiation–Radiation exposure of facility worker

Fissile–Criticality associated with cask collision, railcar derailment, or overturned truck trailer and rearrangement of cask internals

6.2.4.2 Example 2: Carrier Preparation

Area Description–Transportation casks containing SNF and HLW and associated carriers are delivered to the CPB by the onsite diesel-driven prime mover. Within the CPB, carriers and casks are prepared for entering the carrier bay of the WHB. The primary operations include:

- Measure external carrier and cask radiation levels
- Remove and retract personnel barriers
- Inspect carriers and casks for radiation contamination
- Measure external cask temperature
- Remove and retract impact limiters.

The CPB material handling system also functions to prepare empty carriers and casks for dispatch from the repository. Specifically, the carriers and casks are inspected for radiation contamination and the impact limiters and personnel barriers are installed. The empty carriers and casks are removed from the CPB for dispatch by the offsite prime mover. The system performs these functions utilizing remotely operated cranes and manipulators; however, some local operator actions may be required.

Generic Events Applicability–

Collision/Crushing–Yes
Chemical Contamination/Flooding–None identified
Explosion/Implosion–None identified
Fire–Yes
Radiation/Magnetic/Electrical/Fissile–Yes, Radiation/Fissile
Thermal–Yes (see Fire).

Reference–Applicable system description and design documents.

Preliminary Events–

Collision/Crushing–Handling equipment drops on transportation cask, cask collision
Fire, Thermal–Diesel fuel fire
Radiation–Radiation exposure of facility worker
Fissile–Criticality associated with cask collision and rearrangement of cask internals.

6.2.4.3 Example 3: Waste Handling - Carrier Bay

Loaded transportation casks and associated carriers are transported from the CPB to the WHB carrier bay by the onsite diesel-driven prime mover (rail and road). Incoming carriers and casks are prepared for waste removal by upending the cask on the carrier, lifting the cask from the carrier and lowering the cask onto a cask transfer cart. The system also functions to load empty transportation casks and non-disposable canisters onto carriers for shipment from the repository. The system performs these functions utilizing remotely operated cranes and manipulators; however, some local operator actions may be required.

Generic Events Applicability–

Collision/Crushing–Yes
Chemical Contamination/Flooding–None identified
Explosion/Implosion–None identified
Fire–Yes
Radiation/Magnetic/Electrical/Fissile–Yes, Radiation/Fissile
Thermal–Yes (see Fire).

Reference–Applicable system description and design documents.

Preliminary Events–

Collision/Crushing–Transportation cask drop, transportation cask slap down, cask collision, isolation door closes on transportation cask, handling equipment drops on transportation cask

Fire, Thermal–Diesel fuel fire

Radiation–Radiation exposure of facility worker

Fissile–Criticality associated with cask collision or drop and rearrangement of cask internals.

6.2.4.4 Example 4: Waste Handling - Canister Transfer

Transportation casks containing large and small disposable canisters are transferred from the carrier bay to the canister transfer area by means of cask transfer carts. In the canister transfer area, canisters are unloaded from casks, stored as required, and loaded into disposal containers (DCs). Empty casks are also prepared for shipment from the repository. Cask unloading begins with cask inspection, sampling, and lid bolt removal operations. The cask lids are removed and

the canisters are unloaded. Small canisters are loaded directly into a DC, or are stored until enough canisters are available to fill a DC. Large canisters are loaded directly into a DC. Transportation casks and related components are decontaminated as required, and empty casks are prepared for shipment from the site.

Two independent and remotely operated canister transfer lines are provided in the WHB. The lines are operated independently to handle disposable canisters and load them into DCs. Each canister transfer line contains an airlock, cask preparation and decontamination area, and a canister transfer cell. Each cask preparation and decontamination area includes a cask preparation station and a cask decontamination station. Remote handling equipment consists of cask transfer carts, cask preparation manipulators, and equipment required to perform sampling, cask unbolting, lid removal, and decontamination. The canister transfer cells include a canister transfer station and DC transfer cart supported by remote handling equipment including a bridge crane (sized to handle the largest canisters), DC loading manipulator, and an array of large and small canister lifting fixtures. A canister staging rack is provided for the accumulation of small canisters in a shielded area.

Generic Events Applicability–

Collision/Crushing–Yes
Chemical Contamination/Flooding–None identified
Explosion/Implosion–None identified
Fire–None identified
Radiation/Magnetic/Electrical/Fissile–Yes, Radiation/Fissile
Thermal–None identified.

Reference–Applicable system description and design documents.

Preliminary Events–

Collision/Crushing–Transportation cask slapdown, DC slapdown, canister drop, canister slap down, canister collision, canister drops onto DC, canister drop on sharp object, canister drop onto another canister at small canister staging rack, shield door closes on transportation cask, shield door closes on DC, handling equipment drops on transportation cask, canister or DC

Radiation–Radiation exposure of facility worker

Fissile–Criticality associated with small canister staging rack, criticality associated with collision or drop of casks or canisters, and rearrangement of container internals.

6.2.4.5 Example 5: Waste Handling - Assembly Transfer

Area Description–Transportation casks containing uncanistered spent nuclear fuel (SNF) assemblies or Dual Purpose Canisters (DPCs) are transferred from the carrier bay to the assembly transfer area by means of cask transfer carts. Casks are lifted from the transfer cart and placed into a cask preparation pit. The cask interiors are sampled for radioactivity, vented, cooled down with compressed gas, and then filled with water. The cask lid bolts are then

detensioned and removed. The cask is lifted and placed in the cask unload pool, where the cask lid is removed and the assemblies are removed and placed directly into a transfer cart or a staging rack. Assemblies contained in a DPC involve the additional steps of removing the DPC from the cask and DPC opening prior to assembly removal. Following assembly removal, empty transportation casks and DPCs are removed from the pool and prepared for dispatch from the repository site.

Following removal from the cask or DPC, the SNF assemblies are transferred to the assembly cell (either directly or from the staging rack) by an inclined transfer cart. In the assembly cell, the SNF assemblies are placed in the assembly drying station for water removal and then transferred to DC. The DC is then fitted with a temporary seal, decontaminated, evacuated, and backfilled with nitrogen and moved to the DC cell for lid welding.

The system utilizes remotely operated equipment to perform these functions including, a bare fuel assembly transfer machine, fuel assembly grapples, container transfer carts, contamination barriers, inspection instruments, and low-level radioactive waste (LLW) removal subsystems.

Generic Events Applicability–

Collision/Crushing–Yes
Chemical Contamination/Flooding–Yes, Flooding
Explosion/Implosion–None identified
Fire–Yes
Radiation/Magnetic/Electrical/Fissile–Yes, Radiation/Fissile
Thermal–Yes.

Reference–Applicable system description and design documents.

Preliminary Events–

Collision/Crushing–Transportation cask drop, transportation cask slap down, cask collision, SNF assembly drop onto pool floor, SNF assembly drop onto SNF assembly staging rack, SNF assembly drop onto assembly cell floor, SNF assembly drop onto assembly dryer, SNF assembly drop onto DC, SNF assembly collision, loaded SNF assembly basket drop onto pool floor, loaded SNF assembly basket drop onto SNF assembly staging rack, loaded SNF assembly basket drop onto assembly cell floor, loaded SNF assembly basket drop onto assembly dryer, loaded SNF assembly basket collision, uncontrolled descent of loaded incline basket transfer cart

Flooding–Uncontrolled pool water draindown or filling resulting in flooding

Fire, Thermal–SNF overheating due to loss of pool water resulting in excessive clad temperature and possible zircaloy cladding fire, SNF overheating in an assembly transfer basket or dryer resulting in excessive clad temperature and possible zircaloy cladding fire

Radiation–Uncontrolled pool water draindown or filling resulting in flooding and radioactive contamination of adjoining WHB areas, increased radiation levels in the

assembly transfer area and potential uncovering of fuel assemblies, radiation exposure of facility worker

Fissile–Criticality associated with a cask collision or drop and the rearrangement of cask internals, criticality associated with SNF assembly staging rack, criticality associated with misload of assembly dryer, criticality associated with misload of disposal container.

6.2.4.6 Example 6: Waste Handling - Disposal Container Handling and Waste Package Remediation

Area Description–Within the DC handling area, empty DCs are prepared for loading, DCs are transferred to and from the assembly and canister transfer systems, the DC lids are welded, and WPs are temporarily stored. WPs are also loaded into the WP transporter and transferred to and from the WP remediation system. DCs consist of the container barriers, spacing structures or baskets, shielding integral to the container and packing contained with the container. The WP consists of the DC and waste form(s) after the outer lid welds are completed and accepted.

The process begins with empty DC preparation, which includes staging the DCs, installing collars, tilting the DC upright and outfitting the container, and transferring it to DC transfer operations. DC transfer operations include staging DC lids for the weld stations, and transferring the DCs to or from the assembly or canister transfer systems for loading and welding. The DC welding operation receives loaded DCs directly from the waste handling lines or from interim lag storage for welding. The welding operations include mounting the DC on a turntable, removing lid seals, and installing and welding the inner and outer lids. The weld process for each lid includes non-destructive examination. Following examination and weld acceptance, the container is called a WP and is either staged or transferred to a tilting station. At the tilting station, the WP is tilted to horizontal, the collars are removed, and the WP is transferred to WP transporter loading operations. The WP transporter loading operations include survey and decontamination, and lifting and loading the WP into the WP transporter. DCs that do not meet the welding examination criteria are transferred to the WP remediation system for inspection or repair.

The DC handling area is contained within the WHB and includes areas for empty DC preparation, welding, staging, loaded WP staging, WP transporter loading, and the associated operating galleries and required equipment maintenance areas. The empty DC preparation area is located in an unshielded structure.

Disposal container handling equipment includes a DC/WP bridge crane, tilting station, and transfer carts. The welding area includes DC/WP welders, staging stations, and a tilting station. Welding operations are supported by remotely operated equipment including transfer carts, a bridge crane and hoists, welder jib cranes, welding turntables, and manipulators. WP transfer includes a transfer, decontamination, and transporter load area. The operations are supported by a remotely operated horizontal lifting system, decontamination system, decontamination and inspection manipulator, and a WP horizontal transfer cart. All handling operations are supported by a suite of fixtures including yokes, lift beams, and lid attachments. Remote equipment is designed to facilitate decontamination and maintenance, and interchangeable components are provided where appropriate. Set-aside areas are included as required for fixtures and tooling to

support off-normal and recovery operations. Semi-automatic, manual, and backup control methods support normal, maintenance, and recovery operations.

Generic Events Applicability–

Collision/Crushing–Yes
Chemical Contamination/Flooding–None identified
Explosion/Implosion–None identified
Fire–Yes
Radiation/Magnetic/Electrical/Fissile–Yes, Radiation/Fissile
Thermal–Yes.

Reference–Applicable system description and design documents.

Preliminary Events–

Collision/Crushing–WP drop, WP slap down, WP drop onto sharp object, WP collision, equipment drops onto WP, DC drop, DC slap down, DC drop onto sharp object, DC collision, handling equipment drops on DC

Fire, Thermal–Fuel damage by burn through during welding process, SNF overheating in a DC resulting in excessive clad temperature and possible zircaloy cladding fire

Radiation–Radiation exposure of facility worker

Fissile–Criticality associated with the DC/WP staging area, criticality associated with collision or drop of DC/WP and rearrangement of container internals.

6.2.4.7 Example 7: Subsurface Transport, Emplacement, and Monitoring

Area Description–The waste emplacement system transports the loaded and sealed WP from the WHB to the subsurface emplacement area. This system operates on the surface between the north portal and the WHB, and in the underground ramps, access mains, and emplacement drifts. This system accepts the WP onto a reusable rail car, moves the WP into the shielded transporter, transports the WP to the emplacement area, and emplaces the WP in the emplacement drift. The operation cycle is completed when the transport equipment returns to the surface WHB to receive another WP.

Major items and sub-systems of the waste emplacement system consist of the following:

- A shielded transporter with a reusable rail car for the movement and transfer of the WPs. The transporter requires transport locomotives for movement.
- Transport locomotives for the transporter movement and control functions between the WHB and the subsurface repository.

- A remotely controlled emplacement gantry for the WP emplacement functions in the emplacement drifts. The gantry is self-powered through a direct current third rail system.

- A gantry carrier for gantry transfer between the emplacement drifts and the maintenance facilities. The gantry carrier requires a transport locomotive for the carrier movement and control functions.

The sequence of the subsurface WP handling process is described in the following paragraphs:

The WP, positioned on a reusable rail car, is moved into the shielded transporter at the WHB. A remotely controlled loading mechanism moves the rail car into and out of the transporter. The loading mechanism will be an integral part of the transporter.

A pair of transport locomotives is used to move the transporter from the WHB, into and down the north ramp, into the east or west main, and to the vicinity of the designated emplacement drift. At the pre-selected emplacement drift location, one locomotive is uncoupled to allow the transporter, with the transporter doors facing the drift entrance, to be pushed into the emplacement drift turnout. Before the transporter is pushed into the turnout, the locomotive operators leave the locomotive, and the following functions of the emplacement sequence are performed remotely. Once the transporter is partway in the turnout, the transporter doors and the drift isolation doors open remotely, then the transporter is pushed into contact with the subsurface emplacement transportation system drift transfer dock.

Once the transporter is docked, the unloading mechanism moves the reusable rail car with the WP out of the transporter and onto the rails located on the transfer dock. The emplacement gantry moves into position over the WP, it engages the WP by the skirts at both ends, and raises the WP off the reusable rail car. The gantry carries the WP into the emplacement drift, stopping at a pre-determined emplacement position. The WP is lowered onto permanently installed pedestals. The gantry disengages from the WP and moves back to its waiting position at the transfer dock. These operations are reversible to support moving an emplaced WP to another location.

The transporter retracts the reusable rail car, and is pulled away from the drift entrance doors by a locomotive. The transporter doors and the drift doors are then closed, and the transporter returns to the surface WHB for another transport and emplacement operation. The transporter may also receive a WP onto the reusable rail car from the emplacement gantry to support moving the WP to another emplacement drift or to the surface WHB.

Following emplacement, the WPs are monitored between the time the WP is emplaced and the time the repository is closed. Concurrent with the emplacement and monitoring of WPs, construction is underway on the development of additional emplacement drifts. Physical separation of emplacement and development activities is provided by isolation air locks. When a predetermined number of newly excavated emplacement drifts are ready for waste emplacement, the isolation airlocks are moved to include the newly developed drifts in the emplacement area.

Generic Events Applicability–

Collision/Crushing–Yes
Chemical Contamination/Flooding–Yes, Flooding
Explosion/Implosion–No
Fire–Yes
Radiation/Magnetic/Electrical/Fissile–Yes, Radiation/Fissile
Thermal–Yes, see Fire.

Reference–Jackson et al. 1984, MacDougall et al. 1987, Hartman and Miller 1991, Ma et al. 1992, Schelling and Smith 1993, and applicable system description and design documents.

Preliminary Events–

Collision/Crushing–Transporter derailment outdoors, transporter derailment on ramp or in main drift, transporter collision with other stationary or moving equipment, WP reusable rail car rolls out of transporter, runaway transporter, rockfall onto transporter, loaded emplacement gantry derailment, WP drop from emplacement gantry, WP or emplacement gantry collision with equipment or another WP, rockfall onto WP, steel set drop onto WP, failure of isolation air locks due to rockfall, equipment collision, or other impacts as a result of development operations

Flooding–Flooding from water pipe break originating on development or emplacement sides

Fire, Thermal–Fire associated with WP transporter, locomotive, or development equipment

Radiation–Radiation exposure of facility worker, early or juvenile WP failure and resultant release of radioactive material

Fissile–Criticality associated with collision or drop of WP and rearrangement of package internals.

6.2.4.8 Example 8: Site-Generated Waste Treatment - Liquid Low-Level Radioactive Waste

Area Description–Liquid LLW is piped to the waste treatment building for processing. Liquid waste is treated by filtration, evaporation, and ion exchange. Water meeting the requirements for reuse is recovered. Following pH adjustment, non-recyclable liquid is solidified and packaged in drums. The drums are temporarily stored awaiting offsite shipment for disposal.

Generic Events Applicability–

Collision/Crushing–Yes
Chemical Contamination/Flooding–Yes, Flooding
Explosion/Implosion–None identified

Fire–None identified
Radiation/Magnetic/Electrical/Fissile–Yes, Radiation
Thermal–None identified.

Reference–Applicable system description and design documents.

Preliminary Events–

Collision/Crushing–Handling equipment drops on liquid LLW
Flooding–Uncontrolled release of liquid LLW
Radiation–Operator exposure to radioactive material.

6.2.4.9 Example 9: Site-Generated Waste Treatment - Solid Low-Level Radioactive Waste

Area Description–Solid LLW is shipped to the waste treatment building in drums. The waste consists of combustible and noncombustible job control waste (e.g., protective clothing, rags, wood), ion exchange resin and discarded tools and equipment. The waste is treated by shredding, size reduction, compaction, or dewatering as applicable, packaged in drums with a solidification agent and temporarily stored awaiting offsite shipment for disposal.

Generic Events Applicability–

Collision/Crushing–Yes
Chemical Contamination/Flooding–None identified
Explosion/Implosion–None identified
Fire–Yes
Radiation/Magnetic/Electrical/Fissile–Yes, Radiation
Thermal–Yes (see Fire).

Reference–Applicable system description and design documents.

Preliminary Events–

Collision/Crushing–Solid LLW drop, handling equipment drops on solid LLW
Fire, Thermal–Fire involving combustible LLW
Radiation–Operator exposure to radioactive material.

6.2.5 Internal Events Hazards List

The product of this analysis is the Internal Events Hazards List. The Internal Events Hazards List contains the potentially credible internal hazards that cannot be screened out by the process described.

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ACRONYMS

AC	alternating current [electrical power]
BC2	beyond Category 2 [event sequence]
CA	construction authorization
CCF	common-cause failure
CDF	cumulative distribution function
EF	error factor
EMF	electromagnetic force
ESF	Exploratory Studies Facility
ET	event tree
ETA	event tree analysis
FC	frequency category
FT	fault tree
FTA	fault tree analysis
HA	human action
HEP	human error probability
HEPA	high-efficiency particulate air
HFE	human failure event
HRA	human reliability analysis
HVAC	heating, ventilation, and air-conditioning
IE	initiating event
LA	license application
LN	lognormal
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
OAT	operator action tree
PDF	probability distribution function
PRA	probabilistic risk analysis
PSA	preclosure safety analysis
SNF	spend nuclear fuel
SSCs	structures, systems, and components
T&M	test and maintenance
WP	waste package

7. EVENT SEQUENCE (DESIGN BASIS EVENT) FREQUENCY ANALYSIS

This section presents details of the methodology for using sequence analyses in the Preclosure Safety Analysis (PSA).

7.1 EVENT TREE ANALYSIS

7.1.1 Purpose

This section defines the bases and methodology for the construction and use of event tree analysis (ETA) in support of the PSA. This analysis technique is applied when 1) identifying and structuring sequences of events that could potentially result in radiological releases or exposures, 2) identifying and quantifying dependencies between events in a sequence, 3) identifying the degree or magnitude of system failure or damage that correlates to the magnitude of potential releases and exposures, 4) quantifying the frequency (or annual probability) of various event sequences by combining probabilities of initiating and enabling events, and 5) providing a structure for including and propagating uncertainty factors in sequence quantification.

7.1.2 Scope

This section is a cursory, focused guide to the construction, application, and evaluation of event trees (ETs). While some concepts are universal to all ETA, the applications in this Section are focused on the support of the PSA. This section is not meant to be a textbook or exhaustive in scope. Where appropriate, reference is made to literature for additional information.

7.1.3 Overview of Approach

An ET is a graphical logic model that identifies the possible outcomes following an initiating event (IE). ETs are similar to decision trees in depicting the manner in which a chain of alternative outcomes can occur.

Potential accident scenarios (or event sequences) may be displayed in the form of ETs. ETs include an IE (from an identified hazard) and one or more enabling events that must occur to result in a release of radioactivity, a criticality, or an abnormal radiological exposure of the public or a worker. The ET format may also be used to analyze scenarios involving chemical exposures, fires, or explosions (see AIChE 1989, Figure 3.10). The enabling events generally represent the success or failure of some safety features that mitigate the effects of the IE alone or in combination with other events. The enabling events may also represent specific human actions (HAs) or physical conditions that could affect the progression of an event sequence (or scenario).

The ET format provides a framework for estimating the likelihood of event sequences by displaying the frequency of the IE and the conditional probabilities of contributing (enabling) events.

An ET generally represents a chronological sequence of events. However, in many cases an ET can be simplified (i.e., have fewer limbs or branches) by rearranging events such that the more likely or more significant events are addressed first.

ETs can be used in deterministic and qualitative analyses to display alternative possible sequences, to examine the levels of protection that are present in a design concept, or both.

Further, an ET may be simplified by assuming that some events will occur with a probability of one (e.g., all fuel cladding breaches in a dropped fuel assembly). This assumption may be appropriate if insufficient data exist to quantify the probability of a failure, if a conservative analysis is being performed, or if regulatory policy demands it.

The construction of ETs in the PSA will build, primarily, on the IEs or event categories identified in the internal events hazards analysis (see Section 6.2). In addition, ETs may be constructed as required for the events identified by the External Events Hazards Analysis (see Section 6.1). The following discussion primarily addresses the application of ETA for internal events. Section 10.1 describes the use of ETA for seismic event sequences.

IEs are identified in the internal events hazards analysis for each repository surface and subsurface operation that could directly or indirectly impact the various radioactive waste forms. IEs in a given operation may include one or more opportunities for drops, collisions, tipovers/slapdowns, fires, explosions, flooding, criticality; exposure to chemical, radiation, thermal effects; or HAs. In general, system design and good practices will provide features (one or more structures, systems, or components [SSCs]), administrative controls, or human intervention) that will serve as physical or functional barriers that prevent or mitigate the release of radioactivity or the exposure of individuals. The proper functioning and availability of such features provide success paths such that an IE does not lead to an undesired consequence. Depending on the number of features that are unavailable when challenged by the occurrence of a given IE, undesirable event sequences can be described that represent failure paths, abnormal occurrences, or accidents that are usually differentiated by the degree of undesired consequences that characterize the end state of a given failure path. The ET is a useful tool to define the manner in which failure paths may occur, as well as a framework for quantifying the frequencies of the various success and failure paths.

7.1.3.1 Example of Event Tree

Figure 7-1 shows an example of a simple ET structure for a hypothetical sequence of events associated with the handling of a canister containing radioactive waste. The ET was designed to display several of the types of events and dependencies that may come to play in realistic situations. Section 7.1.4 describes the processes for developing ETs and provides a more complex, hypothetical example for instructional purposes. Section 10.1 describes applications of ETs in seismic sequences.

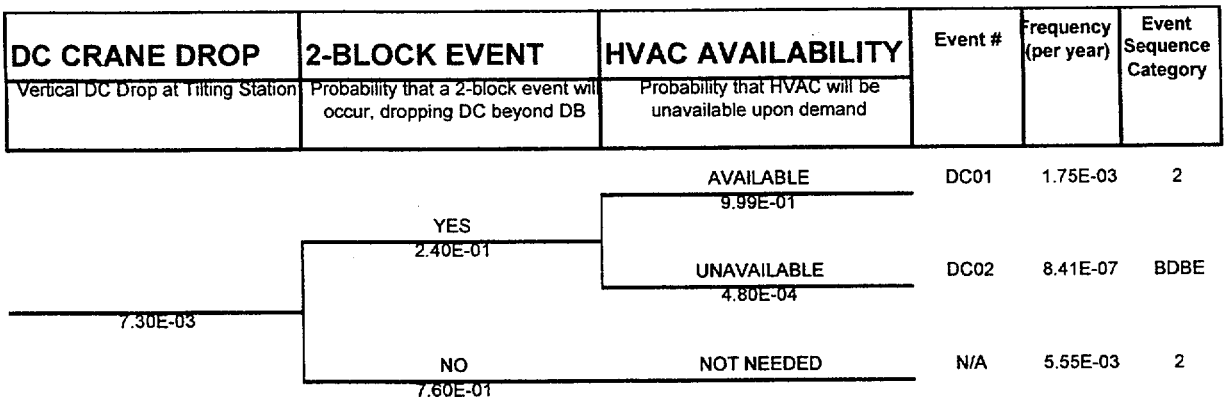


Figure 7-1. Example of a Fork Style Event Tree for a Hypothetical Waste Handling System

The ET in Figure 7-1 includes three events spaced across the top of the Figure. The event labels are known as the event headings. This logic diagram depicts a single line for the IE, but allows for (generally) two branches under each of the contributing (or enabling) event headings. The definitions in the event headings are carefully defined to describe a success. The upward branch above the IE represents a successful (yes or TRUE) IE. The downward branch below the IE represents a FALSE (no) event (e.g., the function fails or is unavailable). The success (or failure) criteria for each safety function must be precisely defined so that the meaning of the "no" branch is unambiguous. In binary logic, partial successes or failures are not permitted. The format for displaying the branches is termed the fork style because the TRUE and FALSE branches diverge from the incoming part. This style of ET is used by SAPHIRE (Russel et al. 1994). By contrast, Figure 7-2 illustrates an ET in the stair-step style. This style is easier to generate by hand (e.g., using the Microsoft Excel spreadsheet program).

Tracing through the branches in Figure 7-2, a particular path defines an event sequence that ends at an End State. Each End State represents the severity of the consequences associated with a particular event sequence (or scenario) expressed as the absence of, or the release of, radioactivity to the environment. The following describe the events represented in the figure, and the results:

- The IE is Drop of Waste Form (onto an unyielding surface). The cause of the drop may be a mechanical failure or human error. As shown in Note 1, the frequency of the IE is estimated from generic crane data for drops-per-lift (14 drops per 1,000,000 lifts) and the handling rate of the hypothetical operation (524 lifts per year). The IE frequency for drops of the waste form is estimated to be 7.3 × 10-3 per year.

- The first enabling event heading is titled "Waste Form Maintains Containment." Since the waste form container will be designed to sustain certain handling stresses and impacts (i.e., those within its design basis, most or all of the possible drop heights could be within the design basis of the waste form and no release of radioactivity would occur). Unless there is absolutely no possible physical means for the operation to result in a breach of the waste form, there is a finite probability that a breach may occur. In the example of Figure 7-2, it is estimated that there is a rather high probability per lift of 0.25 (i.e., one chance in four) that if a drop occurs, it will exceed the design basis of the

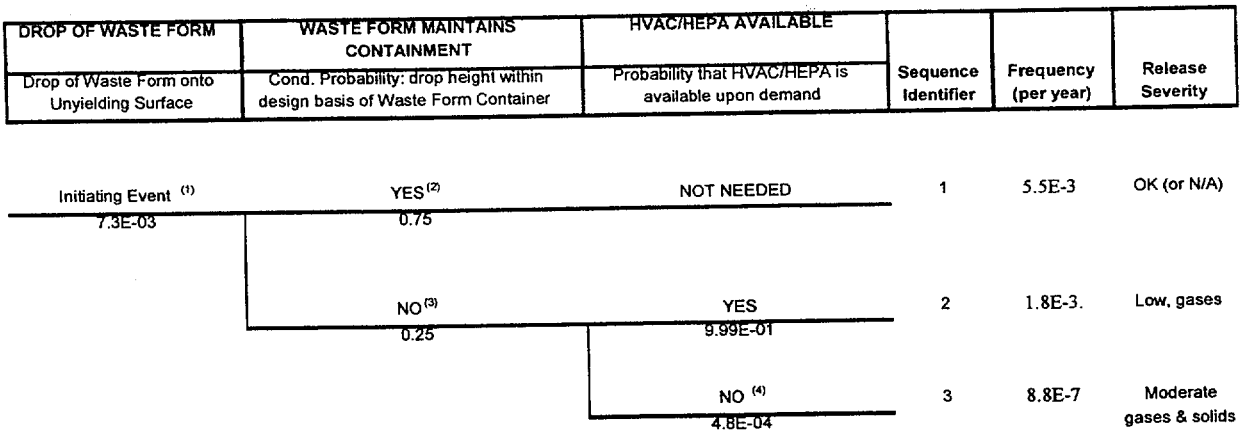
waste form. This probability value could represent the experience data from commercial nuclear power plants (NPPs), independent fuel storage facilities, or other cranes where cases of two-blocking may have occurred. Two-blocking is a term used to describe situation in which lifting continues to a maximum allowable travel height until the strain against a dead pull results in a drop from a high point. The probability value of 0.25 per lift would represent all causes of drops, including hardware failure, software failure, and human errors. It is expected that repository design and operations will not allow such a large conditional probability. In this example, the conditional probability of the NO branch is, therefore, 0.25 and the probability of the YES branch is 0.75. The sum of probabilities for each branch point under each heading must equal 1.0.

- The second enabling event heading is titled "HVAC/HEPA Filter Available." Since there are two exit paths from the event "Waste Form Maintains Containment," the probability of the heating, ventilation, and air-conditioning (HVAC) and high-efficiency particulate air (HEPA) filter being available is conditioned on the need, operational conditions, or both, that are present in each path. In the case of the YES branch for "Waste Form Maintains Containment," there is no need for the HVAC/HEPA filter and a single path labeled "Not Needed" is shown under the heading "HVAC/HEPA Filter Available." For quantification purposes described below, a conditional probability of success of 1.0 is ascribed to dependent events that are not needed. By contrast, a conditional probability of failure of 1.0 is ascribed for dependent or deterministic events that are guaranteed failure.

  In the case of the NO branch exiting event titled "Waste Form Maintains Containment," however, there is a need to mitigate the amount of radioactivity that can escape from the operations building. A reliability analysis (e.g., a fault tree analysis; FTA) may show that the conditional probability of 5×10^{-4} of the HVAC/HEPA filter failing during a certain mission time (for example, 24 hours). The probability that the system is available (i.e., the system does not fail during the 24-hour mission time) is 0.9995 (i.e., $1 - 5 \times 10^{-4}$). Note that the success criteria for the HVAC/HEPA filter branch must include conditions such as: effectively remove 99 percent of particular matter greater than 0.3 microns for a period not less than 24 hours, when called upon. Recall the sum of probabilities at each branch point under each heading must equal 1.0.

- The structure of the ET now provides the means of identifying various event sequences, the means to quantify the frequency of each sequence, and a means of classifying the degree of damage, or amount of release, associated with each sequence.

The path from the IE, through YES on containment, and NOT NEEDED for the HVAC/HEPA filter is a success path. It is identified in Figure 7-2 as Sequence No. 1. The End States for the example in Figure 7-2 represent the source term (labeled Release Severity) associated with each event sequence. Success paths may be labeled "OK" (as is typical in ETA) or "N/A" (for not applicable). The non-success event sequences result in some releases is described qualitatively in the column labeled Release Severity.



Notes:
(1) Initiating event is due to unspecified failure in the lifting crane. From generic data, the frequency of initiating event is estimated to be 524 lifts/yr x 14 drops/million lifts
(2) Drop from normal height or less than design basis.
(3) Drop exceeds design basis due to 2-block event. Conditional probability of 2-block event is assumed to be 0.25 for this illustration.
(4) Unavailability of HVAC/HEPA derived from fault-tree analysis of HVAC/HEPA system.

Figure 7-2. Example of a Stair-Step Style Event Tree for a Hypothetical Waste Handling System

The frequency (or annual probability of occurrence) is estimated for each event sequence that results in a release of radioactivity or abnormal worker exposure. The framework of the ET is used to display the frequency of the initiator and the conditional probabilities of each enabling event in a sequence. The frequency of each event sequence is calculated as the product of the initiator frequency and the probabilities of all success and failure branches that comprise a given event sequence. The ET permits display of dependencies between the IE and enabling events, dependencies between enabling events, or both. Therefore, if there are sequence-dependent couplings between events, different sequences could have different probability values assigned to any given enabling event.

7.1.3.2 Quantification of Event Probabilities and Sequence Frequencies

The frequencies of IEs for internal hazards are estimated from the annual frequency of each operation multiplied by the probability per opportunity (or per operation) that the IE occurs. For example, the frequency of a canister drop is estimated by the product of the frequency of canister lifts (i.e., the number per year) and the conditional probability of dropping the canister per lift. The annual frequencies of each operational step are determined from programmatic information regarding the number of transport casks, spent fuel assemblies, spent fuel canisters, high-level radioactive waste canisters, and waste packages (WPs) that are expected to be processed each year during the preclosure operations.

The conditional probability of each enabling event (usually a failure of some preventive or mitigative feature), such as a drop of a waste form, is estimated from facility-specific data (if available) or generic data for similar operations. Section 7.5 describes the sources and techniques for defining appropriate event probabilities and their uncertainties for use in the PSA. Section 9 describes how uncertainties are applied and propagated. In many cases for the

preliminary event sequence screening analyses, conservative probabilities are assumed for the conditional events (e.g., assuming a probability of 1.0 that all fuel rods breach in a drop sequence). This conservatism is warranted in most cases in early screening analyses because complete design criteria and design details are not available.

A quantitative screening analysis applies the 10 CFR 63.2 definition of Category 2 Event Sequence to screen out event sequences whose estimated frequency results in a probability of less than one chance in 10,000 of occurring during the preclosure operations. Such event sequences are termed beyond Category 2 (BC2) Event Sequences and are screened out (see Section 4, Figure 4-1). Because of uncertainties, the frequency screening is conservatively applied initially so that event sequences within an order of magnitude of the threshold are considered as potential event sequences until additional design or phenomenological data, or detailed analyses including quantitative treatment of uncertainties, demonstrate that the event sequences have frequencies that are BC2. In the preliminary binning, frequencies of IEs and probabilities of enabling events are conservatively estimated and multiplied to estimate the frequencies of event sequences. The conservatisms are thereby stacked. Similarly, event sequences having frequencies within an order of magnitude of the Category 1 lower limit are considered Category 1 until more refined analysis shows otherwise.

In the refined analyses, probability distributions are defined for the IE frequencies and event probabilities to represent uncertainties and are propagated to derive probability distributions for sequence frequencies. The mean value of frequencies of event sequences will be used for binning the results as Category 1 or Category 2 event sequences. The mean value must be less than the frequency of the respective thresholds for Category 1 or 2, as appropriate, to provide the desired level of confidence (see Section 7.6).

7.1.3.3 Alternative Forms and Analysis of Event Trees

It is not feasible to list, by inspection, the important event sequences for a complex nuclear or chemical facility. The ET format provides a systematic and orderly approach to understand and accommodate the many factors that could influence the course of potential accidents. For simpler operations, such as many of the repository operations, the ET display may not be necessary; however, it does provide a powerful and convenient communication tool.

As described in the *PRA Procedures Guide, A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants* (NRC 1983), there are two main analytical formats for using ET and fault trees (FTs) in accident sequence delineation: small ET/large FT versus large ET/small FT. For repository preclosure safety analyses, the small ET/large FT technique is recommended for virtually all of the ETA and is described in the remainder of this Section. The large ET method is summarized for future reference.

Small ET quantification employs the use of FT linking. In this technique individual FTs that represent the respective event headings in the ET are linked through a sequence FT. Each of the function or system FTs is modeled to represent various basic events and dependencies on support systems. Evaluation of interdependencies between the heading events, such as common support systems or common HAs, is accommodated via the boolean algebra in the analysis of the sequence FT.

In the large ET method, by contrast, all of the dependencies and system boundary conditions are explicitly represented in the many headings and branches of the ET. The supporting FTs are small because they represent very specific conditions on the systems or HAs that are represented in the ET headings. In some cases, it is not necessary to use an FT per se, and tabulated probabilities suffice.

There is considerable latitude in the definition of event headings, even in the small ET approach. The same tree may use headings that represent functions, systems, components, and HAs. ET headings may also be used to establish conditions that could ameliorate or exacerbate potential sequences (e.g., the presence of an extreme ambient temperature or the presence of an oversized and overweight load on a lifting device).

Thus, the ET format can be used in two methods to describe potential accident sequence evolution:

- The first method is described in the *PRA Procedures Guide* (NRC 1983) for analyzing potential alternative responses of a complex system to a given IE. This method is sometimes referred to as a pre-incident (or pre-accident) analysis because it models sequences up to the point of having undesired damage states or releases (see AIChE 1989). In this application, a particular IE is postulated and an ET is constructed by listing across the top of the ET the various event possibilities that represent the safety functions or systems that are necessary to mitigate the potential consequences following the IE. For example, in a typical nuclear reactor ET, the IE is a loss of coolant accident and the functions listed across the top of ET would include reactor subcritical, containment overpressurization, and core cooling.

  This type of application is appropriate for dealing with repository operational event sequences. This approach is appropriate for either initiators from internal or external events (including natural phenomena) that are directly associated with the repository operations (e.g., random failures of lifting devices) or those events that are tightly coupled to those operations (e.g., earthquake directly shakes the lifting device).

- The second method for using an ET is similar to the first method, but instead demonstrates how other possible events or conditions could exacerbate the potential accident (see AIChE 1989). Such ETs are sometimes termed post-incident (or post-accident) analyses to identify incident outcomes. For example, an ET developed for a large leakage of pressurized flammable material from an isolated liquid propane gas storage tank might include event headings such as immediate ignition, delayed ignition, flash fire, ignited jet point at liquid propane gas tank, and wind to populated area. Similarly, phenomenological ETs are used to describe the possible modes of containment behavior in the post-core-damage phase of nuclear reactor plants.

  This type of application is appropriate for dealing with potential event sequences initiated by events originating offsite or outside of the repository operational areas such as range fires, toxic releases from transportation accidents, military or industrial hazards, or aircraft crashes that are not tightly coupled to the repository operational functions.

The first part of the ETA involves the probability that a harmful agent interacts with the facility or repository operational equipment.

The remaining discussion applies the pre-incident style of ETs as the primary application in the PSA.

The placement of events across the top of the ET can represent either the time sequence in which the events occur, proceeding left to right, or some other logical order reflecting operational dependencies (or conditions, as noted previously). Initially, the events can be ordered by temporal, functional, or hardware relationships, but the analyst may iterate to determine the best order to simplify the analysis or to clarify the presentation. Typically, a temporal ordering is used initially based on a process flow diagram, an operational description, or a pre-analysis such as an Event Sequence Diagram (see Section 10.1). However, functional or hardware dependencies should be considered, as in cases in which a given failure mode may imply the guaranteed failure of one or more other events in the headings.

For a given IE, the analyst must identify the safety functions that must be performed to control the sources of energy and radiation hazards in the facility. Such safety functions can be provided by active systems through automatic or manual actuation, by passive systems that provide barriers or containment, or from the natural or inherent feedback in the facility. As noted, the success criteria for each function must be unambiguously defined.

Starting with the IE, the analyst must postulate the success or failure of each function or system in the context of boundary conditions established by the states of the functions or systems in the ET headings. As noted, an event heading may connote the presence or absence of an enabling condition (e.g., temperature exceeds normal operating range or operator by-passes interlock). When the analyst considers a succeeding event, such as crane prevents lift beyond prescribed height, the probability of failure may depend on the operating temperature (i.e., one probability of failure based on random hardware failures or human error is used when temperatures are normal, but perhaps a higher probability is assigned when the temperature is abnormally high). This method models the dependency on prior conditions. For conservatism an ET may be constructed such that the abnormal temperature guarantees failure (i.e., has a probability of 1.0 that the crane lift height exceeds the limit).

7.1.4 Details of Approach

7.1.4.1 Constructing an Event Tree

Figure 7-3 summarizes the tasks in required to construct and evaluate an ET. The steps are described in Section 7.1.4.2.

ETs can be constructed at both a functional level and a system level.

Functional level ETs are developed at a relatively high level and serve to order and depict the safety functions according to the mitigating requirements of a given IE. The functional ET can also be used to depict contingent events that may result only if a precursor or conditioning event occurs (e.g., fire occurs after waste form is dropped). Functional ETs are generally simple or short, but each event heading in the functional ET can be supported by a complex FT.

FT linking is used to quantify the sequence frequencies. Dependencies between functions, or their supporting systems, are flushed out when the minimal cutsets are determined (see Section 7.2) for the sequence FT.

If there are potential dependencies between the functional event headings (e.g., two or more functional events depend on the same source of electrical power or the same HA), then a system level ET may be required to understand the dependencies. A complete system heading ET that depicts all of the conditional probabilities and dependencies can be very complex or long.

One or more functional ETs should be developed for each credible IE that has been selected for analysis from the respective Internal or External Events Hazards Analysis. The ET is a primary tool for defining potential accident sequences. As noted, for some complex operations it may be necessary to draw an intermediate diagram known as an Event Sequence Diagram (see Section 10.1) to help simplify the ET.

As noted in Figure 7-3, before starting an ET, the analyst must the system. This familiarization should be done with the help of personnel from design and operations, radiological consequence analysts, a radiation protection program, and safety-specific analyses (e.g., fire hazards, or criticality). The description and results of the Internal (or External) Events Hazards Analysis are a starting place. If more design or operational details are available, such as plan and elevation drawings and concept of operations, the functional ET should go beyond the discussion of potential events and consequences that may be speculative in the hazards analysis.

If necessary to understand the operations and how potential accidents could evolve, the ET analyst must acquire or draw a process flow diagram that shows each operation that interacts with the waste form (e.g., lifts, moves, and lowers). If necessary, an Event Sequence Diagram should be completed (see Section 10.1) to indicate success paths in the operations and how various event sequences may develop:

- For each operation in the system whose malfunction could impact the waste form, define an IE (e.g., crane drops waste form; shield door closes on waste form)

- From an inspection of the flow diagram, system layout, or event sequence diagram, list and order all of the subsequent events that could possibly happen after the IE has occurred. Since the event sequences that lead to release of radioactive material to the environment are the events of importance to the repository PSA, the analyst must consider all possibilities. Subsequent screening and analyses will filter out impossible, incredible, or insignificant event. Some events that may come to play in one or more sequences at the repository include:

  - Waste form containment is breached

  - Fire occurs concurrently

  - Waste form releases mass of radioactive material (amount may differ with or without concurrent fire).

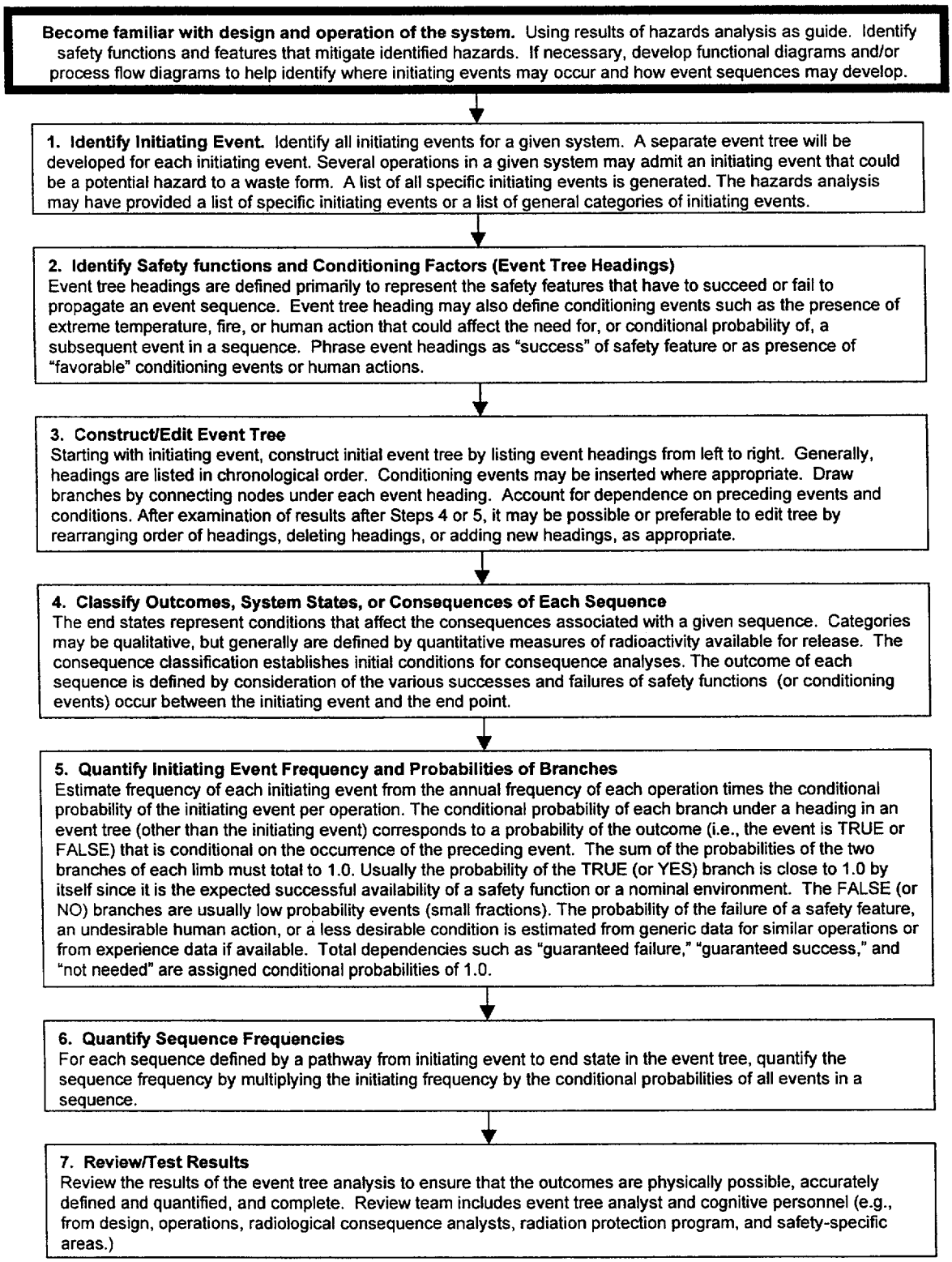


Figure 7-3. Step in Event Tree Construction

The graphical development of the ET may be constructed by hand (using pencil and paper), as a spreadsheet program (e.g., Microsoft Excel), or semi-automatically using special-purpose software such as a probabilistic risk analysis (PRA) workstation (e.g., SAPHIRE). Pencil and paper are recommended for initial conceptualization and ET simplification. A more refined ET can be constructed in a spreadsheet format that can also be used for quantifying sequences involving simple or moderately complex cases. If FT linking is to be used, then the final ET has to be constructed and quantified using a computer program such as SAPHIRE (Russel et al. 1994).

7.1.4.2 Steps in ET Construction

7.1.4.2.1 Identify the Initiating Event

The IE for each ET should be identified from a hazards analysis as an event that has the possibility of leading to an exposure to, or release of, radioactivity. In addition, the event must have been quantitatively screened in (found credible) in the hazards analysis. The IE will usually be an internal event that can impact energy or damage a waste form, such as crane drops [spent nuclear fuel] SNF canister. The IE could also be a fire (external or internal) or another external event (man-made or natural phenomena) such as loss of offsite power, aircraft crashes into waste handling building, or earthquake at waste handling building site.

In general, it is necessary at the outset to define the specific purpose of the ET analysis since concerns associated with the possible outcomes (e.g., public doses versus worker exposures) will influence the event headings, success criteria, and structure of the tree.

7.1.4.2.2 Identify Safety Functions and Conditioning Factors (ET Headings)

For each particular IE that is postulated to occur in a given operational area, an ET is constructed by listing the event headings across the top of the page. Event headings primarily represent the various event possibilities that represent the safety functions or systems that are necessary to mitigate the potential consequences following the IE. Such event headings may represent passive barriers, automatic safety systems, or alarms to alert operators. Thus, in the case of crane drops SNF canister, maintaining the integrity of the canister provides the safety function of containment of radioactivity. The ET heading could be canister is not breached (conditional on being dropped). Another safety function could be HVAC/HEPA filters exhaust air.

However, the headings may also represent conditioning events such as "building containment intact," which, when placed ahead (to the left) of "HVAC/HEPA filters exhaust air," provide a structure for conditioning the probability of failure of "HVAC/HEPA filters exhaust air." That is, if the event titled "building containment intact" is false (NO branch), then the conditional probability is 1.0 (guaranteed failure) that "HVAC/HEPA filters exhaust air" is false. Otherwise, when "building containment intact" is true (YES branch), then the probability that "HVAC/HEPA filters exhaust air" is false depends on the reliability of the HVAC/HEPA filter system. Other conditioning events may represent environmental factors such as temperature anomalies caused by an upstream event or consequential fire.

In some systems there may be a mutual dependence of all active safety functions on a single support active system, such as an onsite power supply. The ET for such a situation should use

the conditioning event "electric power available" early in the event headings. The FALSE branch would then result in a series of guaranteed failures and a simplified ET. Otherwise, the vulnerability posed by the power supply may not be realized until after the FT linking and boolean reduction is performed. If the safety functions and support systems have been designated a priori to be highly-reliable, single-failure proof, or both, then the event heading titled "electric power available" need not be included in the ET since the combinations of dependent failures may be too complex and best handled through FT linking.

The event heading may also represent a HA such as an explicit kind of conditioning event such as "operator installs proper lifting yoke" or an operational condition such as "operator maintains air seals on building containment."

7.1.4.2.3 Construct or Edit the Event Tree

An ET is constructed conventionally left to right, beginning with the IE. Under each event heading, one or more sequence branch points (or nodes) are included to represent the two alternative pathways. Some ETs may use multiple branches, but multiple branches are not discussed here. The branch points may be drawn with two-pronged forks at each node, as illustrated in Figure 7-1, or as stair-steps, as illustrated in Figure 7-2.

The labels for the event headings are conventionally phrased such that an upward branch in the fork style (the convention to be used herein with the SAPHIRE computer software) represents that the heading is TRUE (branch labeled YES) indicates that the function is successful. For conditioning events, the upward breach represents (usually) the more favorable condition, tending toward successful mitigation or reduced consequences. The downward branch (labeled NO) represents the complementary situation (and probability) that is defined in the event heading, thus representing failure of the function or presence of the less desirable condition.

Although the example shown in Figure 7-1 was created with Microsoft Excel, the fork style is difficult to create by hand because changes and branching requires much re-drawing and re-positioning of lines on a page. However, fork-style ETs are very easily created and edited with a computer program such as SAPHIRE.

In the stair-step format (which is easy to implement in the Microsoft Excel spreadsheet program), the YES paths are represented by horizontal lines and the NO paths branch downward (see Figure 7-2).

One advantage of the fork style is the clearer depiction of dependent events (e.g., "guaranteed failure" or "not needed" are shown as horizontal paths that pass through a node without branching up or down). By contrast, in the stair-step style, dependent events resemble success branches unless they are labeled as "guaranteed failure" or "not needed," or are depicted by a dotted line rather than a solid line.

In some instances, the analyst may restructure the headings of the ET to better represent dependencies on conditional or precursor events, or to simplify the ET. This process may occur iteratively after Step 4 in Figure 7-3 is performed.

If the outcomes (i.e., system states, or amounts of material released) of several sequences are the same or nearly the same, some event headings may be seen to be irrelevant to understanding and quantifying the risk. Even though the headings may introduce branching and extra sequences that could occur, the overall frequency of an exposure or release of a given magnitude would be the sum over these sequences. If some of the headings are deleted or subsumed in other headings, a simpler, but sufficient representation of the risk is achieved (see examples in Section 7.1.5).

7.1.4.2.4 Classify the Outcomes, System States, or Consequences of Each Sequence

The endpoint of each event sequence represents a potential state of the system. In ETs for nuclear reactor plants, the end points of the system analysis (i.e., the level 1 PRA) are called plant damage states. For the repository PSA, the endpoints will be termed system states or consequence categories. The end states represent conditions that affect the consequences associated with a given sequence.

For example, for an ET that addresses potential releases to the public, categories of consequences can be very qualitative in preliminary or scoping analyses (e.g., no release, small release – gases only, and small release – gases and particulates). Alternatively, the qualitative consequence categories can be more explicitly tied to the material at risk (e.g., no release, one fuel assembly breached, and basket of 8 fuel assemblies breached). The end states that result in no consequences of interest are usually labeled OK as shorthand.

The outcome of each sequence is defined by consideration of the various successes and failures of safety functions (or conditioning events) that must occur between the IE and the end point. For example, in a sequence where one spent fuel assembly has dropped and breached and the conditioning event "building containment intact" is FALSE, the release of radioactivity (gases, volatiles, and particulates) can escape to the atmosphere unimpeded and without the benefit of being filtered or released from an elevated stack. In a different sequence in which one spent fuel assembly has dropped and breached, the conditioning event "building containment intact" is TRUE and the "HVAC/HEPA filters exhaust air" is TRUE.

The consequence classification establishes initial conditions for the consequence analyses described in Section 8. The source terms, leak path factors, and atmospheric dispersion factors, including credit for stack height (appropriate to the consequence category) are used in the consequence analyses.

7.1.4.2.5 Quantify Initiating Event Frequency and Probabilities of Branches

The frequencies of IEs for internal hazards are estimated from the product of the annual frequency of each operation and the conditional probability of the IE per operation. For example, the frequency of a canister drop is estimated by the product of the frequency of canister lifts (i.e., the number per year) and the conditional probability of dropping the canister per lift. The annual frequencies of each operational step are determined from programmatic information that quantifies the number of transport casks, spent fuel assemblies, spent fuel canisters, high-level radioactive waste canisters, and WPs that are expected to be processed each year during the

preclosure operations. Per 10 CFR 63.112, the PSA will assume maximum throughput rate in these analyses.

Unless the ET is to be quantified using FT linking, branch point probabilities must be specified directly in the ET to aid in sequence quantification (see Step 6 in Figure 7-3).

The conditional probability of each enabling event (usually a failure of some preventive or mitigative feature such as a drop of a waste form) is estimated from the failure rates and repair times applicable to the event represented in the heading. Since little, or no, repository-specific data on equipment reliability is available, the ET and FT analyses will use generic data for similar operations. In many cases for the preliminary event sequence screening analyses, conservative probabilities are assumed for the conditional events (e.g., assuming a probability of 1.0 that all fuel rods breach in a drop sequence). This conservatism may be warranted in the early screening process because design criteria or design details are not in place.

Each branch under a heading in an ET (other than the IE) corresponds to a probability of the outcome (i.e., the event is TRUE or FALSE) that is conditional on the occurrence of the preceding event. The sum of the probabilities of the branches under each event heading in a given event sequence must total to 1.0. Usually the probability of the YES (or TRUE) branch is close to 1.0 by itself since it is expected to be available to successfully perform a safety function or to ensure a nominal operating environment. The FALSE (or NO) branches are usually low probability events (small fractions).

The branch-point probability values may be developed from databases of experience data) from qualified estimates of similar systems or events (see Section 7.5), from human reliability analysis (HRA, as described in Section 7.3), or from FT analyses (FTA, as described in Section 7.2). If the probabilities are independent of the preceding event, the application of data or analyses is relatively straightforward. If the probabilities are dependent (conditional) on the outcome of the preceding event, then appropriate adjustments must be made.

In FTA, adjustments are made within the structure of the FT as boundary conditions (e.g., house events; see Section 7.2). If experience data or estimates from similar systems are available for the specific condition, the analysis is straightforward. However, it may be necessary for the analyst to make reasoned estimates of the effects of previous events on the probability of interest. In such cases, the analyst must provide justification for the adjustment. For HRA, outcomes of previous events represent different performance shaping factors and the adjustments are accounted for in the quantification. For example, in the aftermath of an earthquake, repository operators may experience extra emotional stress that may lead to a higher probability of human error (see Section 7.3).

Some event branching may represent split fractions of highly likely events (e.g., 0.5 and 0.5 for equally likely conditions or 0.75 and 0.25 for cases where one branch is more likely than the other branch). For example, a conditioning event might represent the mix of waste forms being processed that possess different source term characteristics. In this example, 75 percent of the canisters may contain intact spent fuel assemblies and 25 percent of the canisters may contain fuel-rod segments. Depending on what these conditions imply, the event heading "canister contains intact assemblies" might be found late or early in the tree. If the condition affects only

the final consequence, then the event would be placed late and the number of release sequences would double. If the condition could affect the likelihood of a breach given a drop (e.g., the canisters containing fuel rod segments may be designed to withstand all credible drops without a breach), then the event heading would be placed earlier in the tree.

7.1.4.2.6 Quantify Sequence Frequencies

Unless FT linking is used, then the frequency of each sequence on the ET is determined by the multiplication of the frequency of the IE times all of the conditional probabilities appearing in the sequence of events. This method of ET quantification is typically referred to as "Large Event Tree Methodology" irrespective of the actual size of the trees. For example, if the frequency of the IE is 2×10^{-2} per year, the conditional probability of breach is 0.01, and the conditional probability of the HVAC/HEPA filter being unavailable is 0.001, the frequency of a sequence involving the release of gases, volatiles, and particulates is 2×10^{-7} per year (i.e., $2 \times 10^{-2} \times 0.01 \times 0.001$). The frequency of a sequence involving a drop, a breach, and a release of gases and volatiles through the HVAC/HEPA filter is event is 1.99×10^{-4} per year (i.e., $2 \times 10^{-2} \times 0.01 \times 0.999$). The frequency of a sequence involving a drop, no breach, and, therefore, no release is 1.98×10^{-2} per year (i.e., $2 \times 10^{-2} \times 0.99 \times 1.00$). Note that the sum of the frequencies of all of the event sequences equals the IE frequency: $2 \times 10^{-7} + 1.99 \times 10^{-4} + 1.98 \times 10^{-2} = 2 \times 10^{-2}$.

Unless FT linking is used, the event sequence frequencies may be calculated by hand using a calculator or with spreadsheet formulas (e.g., the Microsoft Excel spreadsheet program), or through the use of a computer software routine in a PRA workstation (e.g., SAPHIRE).

A separate FT is created for each event sequence if FT linking is used. These FTs are created internally using PRA software such as SAPHIRE. The ET headings that make up each sequence are inputs into a single AND gate. The single AND gate is the top event of the FT (see Section 7.2). The sequence FT is created by linking all of the event-heading FTs into a single FT. The sequence frequency is quantified by solving the FT using a computer program like SAPHIRE. The boolean algebra routine reduces a complex sequence expression to a table of minimal cutsets (see Section 7.2). Any dependencies between basic events modeled in the respective FTs for the event headings are revealed in the minimal cutsets. Because the ETs and systems used in the preclosure operations are not complex, FT linking is unlikely to be necessary in the repository PSA, particularly in the application for construction authorization (CA). When more design details are available, FT linking may be necessary to quantify event sequences and to support other analyses such as importance or sensitivity studies.

The results of the event sequence frequency analysis are used to classify event sequences as Category 1, Category 2, or BC2 Event Sequences (see Section 7.6). The ET page layout can be expanded to include a column that indicates the category of each event sequence in the tree.

7.1.4.2.7 Review of Test Results

The ET analyst and cognitive associates should review the results of the analysis to ensure that the outcomes are physically possible, accurately defined and quantified, and complete (this is an ideal, but omissions should be noted even if done deliberately for modeling purposes). As with

FT analysis, poor input data or erroneous information will lead to wrong and usually worthless ETs. The review team should include an ET analyst and cognizant personnel (e.g., personnel from design, operations, radiological consequence analysis, radiation protection programs, and safety-specific areas).

7.1.5 Examples of Applications of Event Tree Analysis

This section presents a series of ETs that were developed for instructional purposes. The three example ETs described each involve a hypothetical uncontrolled descent of a WP transporter train. The example variations between the three trees are constructed to illustrate one or more of the factors to be considered.

The hypothetical situation involves the transport of a WP from the surface facilities to the subsurface repository. The WP is enclosed in a shielded transporter car and hauled by one or more locomotives. The locomotives and transporter car are equipped with one or more brake systems, control and actuation systems that monitor and control the speed, and automatic and manual actuation systems for the brakes. During a trip down the North Ramp, an uncontrolled descent is initiated.

For illustration purposes, cases are illustrated for three different IEs. In the first case an undefined random failure in a mechanical, electrical, electronic, or software system causes the initiation of the event. In the second instance, an on-board fire on the controlling locomotive is assumed to result in an uncontrolled descent. In the third case, a human error is assumed to initiate the sequence of events leading to an uncontrolled descent.

7.1.5.1 Example 1: Random Event Initiates Uncontrolled Descent

Figure 7-4 illustrates how a hypothetical sequence of events, initiated by a random failure, can lead to or exacerbate the release of radioactive material. The event headings shown in the figure are essentially self-explanatory, but are elaborated as necessary. Recall that definitions of event headings must include unambiguous success criteria.

7.1.5.1.1 Event Tree Construction

The event headings in Figure 7-4 are arranged essentially in chronological order. They represent safety functions and conditioning events, as will be explained below. For completeness, one or more of the event headings could be defined to represent the successful operation of the mechanical, air, or hydraulic equipment of the brake system(s). For simplicity, it is assumed that these failure modes are included in the two headings that involve stopping the train. Alternatively, it may have been shown in a preliminary scoping analysis that the probability of a brake system failure is very small and only contributes to an incredible sequence. Therefore, the revised tree is simplified.

- **Uncontrolled Descent Initiated**–A random failure in a mechanical, electrical, electronic, or software system on-board the controlling locomotive causes the train to speed up.

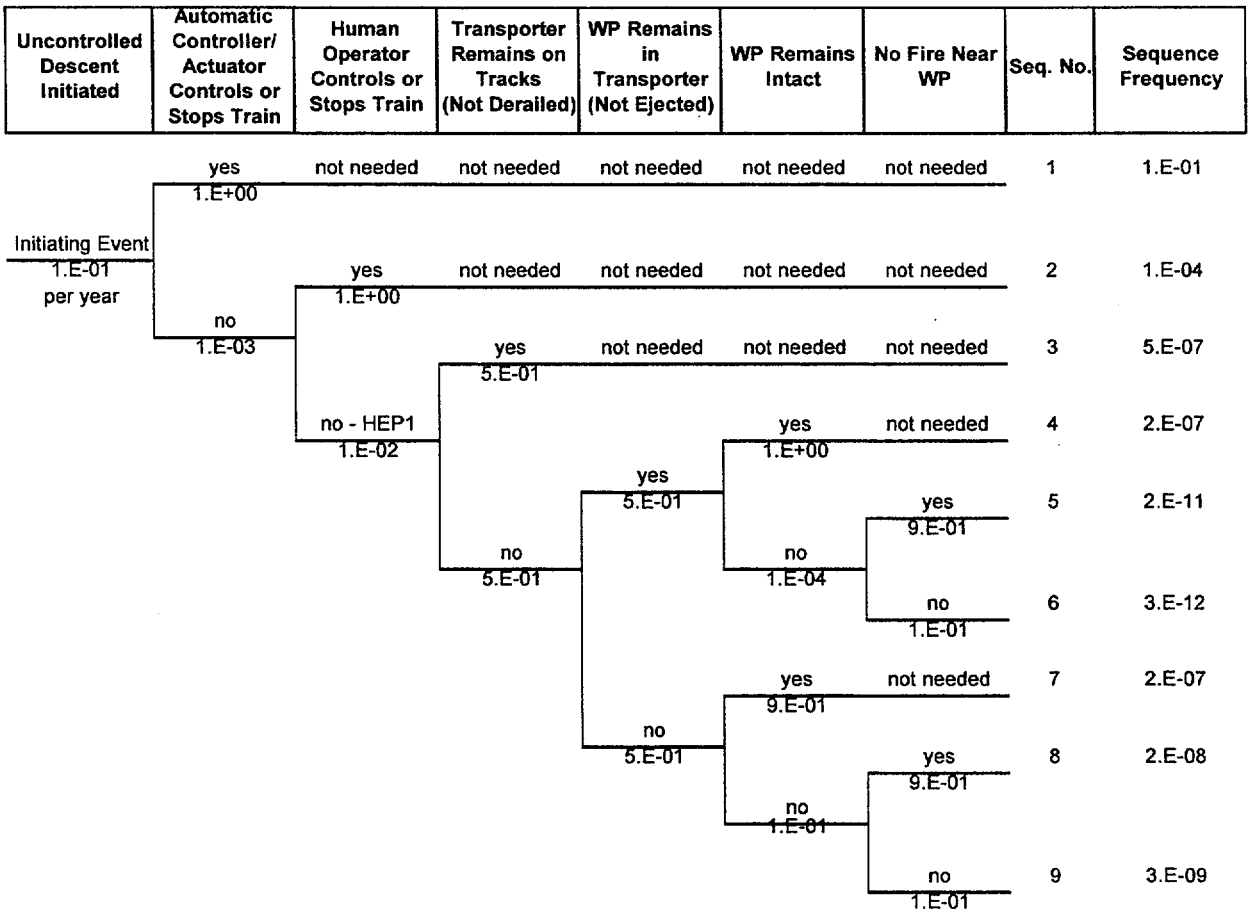


Figure 7-4. Event Tree for Hypothetical Uncontrolled Descent Due to Random-Failure Initiator

- **Automatic Controller/Actuator Controls or Stops Train**–In this example it is assumed that the initiating failure has not disabled the automatic control system that monitors speed and sends signals to slow down or to apply emergency brakes when needed. This heading represents a safety function.

- **Human Operator Controls or Stops Train**–In this example, it is assumed that the initiating failure has not disabled the manual control system that permits a human operator, as a backup to the automatic system, to decrease the train speed or to apply emergency brakes. This heading represents a safety function.

- **Transporter Remains on Tracks (not derailed)**–There is a curve in the track at the bottom of the North Ramp. If the runaway train attains sufficient speed, it will be expected to derail and hit the tunnel walls. If the transporter train remains on the track (even at high speed) it will eventually slow down and will not experience any hard impacts. This heading represents a conditioning event.

- **Waste Package Remains in Transporter (not ejected)**–The WP will be restrained inside the transporter. In the event of a derailment during the runaway, the impact on the WP is expected to be reduced by energy absorption by the transporter car. If the WP

is ejected, however, it could impinge on ground support structures, track rails, rock protrusions, and other items, and all of the kinetic energy would be imparted to the WP. This heading represents a conditioning event. The response to this heading affects the probability of breaching the WP. Although not developed in this example, the response to this heading could also affect the assumed source term if the number of fuel rods breached is correlated to the impact energy.

- **Waste Package Remains Intact**–This is the key event heading with respect to a radioactive release. If the WP is not breached, no radioactivity is assumed to be released. Otherwise, depending on the degree of breaching, varying amounts of radioactivity may be released.

  The WP is designed to withstand credible impacts. The repository safety strategy is to demonstrate that impact on a WP from an uncontrolled transporter is incredible. The event analysis will provide support to that conclusion.

  Nevertheless, it is possible for the WP involved in the derailment to have a manufacturing defect or out-of-specification welded lid seal. At some probability, such defective WPs may breach in an impact that is within the design basis of the WP.

- **No Fire Near Waste Package**–This heading is included in this example to illustrate the modeling of a post-accident environment that could exacerbate consequences. In the example the heading is applied only to sequences where the WP is already breached. The presence of a fire near the WP might increase the fraction of radionuclides that are released from the spent fuel rods inside the breached WP. The source of the fire is not defined in this example, but could result from an electrical fire initiated when the transporter crashes into an electrical supply cabinet. In other ET development involving intense fires, it may be appropriate to order the fire event ahead of the WP Remains Intact event to enable the fire to be a cause of the WP breach as well as a mechanism for exacerbating the release.

  The ET is constructed with consideration given to dependencies and conditioning events. The construction leads to the defining of the nine sequences, as labeled in "Seq. No." in Figure 7-4. The sequence numbers are used to describe the bases for the construction.

  - Sequence 1–The automatic system responds correctly to the IE. None of the other event headings come into play and are labeled "not needed." There is no radioactive material released in this sequence.

  - Sequence 2–After the automatic system fails to respond to the IE, the train operator correctly intervenes. None of the remaining event headings come into play in mitigating the event sequence and are labeled "not needed." There is no radioactive material released in this sequence.

  - Sequence 3–After the automatic system and the train operator fail to respond to the IE, the train descends uncontrolled to the bottom of the North Ramp without

derailing. Because no impact results, the remaining event headings do not come into play and are labeled "not needed." There is no radioactive material released in this sequence.

- Sequence 4–The transporter derails and impacts the tunnel walls. The WP remains inside the transporter and is not breached. The fire issue is not relevant (see the previous discussion) and is labeled "not needed." There is no radioactive material released in this sequence.

- Sequences 5 and 6–The transporter derails and impacts the tunnel walls. The WP remains inside the transporter and is breached. In Sequence 5 no fire is present; Sequence 6 includes a fire. Both sequences result in a release. Because of the fire, the amount of radioactive material released in Sequence 6 may be greater than the amount released in Sequence 5.

- Sequence 7–The transporter derails and impacts the tunnel walls. The WP is ejected from the transporter and may impact walls, rails, or other items, but is not breached. The fire issue is not relevant (see the previous discussion) and is labeled "not needed." There is no radioactive material released in this sequence.

- Sequences 8 and 9–The transporter derails and impacts the tunnel walls. The WP is ejected from the transporter and may impact walls, rails, or other items, but is not breached. In Sequence 8 no fire is present; Sequence 9 includes a fire. Both sequences result in a release of radioactive material. Because of the fire, the amount of radioactive material released in Sequence 6 may be greater than the amount released in Sequence 5.

After constructing the ET, the analyst proceeds with sequence frequency quantification, as described in the following Section.

7.1.5.1.2 Event Tree Quantification

For illustration purposes arbitrary values are assigned to the IE and the branch points in Figure 7-4. Rationale statements are provided for the parameters used in the example.

The values provided in the Figure use scientific notation with one significant digit. Therefore, the probabilities of most of the success branches are shown as 1×10^{0}. The value of each success branch is actually the complement of the probability of the failure branch (i.e., if p(failure) = 1×10^{-3}, then the p(success) = [1 – p(failure)] = [1 – (1×10^{-3})] = 9.99×10^{-1} [which is rounded to 1×10^{0}]).

Note that if more than one branch appears under a given event heading, the values of the probabilities may be different in the respective branches to reflect dependencies or conditions occurring earlier in the tree. Specific instances are described in the following paragraphs.

- **Uncontrolled Descent Initiated**–A frequency of 1×10^{-1} per year is assigned. The emplacement rate for WPs is assumed to be approximately 500 per year. Based on

actuarial data (if available) or analysis (such as FT), if it is determined that an uncontrolled descent could be initiated 2 times in 10,000 trips; the probability would be 2×10^{-4} per demand. Therefore, the assumed frequency is calculated as the product of 500 per year and 2×10^{-4} per demand, or 1×10^{-1} per year.

- **Automatic Controller/Actuator Controls or Stops Train**–Based on actuarial data (if available) or analysis (such as FT), it is determined that the failure rate of the control system is 1×10^{-3}. The complementary probability is $(1\text{-}1 \times 10^{-3}) = 9.99 \times 10^{-1}$ (which is rounded to 1×10^{0}).

- **Human Operator Controls or Stops Train**–Using HRA (see Section 7.3) that take into consideration the situational factors (performance shaping factors) that account for such factors as available instrumentation, control layout, and time pressure on the human, the human error probability (HEP), labeled HEP1, is estimated to be 1×10^{-2} per demand. The complementary probability is $(1\text{-}1 \times 10^{-2}) = 9.9 \times 10^{-1}$ (which is rounded to 1×10^{0}).

- **Transporter Remains on Tracks (not derailed)**–Calculations (hypothetical) indicate that the train may achieve the critical speed for derailing near the middle of the curve if the runaway starts more than halfway up the ramp. Therefore, a probability of derailment of 0.5 is assumed.

  The complementary probability is $(1\text{-}0.5) = 0.5$.

- **Waste Package Remains in Transporter (not ejected)**–No analyses are available for the response of the transporter car and WP to a crash into a tunnel wall. Therefore, it is assumed that there is equal chance of success and failure. Therefore, a probability of WP ejection of 0.5 is assumed and a probability of derailment of 0.5 is assumed. The complementary probability is $(1\text{-}0.5) = 0.5$.

- **Waste Package Remains Intact**–The WP is designed to withstand credible impacts. It is possible for the WP involved in the derailment to have a manufacturing defect or out-of-specification welded lid seal. These weak WPs may breach in an impact that is within the WP design basis. The probability of WP breach is assumed to be correlated with the relative impacts of the WP ejection and non-ejection cases.

  The probability of WP breach when the WP remains in the transporter is assumed to be 1×10^{-4} per demand. The complementary probability is $(1\text{-}1 \times 10^{-4}) = 9.999 \times 10^{-1}$ (which is rounded to 1×10^{0}).

  The probability of WP breach when the WP is ejected from the transporter is assumed to be 1×10^{-1} per demand. The complementary probability is $(1\text{-}1 \times 10^{-1}) = 9.9 \times 10^{-1}$ (which is rounded to 1×10^{0}).

- **No Fire Near Waste Package**–No analysis is available to evaluate whether or not the construction material in the transporter car, or other sources, will ignite on impact with the wall. It is assumed that the probability is 1×10^{-1} per demand. The complementary probability is $(1\text{-}1 \times 10^{-1}) = 9.9 \times 10^{-1}$ (which is rounded to 1×10^{0}).

Using the (hypothetical) values described above, and presented in Figure 7-4, each sequence is quantified by multiplying the frequency of the IE and the probabilities of each event that occurs in that sequence. For example, the frequency of Sequence 1 is simply the product of the probability of the IE (1×10^{-1} per year) and the probability that the automatic control system functions (approximately 1.0). The result is 1×10^{-1} per year.

The frequency of Sequence 9 is more complex, involving the product of the IE frequency and six probability values.

The example in Figure 7-4 was constructed and quantified using the Microsoft Excel spreadsheet program.

Note that the values used for preliminary ET analyses may be viewed as point estimates and are generally assumed to be the median values. As described in Section 9, median values propagate through multiplication; thus, the sequence frequencies shown in Figure 7-4 are median values. For sequence frequency binning, however, the mean value of frequencies will be used. To obtain the mean values, uncertainties are quantified as described in Section 9. The IE frequency and each probability value will have a probability distribution function (PDF) assigned to it; usually a log normal distribution defined by its median value and an error factor (EF). The PDFs are then combined analytically (if simple) or using a Monte Carlo routine (for more complex problems).

7.1.5.1.3 Interpretation of Event Tree

The sequences of interest are those having "yes" in the Release column of Figure 7-3 (i.e., sequences 5, 6, 8, and 9). None of these sequences have a median frequency greater than 1×10^{-6} per year, so all of the examples have frequencies that are BC2. If it were desired to show margins to regulatory limits, consequence analyses would be performed for these sequences using methods described in Section 8.

7.1.5.1.4 Simplification of Event Trees

Consequence Binning–Consequence analyses may indicate that the release fractions from a breached WP do not vary significantly, regardless of whether or not a credible fire is present. A credible fire, in this case, is defined as one that could be initiated as a result of the runaway rather than an independent fire initiated by petroleum-based fuels. If this is the case, the ET heading "No Fire Near WP" can be eliminated because the resulting dose consequences are not different enough to warrant carrying the distinction forward in the ET. In this situation, Sequences 5 and 6 would merge into one sequence (labeled as 5A) and Sequences 8 and 9 would merge (labeled as 8A). The frequency of Sequence 5A is essentially the same as the former Sequence 5 and the frequency of Sequence 8A is essentially the same as that for Sequence 8. The ET would now have only 7 outcome sequences and only two sequences that have radioactive material releases. The modified tree is not shown.

This simplification is applied in the other examples presented in Sections 7.1.5.2 and 7.1.5.3.

Event Heading Definitions/Success Criteria–In this situation the design criteria for the WP will not withstand the potential maximum impact during the runaway. Here one or more branches under the heading "WP Remains Intact" may be candidates for simplification or deletion. The discussion of this situation starts with the original ET presented in Figure 7-4.

In one case the WP may breach whenever it is ejected from the transporter at the runaway speed. In this case the "yes" branch is eliminated (eliminates Sequence 7 in Figure 7-4) and the probability of the "no" branch becomes 1.0 (dependent failure guaranteed by the ejection). This modification would increase the frequencies of Sequences 8 and 9 by a factor of 10 (the inverse of 1×10^{-1} per demand). The probability of WP failure when it remains in the transporter might also be increased (e.g., to 1×10^{-2} per demand), thus affecting the frequencies of Sequences 5 and 6. This modified (simplified) ET is presented in Figure 7-5.

In another case, where it is shown or assumed that it does not matter whether or not the WP is ejected from the transporter, the heading "WP Remains in Transporter (not ejected)" is irrelevant and can be deleted from the tree. Therefore, Sequences 4 through 7 are eliminated from the original ET. The frequencies of the releases in Sequences 8 and 9 increase. The heading "WP Remains Intact" could be merged with "Transporter Remains on Tracks (not derailed)" to further simplify the analysis (under these circumstances any derailment results in a release) or the headings could be retained to enhance communication of the events in the sequence and gain insights. This modified (simplified) ET is presented in Figure 7-6.

7.1.5.2 Example 2: On-board Fire Initiates Uncontrolled Descent

This example is presented to illustrate how a previously developed ET may be modified to represent other initiators. In particular, this example illustrates how the ET for the uncontrolled transporter descent, initiated by a random failure internal to its operational systems, can be modified to represent potential events initiated by a fire. Figure 7-7 illustrates this example.

7.1.5.2.1 Event Tree Construction

The ET depicted in Figure 7-4 and the event descriptions in Section 7.1.5.1.1 are used with modifications, as described in the following text. The ET is initially simplified by assuming that the event heading "No Fire Near WP" is irrelevant (see Section 7.1.5.1.1). The IE titled "Uncontrolled Descent Initiated" is not shown explicitly in this ET; it is a potential consequence of subsequent failure events.

The following event headings are used:

- **Fire Initiated in Transporter Locomotive**–This IE represents a fire that could occur in any of the electrical components and wiring in the controlling locomotive.

- **Fire Suppression System Extinguishes Fire**–The transporter locomotives will be equipped with automatic fire-suppression systems in accordance with the need defined through a fire hazards analysis. The successful operation of this system influences dependent events, as described below.

- **Automatic Controller/Actuator Controls or Stops Train**–In this example, two different pre-conditions are modeled. In the first case, shown in the upper portion of Figure 7-7, the fire suppression system is successful in extinguishing the fire before it causes failure of the automatic control system. However, the automatic control system could subsequently fail for other independent causes. Should such a failure occur, given that a runaway was initiated by the initial fire, the "no" branch is developed in the same manner as that depicted in Figure 7-4.

  In the case where "Fire Suppression System Extinguishes Fire" is unsuccessful (the no branch), it is assumed that there is a dependent failure; that is, a common-cause failure (CCF) of the function titled "Automatic Controller/Actuator Controls or Stops Train." This failure is given as "GF (CCF/Fire)" in Figure 7-7 to indicate a guaranteed failure due to the CCF.

- **Human Operator Controls or Stops Train**–For illustration it is assumed in this example that the human-actuated controls are not failed by the fire; however, the probability of human error is affected. In the upper portion of the ET depicted in Figure 7-7, following the independent failure of the automatic control system, the probability of human error is assumed to be the same as in Figure 7-4 (labeled as HEP1). In the lower portion of the ET, in the aftermath of the fire that progresses far enough to cause failure of the automatic control system, the operator may react with lower reliability because of the extra distractions and stresses. This probability is labeled as HEP2 in Figure 7-7.

- **Transporter Remains on Tracks (not derailed)**–Same as in Section 7.1.5.1.1.

- **Waste Package Remains in Transporter (not ejected)**–Same as in Section 7.1.5.1.1.

- **Waste Package Remains Intact**–Same as in Section 7.1.5.1.1.

7.1.5.2.2 Event Tree Quantification

This example will discuss the features of Figure 7-7 that are different than Figure 7-4.

- **Fire Initiated in Transporter Locomotive**–For illustration, an arbitrary frequency of 1×10^{-1} per year is specified. An actual analysis would apply actuarial data for electric locomotives.

- **Fire Suppression System Extinguishes Fire**–An estimate of the failure probability is developed from FT analysis or from actuarial data, supported by a fire-propagation analysis.

- **Automatic Controller/Actuator Controls or Stops Train**–If the fire suppression system is successful in extinguishing the fire before it causes failure of the automatic control system, the same value for independent failure from Figure 7-4 is used (i.e., 1×10^{-3} per demand).

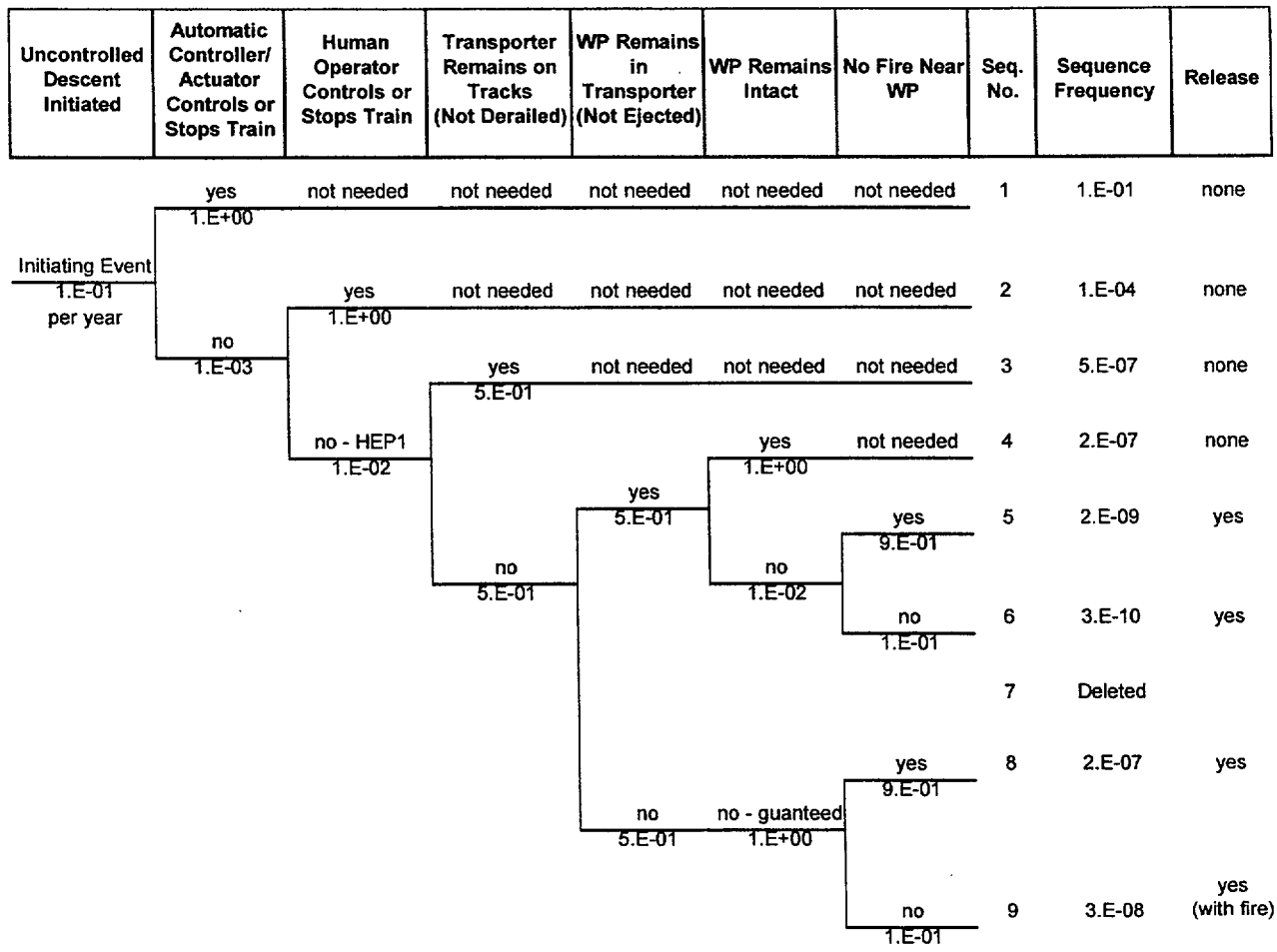


Figure 7-5. Simplified Event Tree for Hypothetical Uncontrolled Descent (First Example)

In the case where "Fire Suppression System Extinguishes Fire" is unsuccessful, the automatic system fails due to a CCF. This is given as "GF (CCF/Fire)" in Figure 7-7, and the conditional probability is 1.0.

- **Human Operator Controls or Stops Train**–In the upper portion of the tree (Figure 7-7) following the independent failure of the automatic control system, the probability of human error is assumed to be same as in Figure 7-4, labeled as HEP1. It is quantified as 1×10^{-2} per demand.

  In the lower portion of the tree, in the aftermath of the fire that progresses far enough to cause failure of the automatic control system, the operator may react with lower reliability because of extra distractions and stresses. This probability is labeled HEP2 (Figure 7-7). Using HRA (see Section 7.3) that accounts for the situational factors (performance shaping factors) that account for such factors as available instrumentation, control layout, and time pressure on the human, the HEP, labeled HEP2, is estimated to be higher by an order of magnitude (i.e., 1×10^{-1} per demand).

  The quantification of the remaining events in Figure 7-7 are the same as in Figure 7-4.

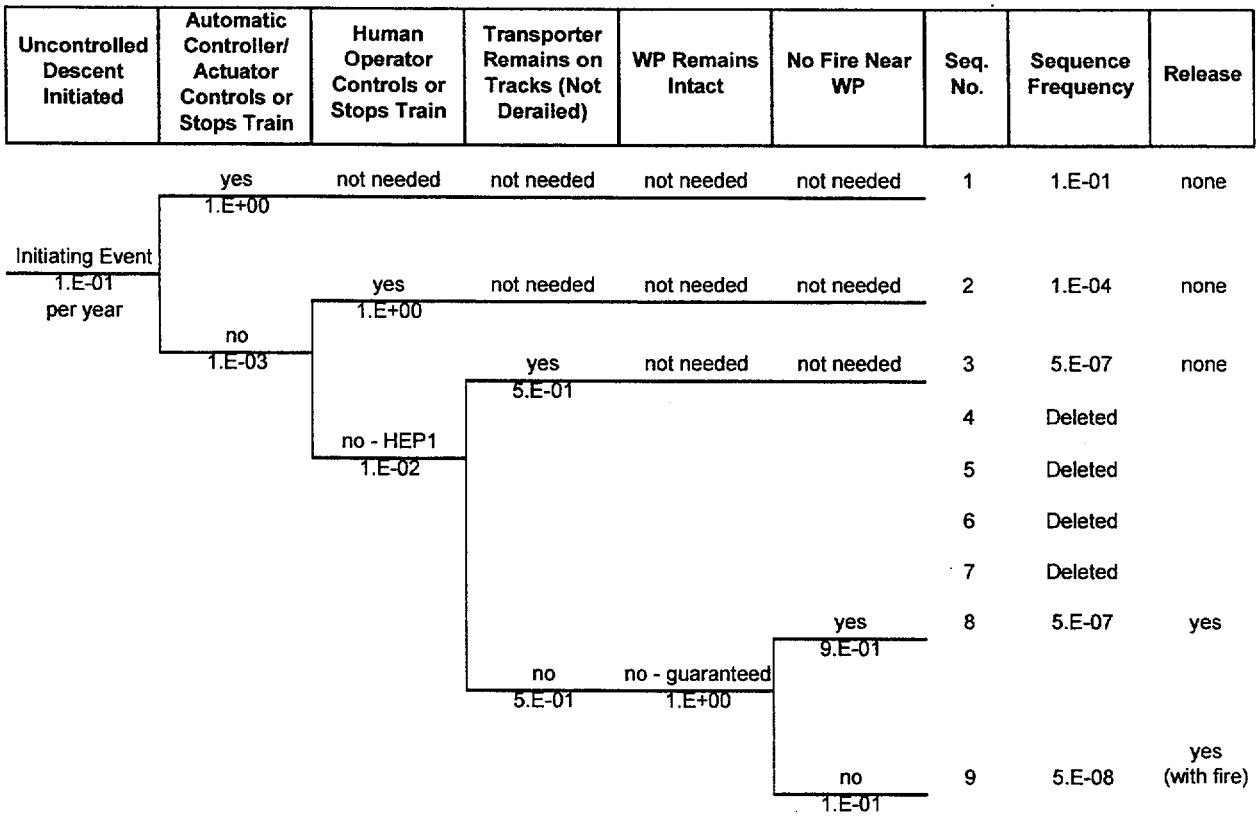


Figure 7-6. Simplified Event Tree for Hypothetical Uncontrolled Descent (Second Example)

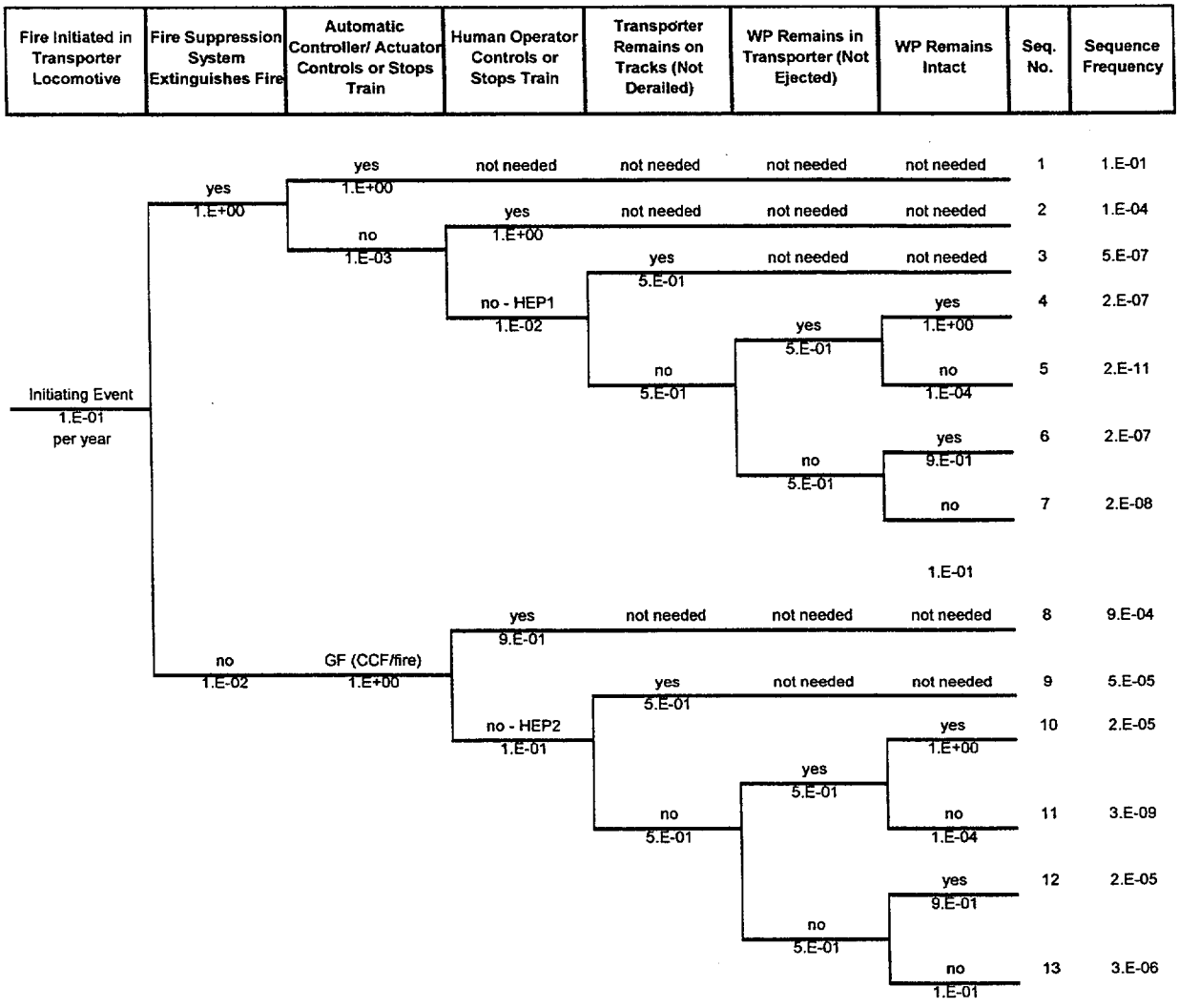
- **Transporter Remains on Tracks (not derailed)**–Same as in Section 7.1.5.1.2.
- **Waste Package Remains in Transporter (not ejected)**–Same as in Section 7.1.5.1.2.
- **Waste Package Remains Intact**–Same as in Section 7.1.5.1.2.

The quantification of sequence frequencies proceeds the same as described in Section 7.1.5.1.2, using the Microsoft Excel spreadsheet program.

7.1.5.3 Example 3: Human Operator Initiates Uncontrolled Descent

This example is presented to further illustrate how dependent events affect the construction and quantification of ETs.

In this example, it is assumed that an operator on the control locomotive or in a central control room commits an erroneous action that not only initiates an uncontrolled descent, but also disables all of the systems that can be used to control the speed or apply emergency brakes.



NOTE: GF = guaranteed fault.

Figure 7-7. Event Tree for Hypothetical Fire Initiated Uncontrolled Descent

7.1.5.3.1 Event Tree Construction

The example ET is shown in Figure 7-8. The event descriptions in Section 7.1.5.1.1 are used, with modifications as described in the following paragraphs. The tree is simplified by assuming that the event heading "No Fire Near WP" is irrelevant (see Section 7.1.5.1.1). The IE titled "Uncontrolled Descent Initiated" is not shown explicitly in this tree; it is a potential consequence of subsequent failure events.

The following event headings are used.

- **Uncontrolled Descent Initiated by Operator Error**–An operator on the control locomotive or in a central control room, commits an erroneous action that initiates an uncontrolled descent.

The event frequency is estimated to be 1×10^{-3} per year based on actuarial data or HRA.

- **Automatic Controller/Actuator Controls or Stops Train**–In this example, it is assumed that the initial operator error also causes a dependent (common-cause) failure of the automatic controller. This dependent, guaranteed failure deletes the chance for a success (yes) branch under this event heading. It is labeled "GF (CCF)" in Figure 7-8.

  The conditional failure probability is 1.0.

- **Human Operator Controls or Stops Train**–This event may be considered to be the same event as the IE and could be deleted from the tree structure. However, it could also be a true dependency where the initial operator error disables the system that an operator (not necessarily the same one) would attempt to use as an emergency action.

  For this example, a CCF is assumed, and no success branch is shown. The "no" branch is labeled "GF (CCF)" in Figure 7-8 with a conditional failure probability is 1.0.

  In other constructions, the probability of operator recovery might be included to generate a success branch under this event.

  The definitions and quantification of the remaining events in Figure 7-8 are the same as in Figure 7-4.

- **Transporter Remains on Tracks (not derailed)**–Same as in Section 7.1.5.1.1.

- **Waste Package Remains in Transporter (not ejected)**–Same as in Section 7.1.5.1.1.

- **Waste Package Remains Intact**–Same as in Section 7.1.5.1.1.

7.1.5.3.2 Quantification

The quantification of sequence frequencies proceeds the same as described in Section 7.1.5.1.2, using the Microsoft Excel spreadsheet program.

7.2 FAULT TREE ANALYSIS

7.2.1 Introduction

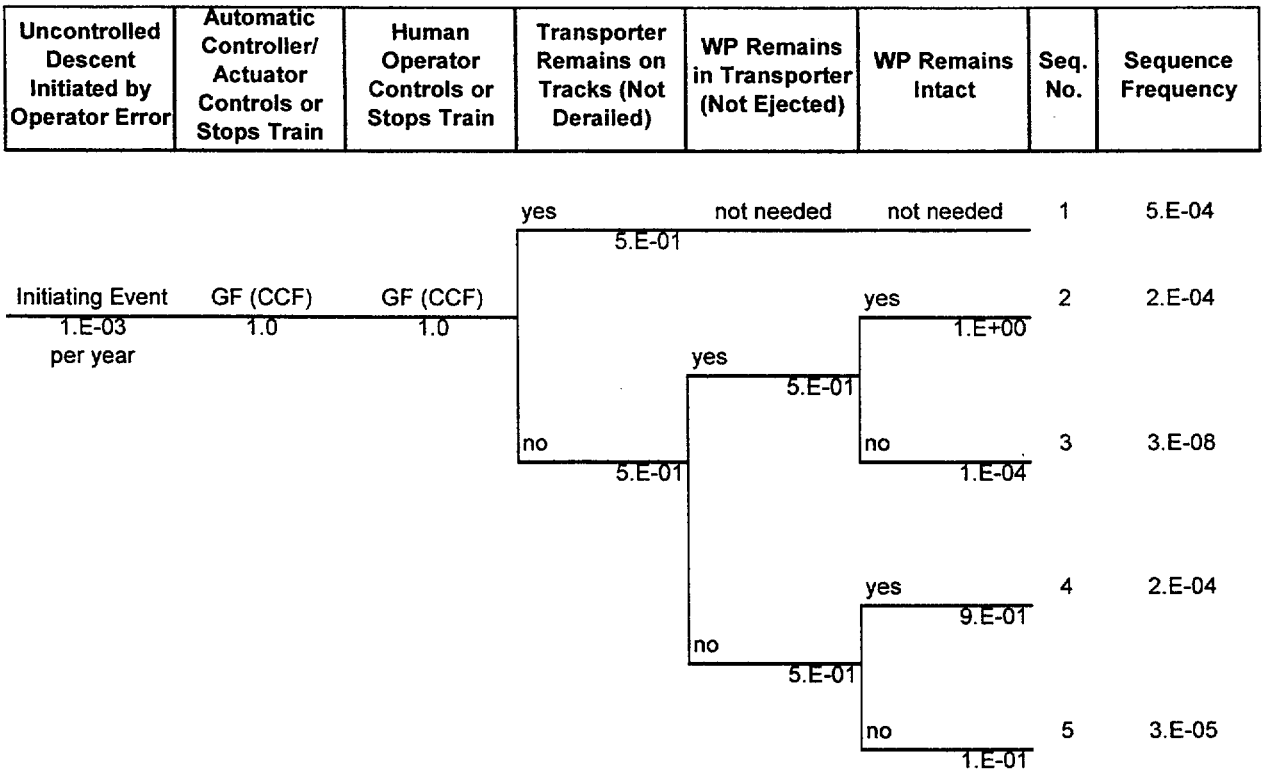
This section defines the bases and methodology for the construction and use of FTA in support of the PSA. Logic models of physical system are applied in FTA for the purpose of quantifying the probabilities of top events based on combinations of basic events that represent mechanical failures or human error. The use of FTA has application in 1) quantifying the frequency of IEs as well as the conditional probability of enabling events that contribute to event sequences, 2) explicit modeling and quantifying of dependencies between primary (front-line) safety systems and support systems, 3) top-down modeling of combinations of events that lead to an undesired outcome, including development of master logic diagrams, 4) defining how operation-specific controls and management measures can be used to prevent or mitigate releases of radioactivity, and 5) providing a structure for propagating uncertainties in basic events to the top event.

This section provides a cursory, focused guide to the construction, application, and evaluation (both qualitative and quantitative) of FT models. While some concepts are universal to all FTAs, the applications in this section are focused on support of the PSA for a repository. The guide is not meant to be a textbook or exhaustive. Where appropriate, reference is made to literature for additional information.

7.2.2 Overview of Approach

The use of FTAs is a special branch of systems analysis. The goal of FTA, similar to other systems analysis, is to effect a structured analysis of complex systems using abstractions and approximations to support decision-making in safety and engineering. FTA is used to synthesize information from which to infer potential vulnerabilities as well as to estimate the probabilities of undesired events.

General Description–An FT model maps physical systems into a logic model based on deductive logic. The deductive model begins at some undesired event (or consequence), such as release of radioactivity from surface facility, and identifies (deduces) all of the causes of the undesired event. The undesired event is termed the top event in FTA and must be defined precisely. The model is developed downward from the top event through the various levels of assembly and usually stops at the basic event level. That is, an FTA for the top event, "release of radioactivity from surface facility," would proceed from facility to building to operation to system to subsystem to the basic events that are failures in specific hardware components, software, electronic control or logic elements, human errors, or loss of essential support functions, such as loss alternating current (AC) electrical power. The FT can include the loss of, or circumvention of, design and administrative controls. The basic events for a given component, therefore, may represent independent failures, CCFs, or dependent failures (see Section 7.5 for more information on CCFs and dependent failures).



NOTE: GF = guaranteed fault.

Figure 7-8. Event Tree for Hypothetical Human Error Initiated Uncontrolled Descent

Master Logic Diagram–An FT developed for a top event such as "release of radioactivity from surface facility" is sometimes termed a master logic diagram as a framework for identifying and organizing all of the hazards at a given facility. In this application, the top event is defined broadly but explicitly. The causes and probability of a given accident or class of accidents for a specific facility are also analyzed with FT logic. In this application, the top event might be "release of radioactivity from transport cask unloading facility resulting in dose greater than 5 rem at site boundary." The FT logic is applied to identify all of the fault combinations that must occur to result in the defined top event. Various paths from the top event down to the fundamental or basic events (e.g., human errors, equipment failures, and earthquakes) comprise alternative event sequences (or accident scenarios). Thus, the FT logic will usually capture the same scenarios as identified in ET analysis. However, individual sequences of events may be difficult to define in complex FTs.

System Analyses/ET Headings–Most applications of FTA, however, involve evaluations of the vulnerabilities within a given system or of the unreliability (or unavailability) of that system. The system unavailabilities are needed, for example, to quantify the probabilities of event headings in ETs and support quantification of event sequence frequencies. For example, an ET for the waste handling building might have an event heading "HVAC/HEPA filter starts and runs for 24 hours," expressed as a success criterion. An FTA of the HVAC/HEPA filter system is

developed to reveal how failures of the system may occur (the vulnerabilities), and to estimate the probability of the failure branch under that ET heading.

Selection of Top Event and Success Criteria–The FT top event for a system is generally defined as a complete, or catastrophic, failure of the system resulting in the unavailability of the desired function. It is important to be careful in choosing the top event and its success criterion. If the definition is too general, the analysis will be unmanageable. The analysis will not provide a sufficiently wide view of the system and its interfaces if the top event is too specific.

Qualitative Evaluation/Cutset Generation–The FT model is solved qualitatively using the rules of boolean algebra to reveal the number of combinations of basic events that can result in the occurrence of the top event. Section 7.2.4.1 presents basic boolean algebra as background material for the FT analyst. A summary of boolean algebra is presented in Section VII of the *Fault Tree Handbook* (Vesely et al. 1981). The combinations of events that lead to the top event are termed cutsets. Through complete boolean reduction, the least number of unique cutsets are determined and are termed the minimal cutsets. The occurrence of at least one of the minimal cutsets will result in the occurrence of the top event. The probability that the top event will occur is the union (or OR logic, or arithmetic sum) of the probabilities represented by the minimal cutsets.

The results of a qualitative FTA provide insights into potential system vulnerabilities that may, in some cases, be prevented or reduced in probability through design or operational modifications. For example, if the cutset analysis reveals that the system is very vulnerable to a human error by the facility operator (e.g., to ensure building air-tightness) then an interlock switch could be introduced into the design such that the system failure requires the concurrent failure of the interlock and the operator error.

Stated another way, qualitative FTA also serves to demonstrate the defense-in-depth of a system. A simple FT can determine if a potential accident condition or a system performance is defended against a single failure (or single contingency). A hand-drawn FT also can be a useful tool for the safety analyst.

In applications of an FTA program such as SAPHIRE (Russel et al. 1994), the analyst can truncate the qualitative analysis by specifying the maximum order of cutsets to be generated. The order is the number of concurrent basic events to be included in a minimal cutset. A singlet cutset includes one basic event (i.e., it represents a single-point failure) and may include a known and unlikely passive failure such as the collapse of a shield wall or may reveal the key human error, as discussed previously. A doublet cutset represents the concurrent occurrence, or intersection (or AND logic, or arithmetic product) of two basic events. In the previous example, a design modification that added an interlock to prevent the human error single point failure would produce a doublet in a revised FTA: the human error is ANDed with failure of the interlock. The cutset ordering continues through triplet, quadruplet, and so forth. In practical terms, it is seldom necessary to go beyond doublets or triplets unless the system is very complex.

Quantitative Evaluation/Top Event Probability–The FT model may be solved quantitatively after the minimal cutsets have been derived. The probability of the top event is represented by the union (or OR logic, or arithmetic sum) of all of the minimal cutsets. Quantitative

probabilities are inserted for all of the basic events that appear in the minimal cutsets. The symbolic boolean operations of intersection (AND) is replaced with the arithmetic operation of multiplication and the union (OR) is replaced by summation. The basic event probabilities are derived as described in Sections 7.3, 7.4, and 7.5. Quantitative FTA is used in the quantification of event sequence frequencies (i.e., by direct or indirect linking to ETs) and categorization of event sequences.

The probability of each minimal cutset is quantified by the multiplication of the probabilities of all of the basic events appearing in it. The top event probability is calculated by adding the probabilities of all of the minimal cutsets.

The results of a quantitative FTA provide a different degree of insight into potential system vulnerabilities than is provided by the qualitative FTA. For example, by maintaining the discrete probabilities of individual cutsets, it is revealing to rank their contribution to the top event probability. This methodology provides visual insights into the dominant contributors as well as a means for formal importance ranking. Knowledge of the relative importance of various cutsets and the basic events that contribute to the top event (e.g., hardware failures, software failures, human errors, and CCFs) can be used to prioritize design alternatives, importance to safety classifications, and other risk-informed analyses.

The analyst can truncate the quantitative analysis by specifying the minimum cutset probability to be generated in an FTA application program such as SAPHIRE. Thus, if the analyst is interested in finding the dominant contributors to a total system unavailability that is on the order of 10^{-3} per demand, a minimum cutset probability of perhaps 10^{-4} to 10^{-5} might be specified since 10 to 100 cutsets are required to produce the top event probability range. On the other hand, if a top event probability of 10^{-6} is needed, the cutoff probability for individual cutsets might be set at 10^{-8} to 10^{-9}, at least initially, to ensure that all significant contributors are accounted for. Several iterations are usually required to settle in at an appropriate cutoff probability for a given system.

7.2.3 Details of Approach

This section presents a brief introduction to the fundamental elements of FTA. The PSA analyst should consult the *Fault Tree Handbook* (Vesely et al. 1981), the *PRA Procedures Guide* (NRC 1983), and the SAPHIRE Users' Manual (Russell et al. 1994) for more information.

7.2.3.1 Essential Boolean Algebra

It is not necessary for the FT analyst to understand boolean algebra unless it is required to solve an FT by hand. The FT programs such as SAPHIRE (Russell et al. 1994) provide all of the manipulations of boolean expressions for the analyst. In many cases, simple FTs can be solved by hand using the rudimentary elements of boolean algebra. The following discussion presents the boolean operations, their arithmetic (engineering) equivalent notations, and their corresponding probability expressions. The examples represent the occurrence of event C after operating on events A and B, and their respective probabilities (i.e., p(A), p(B), and p(C)).

Union [OR logic, sum of event probabilities]	$C = A \cup B$; C = A OR B; p(C) = p(A) + p(B) – [p(A) p(B)]	(Eq. 7-1)
Intersection [AND logic, multiplication of event probabilities]	$C = A \cap B$; C = A AND B; p(C) = p(A)p(B)	(Eq. 7-2)
Absorption (reduce condition for TRUE expression to minimum), for example,	$C1 = A \cup (A \cap B) = A$; C1 = A OR (A AND B) = A; p(C1) = p(A) + (p(A) p(B)) = p(A) $C2 = A \cap (A \cup B) = A$; C2 = A AND (A OR B) = A; p(C1) = p(A) (p(A)+ p(B)) = p(A) Note that if A is TRUE then C is TRUE no matter whether B is TRUE or FALSE. The sub-expressions involving B has been absorbed by those expressions involving A.	(Eq. 7-3) (Eq. 7-4)
Complementation [Event NOT A (or $\underline{A}$, or A') is the complement of event A]	$C3 = A \cup \underline{A} = 1$; $C3 = A + \underline{A} = 1$; $p(C3) = p(A) + p(\underline{A}) = 1$ $C4 = A \cap \underline{A} = \phi$ [null]; $C4 = A\,\underline{A} = 0$; $p(C4) = p(A)p(\underline{A}) = 0$	(Eq. 7-5) (Eq. 7-6)

The boolean logic of AND and OR form the basic building blocks of an FT structure. Specialized adaptations of the AND logic have been introduced into FT symbology as described below. The rule of boolean logic, especially ABSORPTION and COMPLEMENTATION are used in solving an FT (i.e., finding the minimal cutsets among all the possible combinations of basic events).

7.2.3.2 Fault Tree Symbols

The symbols used in FT construction are illustrated in Figure 7-9. These symbols have been standardized and have been incorporated into the graphics and logic of programs such as SAPHIRE. It is unlikely that FTA performed for preclosure safety will use all of the symbols and their associated logic, but all are presented for completeness.

7.2.3.2.1 Top Events and Intermediate Events

A rectangle used to enclose the precise statement about the top event or an intermediate event. The event described in the rectangle represents a fault event that occurs because of the occurrence of one or more antecedent events acting through logic gates. A rectangle is usually opened by specifying a logic gate (an AND or OR gate) as a place to enter the textual description of the top or intermediate event in a program such as SAPHIRE. But, intermediate event descriptions are often included in rectangles in a tree structure as clarifying descriptions with pass through logic (i.e., no AND or OR).

Several symbols are used to indicate the types of primary or fundamental events that act as antecedents or conditioning events for faults higher in a tree.

7.2.3.2.2 Primary Events

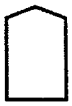
Basic Event–A basic event is a fault that requires no further development; it is represented by a circle. The circle signifies that the appropriate limit of resolution has been reached. It signifies that the stopping rule for the analysis scope has been satisfied. A basic event may be a component failure, a system failure, software

PRIMARY EVENT SYMBOLS

BASIC EVENT — A basic initiating fault requiring no further development

CONDITIONING EVENT — Specific conditions or restrictions that apply to any logic gate (used primarily with PRIORITY AND and INHIBIT gates)

UNDEVELOPED EVENT — An event which is not further developed either because it is of insufficient consequence or because information is unavailable



EXTERNAL EVENT — An event which is normally expected to occur

INTERMEDIATE EVENT SYMBOLS

INTERMEDIATE EVENT — A fault event that occurs because of one or more antecedent causes acting through logic gates

GATE SYMBOLS

AND — Output fault occurs if all of the input faults occur

OR — Output fault occurs if at least one of the input faults occurs

EXCLUSIVE OR — Output fault occurs if exactly one of the input faults occurs

PRIORITY AND — Output fault occurs if all of the input faults occur in a specific sequence (the sequence is represented by a CONDITIONING EVENT drawn to the right of the gate)

INHIBIT — Output fault occurs if the single fault occurs in the presence of an enabling condition (the enabling condition is represented by a CONDITIONING EVENT drawn to the right of the gate)

TRANSFER SYMBOLS

TRANSFER IN — Indicates that the tree is developed further at the occurrence of the corresponding TRANSFER OUT (e.g., on another page)

TRANSFER OUT — Indicates that this portion of the tree must be attached at the corresponding TRANSFER IN

Figure 7-9. Standard Fault-Tree Symbols

failures, a human error, or a CCF. The probability or failure rate of a basic event, along with its uncertainty distribution, represents the fundamental input to a quantitative FTA.

- **Undeveloped Event**–An undeveloped event is represented by a diamond. This symbol represents an event that could be developed further toward basic events. However, it is not further developed because it does not cause significant consequences, sufficient information is not available to warrant decomposition, information is available for faults at the higher level, or the analyst wants a placeholder. For example, an event titled "loss of AC power supply 'Train A' to HVAC/HEPA filters" might be shown as a diamond on an FT as an input to "HVAC/HEPA filter fails to start and run for 24 hours." The analyst may either quantify the probability of the loss of AC "Train A" or later change the diamond to a TRANSFER (definition to follow) to a detailed FT for the AC power system.

- **Conditioning Event**–A conditioning event is represented by an ellipse (oval). This symbol represents a restriction or condition that can be applied to any logic gate but is used primarily with PRIORITY and INHIBIT gates. For example, an FT for a potential criticality event might have a conditioning event titled "moderator is present" as an input to an AND gate that also includes "misload of WP" and "neutron absorber omitted from WP."

- **External Event**–An external event is represented by a house. This symbol does not represent a fault; it represents an event that is expected to occur. It may play the role of a conditioning event or a contingency event. For example, an FT might model an event such as "AC applied to motor startup sequencer" due to an out-of-sequence relay operation whose primary fault be "relay contacts fail closed." An EXTERNAL EVENT titled "AC power available to motor start sequencer" would show the need for the presence of the additional event or condition before the fault could occur.

7.2.3.2.3 Gate Symbols

The gate symbols and the logic they represent provide the backbone of an FT structure. The operational aspect of a gate is to define whether the output of the gate is TRUE or FALSE depending on the status of several inputs to the gate. When the output of a gate is TRUE in an FT, the fault described in the event box occurs (exists). The logical operation of each kind of gate is described as follows:

- **AND**–The AND gate is represented by a flat-bottomed arch (or mailbox). The OUTPUT fault occurs if, and only if, all of the input events or faults occur.

- **OR**–The OR gate is represented by an arch-bottomed barn roof (or bishop's hat). The OUTPUT fault occurs if at least one of the input events or fault occurs. This gate is sometimes called the INCLUSIVE OR to distinguish it from the EXCLUSIVE OR (description to follow). However, most FTAs encountered in the PSA for the repository will use the basic (or inclusive) OR (see discussion of EXCLUSIVE OR).

- **Exclusive OR**–The exclusive OR is represented by a modified OR symbol that has an arch-bottomed triangle inside the "barn," or "rafters" from the peak of the barn to the bottom. The output fault occurs if exactly one of the input events or faults occurs. Alternatively, this logic could be represented by an OR gate with a conditioning event specifying a required order of the inputs or exclusion statement "A not B, or B not A." It is noted in the *Fault Tree Handbook* (Vesely et al. 1981) that the quantitative difference between the inclusive and exclusive OR events is generally insignificant.

- **Priority AND**–Priority AND is represented by an AND gate with an inscribed triangle (caution: it looks similar to the exclusive OR gate but has a flat bottom). The output fault occurs only if all of the inputs occur (like the AND gate) in the prescribed sequence order. If A, B, and C are three inputs to the PRIORITY AND, read left to right, the output occurs only if A occurs before B, B occurs before C, and C occurs. Alternatively, this logic could be represented by an AND gate with a CONDITIONING EVENT specifying the required order of the inputs (as "A before B, B before C").

- **Inhibit**–An INHIBIT is represented by a hexagon. The INHIBIT is a special kind of AND gate that propagates a fault in the presence of an enabling condition. The single input fault is shown as the only input into the bottom apex of the hexagon and the enabling condition as a CONDITIONING EVENT connected to the side of the hexagon. For example, an INHIBIT event might be defined as "fire protection system fails to prevent control system failure" with the only input fault being "fire protection system fails" while the conditioning event is "fire greater than Z degrees occurs in control area." There is little distinction in this example between the fires as conditioning events, rather than external (house) event, except in the specificity of fire severity.

- **K-out-of-N**–K-out-of-N is represented by an OR gate with an attached oval. This gate symbol states the condition for occurrence of the intermediate event, which requires failure of K components out of N total to cause the described intermediate fault event. This gate symbol is a shortcut for the actual boolean logic, which is a combination of AND gates with combinations of the basic events as inputs. Here the AND gates are input to the OR gate of the intermediate event. This gate symbol is often used in modeling the failure logic of safety-related instrumentation and control systems in which safety is balanced against trip avoidance. It is unlikely that instrumentation and control systems for a repository will use such logic; however, other systems having multiple levels of redundancy, such as the HVAC system of a waste-handling building, may use this type of gate.

7.2.3.2.4 Transfer Symbols

The transfer symbols serve several purposes:

- Assist the analyst in controlling the complexity and graphic scale of an FT so text remains legible (e.g., to put a complex tree on multiple pages),

- Allow modularization to direct the flow of fault to repeated elements without redrawing portions of the FT (e.g., a fault in a motor-control center may be a common input to several fans in a complex HVAC system), and

- Permit linking of trees of main systems to subsystems or to support systems (e.g., the main HVAC FT may link to subsystems in primary and secondary isolation zones to portions of an AC power supply system).

The TRANSFER IN and TRANSFER OUT symbols work together, often as pairs. For each TRANSFER IN, there must be a corresponding TRANSFER OUT in another page of the FT or in an FT for the corresponding subsystem or support system. Note that it is possible for multiple TRANSFER INs to be linked to a single TRANSFER OUT.

A TRANSFER IN is indicated by a triangle with a connection from its top apex to an EVENT BOX. The TRANSFER IN indicates that the event defined is developed further at the occurrence of the corresponding TRANSFER OUT. For example, two inputs to the event "HVAC/HEPA filter system fails to start and run for 24 hours" through an AND gate might be "Train A of HVAC/HEPA filter system fails to start and run for 24 hours" and "Train B of HVAC/HEPA filter system fails to start and run for 24 hours." Each of the latter events could be shown as a TRANSFER IN events. The corresponding TRANSFER OUT events would be attached to the top events of FTs representing, respectively, "Train A ..." and "Train B ..."

A TRANSFER OUT is indicated by a triangle with connection out of its side to an EVENT BOX. The TRANSFER OUT symbol indicates that the tree structure represented below the top event is effectively a part of one or more other FTs that have faults at higher levels of assembly.

The application of the various symbols will be described later in several examples.

7.2.3.3 Guidance on Fault Tree Construction

This section describes how FT models are constructed using deductive logic. The discussion is oriented toward logic modeling to support the PSA of a repository at relatively high level of design detail.

Actual applications of FTA to the repository PSA are provided in Subsurface Transporter Safety Systems Analysis (CRWMS M&O 2000) based on FT models developed in Application of Logic Diagrams and Common-Cause Failures to Design Basis Events (CRWMS M&O 1997). The logic models were based on a limited amount of design detail but were quite extensive in defining the potential human errors and CCFs that lead to the undesired top event. Portions of this application were used as examples in the following discussion.

The necessary ingredients in FT construction include an understanding of the systems and an understanding of how things may go wrong. The Fault Tree Handbook (Vesely et al. 1981) has attempted to make FT construction more systematic, by developing rules for FT construction. The analyst is referred to Chapter V of the Fault Tree Handbook (Vesely et al. 1981) for a discussion on the fundamentals of FT analysis of complex systems. The following material is provided as background information and terminology that is useful in helping the PSA team gain experience as FT analysts.

Each event in an FT has a name and a description. The name is an abbreviated set of letters, numbers, or characters that is used as a unique label on graphics, in databases, and reports. The name is generally recognizable by key letters, although not in complex trees or if system-specific identification tags are used. The description may be a verbose, full definition of the event that may be tabulated with the event name, or it may be an abbreviated version that fits conveniently into the graphic displays and printouts.

This section adapts several of the rules of the *Fault Tree Handbook* (Vesely et al. 1981) in examples that are more appropriate to the PSA.

Rule 1 - Top Event Definition–The top event is defined as precisely as it can be expressed. It is an undesired event (e.g., an entire accident sequence) or a description of specific events that contribute to an accident sequence (e.g., the IE, the failure of a specific safety function or system, or a particular human error). The FTs will represent the failure or unavailability of an event defined in an ET model of potential accident sequences in most cases. As noted, the headings of an ET are defined in terms of specific success criteria that must be achieved to take credit for the safety function. The corresponding FT models the complement of the event heading success criteria; that is, the top event of the FT represents the probability that the success criteria are not met.

For any events described in an FT model, precision is the key factor to proper logic development. The statements entered in the top event (and other event boxes) are expressed as a fault (or a failure). The fault (WHAT condition) and when it occurs (WHEN condition) should be precisely stated. The WHAT condition describes the relevant failed (or undesired operating) state of the function, structure, system, or component. The WHEN condition describes the condition of the system that makes the WHAT condition a fault. The analyst should be as verbose as necessary to precisely define the fault condition. The event box in the tree diagram should not dictate the event description. Words, but not ideas, should be abbreviated if necessary.

An example undesired event sequence involves a runaway transporter train on the North Ramp during a descent to emplace a WP. After the occurrence of an event that initiates a runaway, automatic systems and HAs are called upon to arrest the runway before a derailment or impact on the WP occurs. The success criteria would be "runaway is controlled before train attains derailment speed on the North Ramp (during descent of the North Ramp)." The first part of the description defines the WHAT condition, and the phrase in parentheses defines the WHEN condition. The phase in parentheses might be omitted for brevity in the FT, but must be clearly stated in the definition of the condition of interest. The corresponding top event of an FT model would be "failure to control runaway before train achieves derailment speed during descent of the North Ramp," as illustrated in Figure 7-10. The name given to the top event is CONTRUN.

The specification of the WHEN condition during descent of the North Ramp may serve to identify the event, by contrast, to a similar event (e.g., during an ascent or the North Ramp, or during the descent of a different portion of the main tunnel, such as a North Ramp Extension). The WHEN condition may also assist in the definition of a specific time span, or mission time, during which success is required.

Deductive logic is then applied successively at lower and lower levels of decomposition until the model is sufficient to support the analysis or has reached the lowest level of detail (e.g., at the component level).

Rule 2 - Development of Immediate Cause–The next step in FT development is to define the immediate, necessary, and sufficient causes for the top event. These causes are not the basic causes, but are immediate causes or immediate mechanisms. If all of the immediate causes are independent of each other and each fit definition of immediate, necessary, and sufficient to result in the top event, the top event is developed as an OR gate. If the top event occurs only if two or more causal events occur concurrently, then the top event is developed as an AND gate. The top event is often developed as an AND gate to represent some conditioning event that must be present for the fault to occur.

In the example "failure to control runaway before train achieves derailment speed during descent of the North Ramp," the immediate causes might be identified as "human operators fail to apply brakes in timely manner" and "failure of brake system to apply sufficient braking force upon demand." Since the occurrence of either event will result in the occurrence of the top event, the two events are input through an OR gate to the top event. At this stage of FT development, the definition of the immediate cause can be general or universal and does not require specific design details.

The development can be made more general, or inclusive, by replacing the causal event "human operators fail to apply brakes in timely manner" with "failure to detect runaway initiation and failure to apply brakes in a timely manner," which is illustrated in Figure 7-10 by the event named DETAPPL. This definition allows for flexibility in further development if it is not known, or decided at the time of the analysis, whether human operators or automatic systems will be the primary means of detecting an initiation of runaway and actuating brakes. One application of the FTA is to assist in the determination of the design requirements needed to achieve the necessary functional reliability. The event DETAPPL is depicted as an undeveloped event by the use of a diamond under the event description box.

The timely manner phrase is a reminder that restrictions may be placed on the definitions of the causal events that correspond to the WHEN portion of the top event criteria. The mission-time parameters can be used in the event descriptions if they are known. For example, if the rate of acceleration and distance to the "point of no return" are known, a minimal response time can be specified (e.g., 30 seconds). The causal event might then be defined as "failure to detect runaway initiation and failure to apply brakes within 30 seconds." The probability of failing to respond could potentially be calculated from a time-dependent reliability model for the respective electronic and human systems and the required response time of 30 seconds.

The name BRKFORC is given to the event titled "failure of brake system to apply sufficient braking force upon demand," as illustrated in Figure 7-10. The event titled BRKFORC is depicted as an undeveloped event by the use of a diamond under the event description box. An explicit mission time could also be applied to the causal event titled BRKFORC. In this case, however, the mission time is defined as the "time on the ramp" during each descent operation (e.g., 30 minutes). The probability of failure on demand may be estimated from the system

failure rate and the potential exposure time of 30 minutes. These matters are described further in the discussion of basic event quantification in Section 7.2.4.5.

All descriptive (causal) events located below the top event are termed Intermediate Events.

Rule 3 - Complete the Gate–All inputs to a particular gate (i.e., a boxed event description with an event name) should be completely defined before any of them are analyzed (decomposed) further. This rule is important for maintaining discipline in the deductive logic decomposition of a top event down to lower level events. All of the causal (input) events must be precisely defined, as described previously.

Rule 4 - No Miracles–The logical development of causal events is based on the occurrence of faults or failures in which the normal or expected functions do not take place. A corollary to this logical development is the No Miracles rule, as defined in the *Fault Tree Handbook* (Vesely et al. 1981). That is, if the normal functioning of a system, component or human actions propagate a fault sequence, it is assumed that the normal function occurs (i.e., there is no miraculous interdiction of the fault propagation). By contrast, if the normal functioning of a component blocks the fault propagation, then faults must be introduced into the tree to defeat the blocking function. This situation usually results in the introduction of an AND-gate: primary fault sequences are propagated upward in the tree and connected with the failure of the fault blocking function with an AND gate.

Rule 5 - Development of Intermediate Events–The immediate causes of the top event are each, in turn, treated like a top event and the immediate, necessary, and sufficient causes for each event are defined. This process is essentially a sequential application of Rule 2 that is continued down through the levels of assembly, continually transferring the point of view from failure mode (result) to the failure mechanism (cause). The process stops when the lowest level of resolution is reached, usually at the failure mode level of individual components or subsystems.

This discussion continues with the example shown in Figure 7-10.

If it is possible in the system design for either a human or an electronic system to detect the need for applying brakes, and then to apply them, an event named DETAPPL is developed as an AND gate with two inputs. These inputs are titled AUTOSPD (the failure of autospeed controller to detect overspeed and apply brakes) and HASPEED (the failure of operator to detect overspeed and apply brakes), which is not illustrated in Figure 7-10.

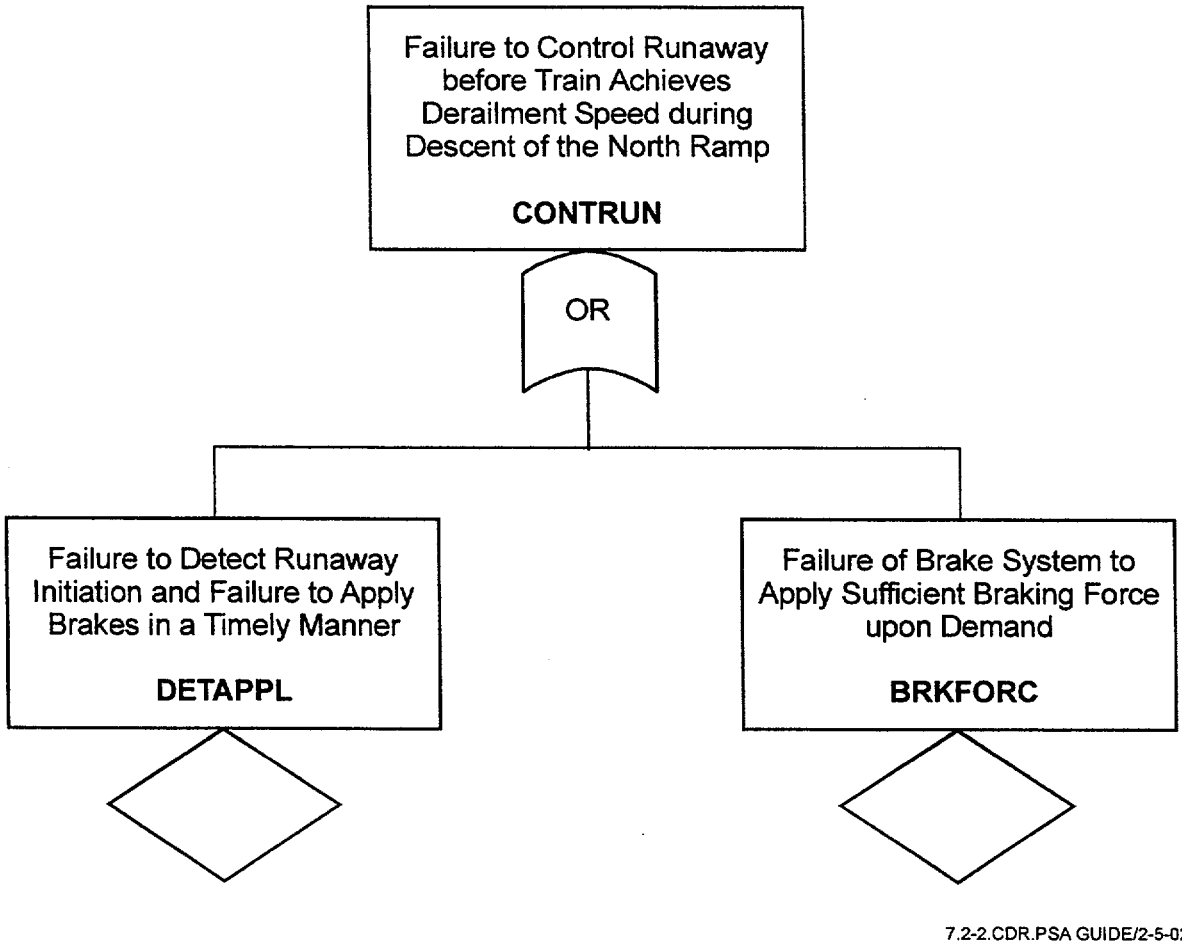


Figure 7-10. Illustration of Fault Tree Development

The event BRKFORC is developed as an OR gate since (in this hypothetical example) a failure of either a brake control system (the event titled BRKCONT) or a failure of the brake mechanisms (the event titled BRKMECH) will result in the event titled BRKFORC, which is not illustrated in Figure 7-10).

Rule 6 - Identify Potential Dependent or Common Cause Failures–Note that the *Fault Tree Handbook* does not have a rule to explicitly identify and model common-cause or dependent failures. For emphasis, this PSA Guide adds this rule to ensure that the PSA analyst does not overlook these important mechanisms.

7.2.3.4 Basic Event Quantification

Quantitative data are input at the lowest level of resolution of each branch of an FT. The analyst must ensure that the data are appropriate to the precise definition of the basic event. In the analysis of system reliability, the lowest level is usually the failure probability for a specific failure mode of a component. For example, in an FT for a fluid system, one or more branches would terminate in basic events such as "pump A fails to start," "pump A fails to run for 8 hours," or "pump A out of service for maintenance."

If the top event is quantified as a probability (e.g., probability that system fails to supply adequate cooling flow for 24 hours), then all input data must be expressed as probabilities (as unitless or per demand).

If the top event is quantified as a frequency of an undesired event (e.g., radioactive release from canister transfer system), however, then input data must be a mixture of probabilities and event frequencies or rates that become joined through AND gate(s). For example, there may be two scenarios that lead to the top event (filtered release and unfiltered release). The top event is shown as an OR gate. Under each of the intermediate events titled "filtered release" and "unfiltered release," respectively, there would be an AND gate. One input to each AND gate would be an IE (such as crane drops canister a distance further than design height) quantified as a frequency or rate of occurrence (i.e., per unit time) and an event representing the conditional probability of a "radioactive release given drop of canister further than design height" (unitless as per demand or per opportunity).

If the top event is quantified as a failure rate (e.g., "the system fails to supply adequate cooling flow" at a rate of λ [e.g., failures per million hours]), then the basic input data generally are expressed as failure rates (units of inverse time). However, if the top event requires combinations of failures of subsystem or components (i.e., using AND gates), then all but one of the inputs to each AND gate must be expressed as a conditional probability (i.e., probability per demand, given the occurrence of the first, or triggering, event).

The product of a frequency and one or more probability terms is a frequency. It is never appropriate to multiple a frequency (or rate) by another frequency (or rate) because the resulting units are not physical (i.e., units of hours^{-2} have no meaning).

Section 7.5 provides guidance on developing input information for preclosure safety analyses. This section provides a brief discussion for continuity.

All available historical (actuarial) event data for the actual SSCs of a repository should be used to define the quantitative probabilities and frequencies used in FTA and ETA. Since there will be no repository operational data prior to the license application (LA) submittal, other sources of information are needed. Again, when available, performance data for SSCs of the same design and operational environment as that intended for each operation in a repository should be used. The analysis must otherwise proceed with the best available data for SSCs that closest resemble those to be used in the repository design, such as data from other fuel handling facilities. In many cases, especially for the CA submittal, it will be necessary to use generic tabulated data (e.g., electrical data, electronic data, and various mechanical systems and components data used in many PRAs). In other cases, it will be necessary to use surrogate data (i.e., railroad accident statistics) to estimate the probabilities of events during WP transport. Except for direct data from repository operations, it may be necessary to modify the probabilities to account for conditions at the repository that are different from those for which the data represent. In some instances, the probabilities may be higher (e.g., a more severe operating environment). However, these probabilities may be smaller in other cases (e.g., additional quality assurance or administrative controls preclude some of the events in the surrogate database). See Section 7.5 for an additional discussion on this process.

Basic event probabilities or failure rates are derived from experience data, as described in the following section:

7.2.3.4.1 Basic Event Probability

An event probability is a pure number ranging from 0 to 1.0. As a probability, it is physically unitless. Component faults are characterized as one of the following probabilities:

- Failure on demand – the probability of a failure per demand
- Standby failure – the probability of a failure on demand after a given non-operational period, usually given as time-between-inspections
- Operational failure – the probability of failing to run or operate (provide required function) during a specified time period (i.e., the mission time).

The symbol used for the probability in discussions, tables, or qualitative FTA is very often a "p." However, in many cases the symbol "q" is used to connote the probability of failure (per demand), or unavailability (i.e., the probability of being unavailable when called upon for the time required).

The value of q may be derived directly from demand-based experience data, or indirectly from rate (or frequency) based experience data, as described in the following definitions.

Demand-Based Experience Data–K failures are observed in N challenges (demands) on components in records or test data. Demand-based data analysis would estimate the failure rate (or probability per demand), also termed the component unavailability, to be:

$$q = K/N \text{ failures per demand} \qquad \text{(Eq. 7-7)}$$

When a component or system failure probability is needed for quantifying an input to a basic event in an FT, q has the proper characteristic.

Rate Based Experience Data–M failures are observed in exposure (operational or test) time T for components in records or test data. Rate-based data analysis would estimate the failure rate (in units of numbers of failures per unit time), also termed the component failure frequency, to be:

$$\lambda = M/T \text{ failures per hour} \qquad \text{(Eq. 7-8)}$$

When a component or system failure rate is needed for quantifying an input to a basic event in an FT, λ has the proper rate-based characteristic.

If the probability of failure (unavailability) of a component or system is needed, however, the rate data must be used to calculate an appropriate unavailability factor.

Operational Unavailability (No-repair Model)–The unavailability of a component or system in the exponential reliability model without repair is calculated as:

$$q = 1 - \exp(-\lambda * t_M) \quad \text{(Eq. 7-9)}$$

Where t_M is the mission time and q is the probability that that the component or system will not perform its safety function for at least a time t_M when it is needed. The expression for q is usually approximated as

$$q \approx \lambda * t_M \quad \text{(Eq. 7-10)}$$

when λ, t_M, or both are small values.

Standby Unavailability (with-repair or renewal)–The average unavailability of a system that is on standby but is periodically inspected at a time interval (t_I) and repaired, if necessary, is given by

$$q \approx (\lambda * t_I)/2 \quad \text{(Eq. 7-11)}$$

where it is assumed that the component or system is as good-as-new after inspection or repair.

Common Cause Failures–A more complete discussion of dependent failures and CCFs is presented in Section 7.4.

In developing FT models that include redundant components or subsystems, it is generally recognized that the joint probability of concurrent failure of two or more redundant components may not be the product of independent failure probabilities. That is, the failures of the individual components or subsystems may be dependent (i.e., coupled). This possibility is modeled in the FT when the construction rules are applied.

The probabilities of the CCFs are quantified using demand-based or rate-based parameters, as appropriate, for the event being quantified. In FTA for repository preclosure safety, it is expected that most CCF quantifications will apply the beta factor method (see Section 7.5) in a repository preclosure safety FTA.

7.2.3.4.2 Initiating Event Frequency

When the purpose of an FTA is to quantify the frequency of an event sequence (or accident scenario), the frequency of the IE must be scaled to match the operational load of the system. For example, the IE definition may be "crane drops SNF canister" and the quantification required would be "F_D drops per year." The operational throughput of the system may be Z canisters per year. Demand-based and rate-based data can be used to calculate the frequency of the IE, as explained in the following examples:

Demand Based: Experience data could show that the probability of dropping any given canister during a lift is Q_D drops per lift (i.e., more precisely defined as the probability of a canister drop per lifting operation). If the frequency of lifting the canisters is Z per year, then the frequency of the postulated IE is:

$$F_D = Z * Q_D \text{ (drops per year)} \quad \text{(Eq. 7-12)}$$

Rate Based: Experience data could show that the rate of dropping any given canister during operational time is λ_D drops per hour (e.g., this rate might be derived from related information such as a crane failure rate). In this situation, the exposure time (or mission time) must be defined for each lift operation to derive the probability of drop per lift. The estimated time that each canister is suspended in a vulnerable condition during each operation is T_L minutes. The probability of canister drop per lift is calculated as

$$Q_D = \lambda_D * T_L \text{ (drops per lift)} \quad \text{(Eq. 7-13)}$$

The time units must be converted, as appropriate, in these examples.

Proceeding in the same manner as for the demand-based case, the frequency of the postulated IE is calculated as:

$$F_D = Z * Q_D \text{ (drops per year)} \quad \text{(Eq. 7-14)}$$

7.2.3.4.3 Human Error Probabilities or Rates

Many basic events in FTs may represent human errors in operations or maintenance. Special techniques have been developed for estimating the probabilities of various types of human errors. The events are sometimes called HAs to include the positive effects (recoveries or interventions) as well as to recognize that the basic causes of an undesired event involving a human may be situational and not a true human error. An HRA is the process of analyzing situations where human errors (or human recovery actions) may occur and the process of quantifying the probability of those actions. Section 7.3 describes the recommended approach for the support of the PSA HRAs for the respective phases of LA submittals. This section provides a brief guide to their application in FTA.

Quantification is often described as HEP, which is usually quantified in terms of the probability per opportunity (or exposure). The HA event is treated in FT logic as a command fault; that is, as a mode of failure for a given component or system. It is sometimes helpful to examine each situation to identify the potential errors of commission, in which a human acts improperly (spuriously or induced by the contextual situation) to initiate an unwanted state or response of the system. It is also helpful to identify potential errors of omission in which the human fails to perform a required act that would prevent an unwanted state or response of the system. Such HAs may occur during maintenance activities (including test, inspection, and calibration), leaving a system or component in an unavailable or failed state. They also may occur during on-line maintenance (initiating an unwanted event sequence) or during operations (as IEs of unwanted sequences, or when failing to respond to, and recover from, unwarranted conditions).

The probability (for use in FT quantification) that a given component is unavailable when called upon because of maintenance errors is termed Q_{HM}. The frequency of maintenance of the component is F_M per year. The probability of a human error that leaves the component unavailable is quantified as HEP_{HM} (per opportunity; i.e., per each maintenance on the component).

Note that there is also a term for the time that the component or system is unavailable during (error free) maintenance; this term represents the time that the system is offline.

7.2.4 Examples of Application

This section provides an example of the process for creating an FT logic model for the specific failure mode of a relatively simple system. The example is derived from the *Fault Tree Handbook* (Vesely et al. 1981, Section VIII) for the Pressure Tank System (Figure 7-11). The system is not necessarily similar to any repository systems.

7.2.4.1 System Familiarization

The first step in any PSA is to define the system and understand how it functions. This step is the necessary prerequisite for FT analyses as well as for hazards analyses, common cause failure analyses, and ET analyses.

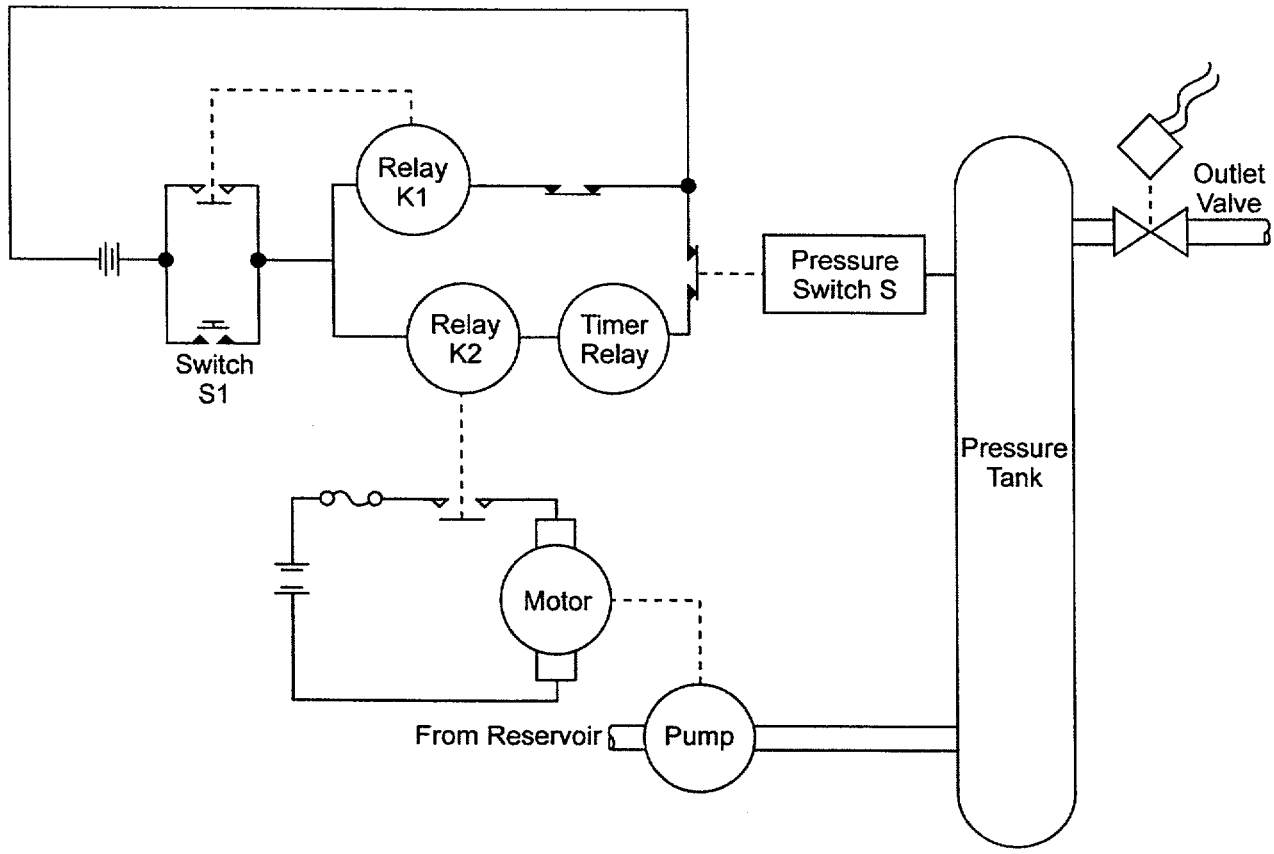
Several operating modes are possible for the system configuration:

- Dormant mode
- Pumping mode
- Ready mode
- Emergency shutdown.

The function of each component of the system varies according to the operating mode. The function of the control system is to regulate operation of the pump. The pump brings in fluid from an infinite reservoir. Ten seconds are normally required to pressurize the tank.

The pressure switch contacts are closed when the tank is empty but open when the threshold pressure is reached. The opening of the pressure switch contacts de-energize the coil of relay K2, whose contacts then open to stop the power to the pump and cease pumping. The tank is fitted with an outlet valve that drains the tank; however, there is no pressure relief valve on the tank. When the tank is emptied, the pressure switch closes, thereby energizing relay K2 and the pump to repeat the cycle.

Switch S1 contacts are open in the dormant state, which de-energizes the coils of relays K1 and K2 and, thereby, opens the contacts of both relays. Relay K1 is self-latching and closes, and remains closed, after switch S1 is pressed momentarily to startup the system. The timer contacts remain closed in the dormant state (and during system startup) for up to 60 seconds of continuous energization. The timer is reset every time the power to the timer is interrupted by the opening of the pressure switch contacts. The timer provides an emergency shutdown function in case the pressure switch fails. If the pressure switch fails to break the pump control



Source: modified from Vesely et al. (1981, Figure VIII-1).

Figure 7-11. Pressure Tank System

circuit, the timer contacts open to de-energize relay K2, whose contacts then open to stop the power to the pump.

This system description is applied to an example of FT construction using the rules and definitions in the Fault *Tree Handbook* (Vesely et al. 1981). A skilled FT analyst may not go through the steps mechanically but would use such rules intrinsically.

7.2.4.2 Fault Tree Construction for Pressure Tank Example

It was decided in this example to resolve the FT down to the component level.

The first step in the FT construction is to define the top event as a precise statement of the undesired system effect and a system failure mode of interest. This is an application of Rule 1.

> Write a statement in the top event box as a fault. State precisely WHAT the fault is and WHEN it occurs.

For the example, the top event is defined as: Rupture of Pressure Tank After the Start of Pumping. The next step is application of Rule 2 and the immediate cause principle. The analyst identifies three immediate and necessary causes for the top event and adds an OR gate below the

top event. One cause is identified as "Tank Rupture (Primary Failure)" to indicate the possibility of a random failure of a tank operating under normal, expected environmental conditions. This fault is shown on the FT diagram as a circle (i.e., a basic event).

Two other immediate faults are identified. The first is named "tank ruptures due to improper selection or installation," which disqualifies the tank for the operating conditions. This fault is shown in the FT diagram as a diamond to indicate that it will remain undeveloped. As noted in the *Fault Tree Handbook* (Vesely et al. 1981), under the ground rules set for the analysis, this fault may be introduced for completeness and then immediately pruned from the tree as being outside the scope of the analysis. It is noted that the potential mechanisms are potentially related to human error in this example.

The other secondary fault is simply identified as such (i.e., tank ruptures (secondary failure)) to acknowledge that there may be several fault paths that can cause the top event by creating an environment or operating condition that is beyond the qualification basis of the tank.

Rule 3 is applied to complete the gate by explicitly diagramming the three faults under the top event.

Rule 2 is now applied to the event titled "tank ruptures (secondary failure)." Because this is a component fault, an OR gate is added under the event box and immediate causes are identified. In the example, two faults are identified. One is an undeveloped event titled "Secondary Tank Failure from Other Out-of–Tolerance Conditions (Thermal, mechanical);" the other input fault is titled "Tank Rupture due to Over Pressure Caused by Continuous Pump Operation > 60 sec." This fault description is seen to be a precise statement of a fault that addresses the fault effect, mode, and mechanism in a single statement. It is concluded that this is not a component fault and therefore must be a system fault. The input to a system fault event box may be an OR gate, an AND gate, an INHIBIT gate, or no gate at all. In this case, motor running is a normal condition and results in a fault mechanism for the tank only if it runs for more than 60 seconds. Therefore, the fault is represented as an INHIBIT gate in which the input event is "pump operates continuously for > 60 sec" and the conditioning event is "if pump runs > 60 sec tank will rupture (probability = 1.0)." The conditioning event is not developed further; it is a statement of the condition or assumption.

The event titled "pump operates continuously for > 60 sec" is developed further to identify the basic causal faults. The application of Rule 2 (principle of immediate cause), the analyst cannot identify the need for a gate because there is a unique event titled "pump motor runs for > 60 sec" that is tightly coupled to the pump impeller. An application of Rule 3 (No Miracles) indicates that it cannot be assumed that the pump shaft will break or that the motor winding will burn out to avoid the undesired pumping time. The event titled "pump motor runs for > 60 sec" is coupled directly to the event titled "power applied to pump motor > 60 sec." There are no miracles to interrupt the power; therefore, a "no gate" input is appropriate.

Applying Rule 5, the process is repeated for the event titled "power applied to pump motor > 60 sec." Using Rule 2 indicates that the immediate cause is "K2 relay contacts remain closed > 60 sec." Thus, the FT structure below the INHIBIT gate input to "Tank Rupture due to Over Pressure Caused by Continuous Pump Operation > 60 sec" appears as a series of intermediate

events without any gates. This structure is typical of initial FT construction. As will be described later, the series of pass through fault descriptions do not contribute to FT evaluations either in qualitative or quantitative analyses. This series is usually collapsed into as few fault statements as possible without losing information.

Rule 2 is next applied to the fault titled "K2 relay contacts remain closed > 60 sec." This component fault requires the addition of an OR-gate. Three faults are defined as immediate causes. The fault "K2 relay contacts fail to open" is a primary failure. It is implied in the primary failure that all other portions of the relay unit are functioning properly; however, the relays do not open (perhaps because of corroded contacts or broken springs if the contacts are to open when the coil is de-energized). The secondary failure titled "K2 relay (secondary failure)" is included for completeness, but is not developed further. The command fault is titled "EMF [electromagnetic force] applied to K2 relay coil > 60 sec;" it is developed further for defining the basic causes.

An examination of the control circuit indicates that the immediate cause is a condition that requires the concurrence of two events: "Pressure switch contacts closed > 60 sec" AND "EMF remains on pressure switch when pressure switch closed > 60 sec." An AND gate is added below "K2 relay contacts remain closed > 60 sec" and the event boxes for the two input events are also added.

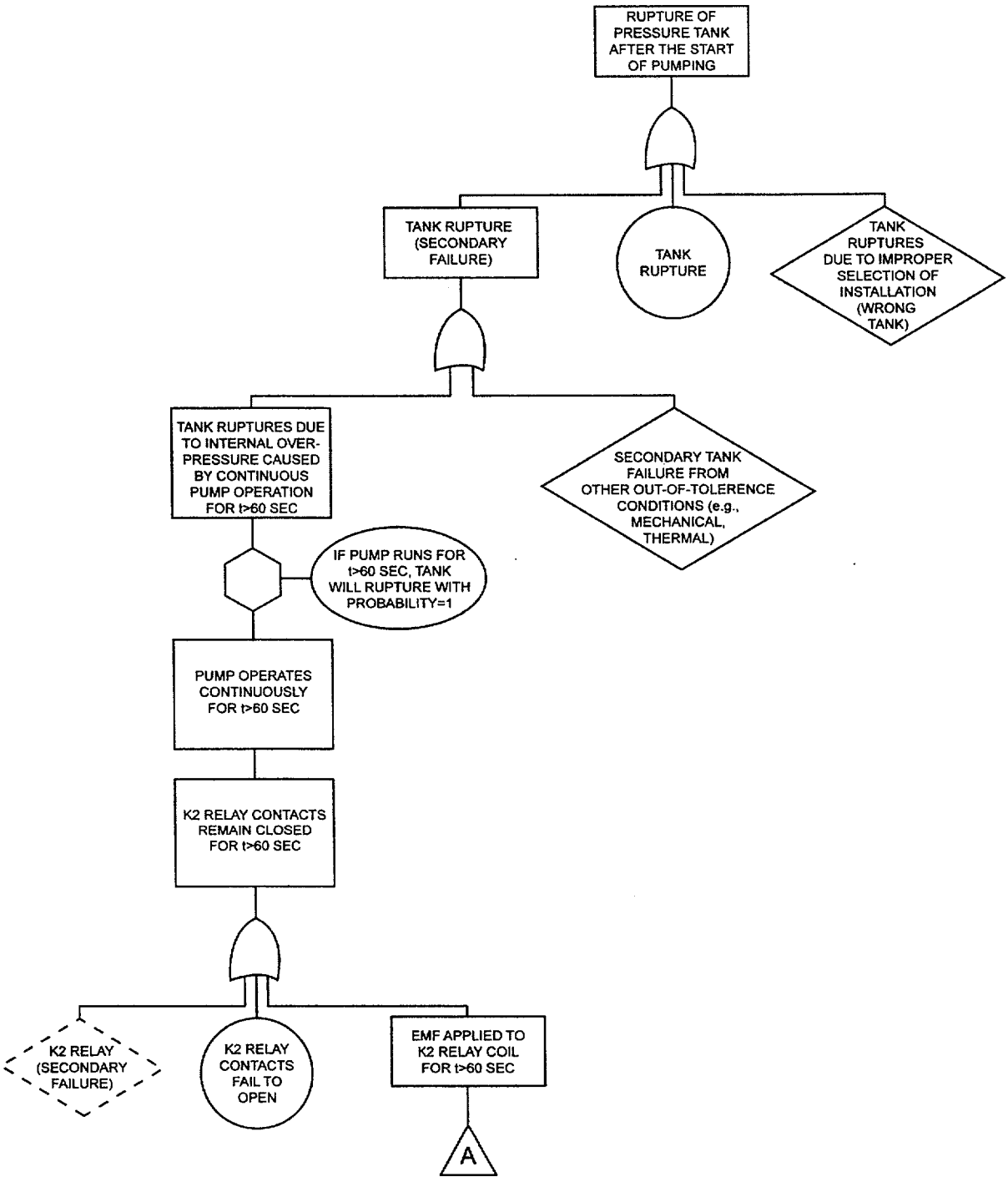
The development of the event titled "EMF remains on pressure switch when pressure switch closed > 60 sec" proceeds in a similar manner. The development continued per Rule 5. The discussion of this example is terminated, however, because the process is repeated until every path down the tree from the top event is terminated at primary or secondary faults of components or command faults that are not developed further. The complete FT for the example is presented in Figure 7-12. The reader should consult the *Fault Tree Handbook* (Vesely et al. 1981, Section VIII) for the full description of the development of this FT example for the pressure tank system, as well as other examples.

Rule 6 should now be applied to examine the system for potential dependent or common-cause failures. Since the example system has nonredundant components, there are no common-cause failures to include. The FTA could be expanded to show explicit dependence on an external electric power supply.

The complete tree should be examined and simplified if it is too complete (i.e., contains events that do not contribute to the understanding of the basic causal factors or do not contribute to the analysis of minimal cutsets or quantification). The *Fault Tree Handbook* (Vesely et al. 1981), for example, deletes many of the secondary faults. As noted previously, many of the intermediate events can be deleted or merged with other event descriptions. The simplified FT, illustrated in Figure 7-13 terminates with primary failures. The primary failures are indicated by circles and are, therefore, treated as basic events in the FT structure.

Simplification of an FT is not necessary when using a program such as SAPHIRE to solve the FT for the minimal cutsets or for quantification. However, it may be advisable to simplify a complex FT for reporting. Documentation of complex trees may run from 10 to 50 pages if legible font sizes are desired. Such a presentation adds numerous TRANSFER IN and

TRANSFER OUT symbols to the FT, making the FT very difficult to follow, especially for readers not familiar with FTs. Detailed trees are appropriate for documenting the analysis. However, simplification of an FT to a few (one to four) pages is recommended for summary reports, including those supporting an LA submittal.



Source: modified from *Fault Tree Handbook* (Vesely et al. 1981, Section VIII).

Figure 7-12. Fault Tree Example for Pressure Tank Rupture

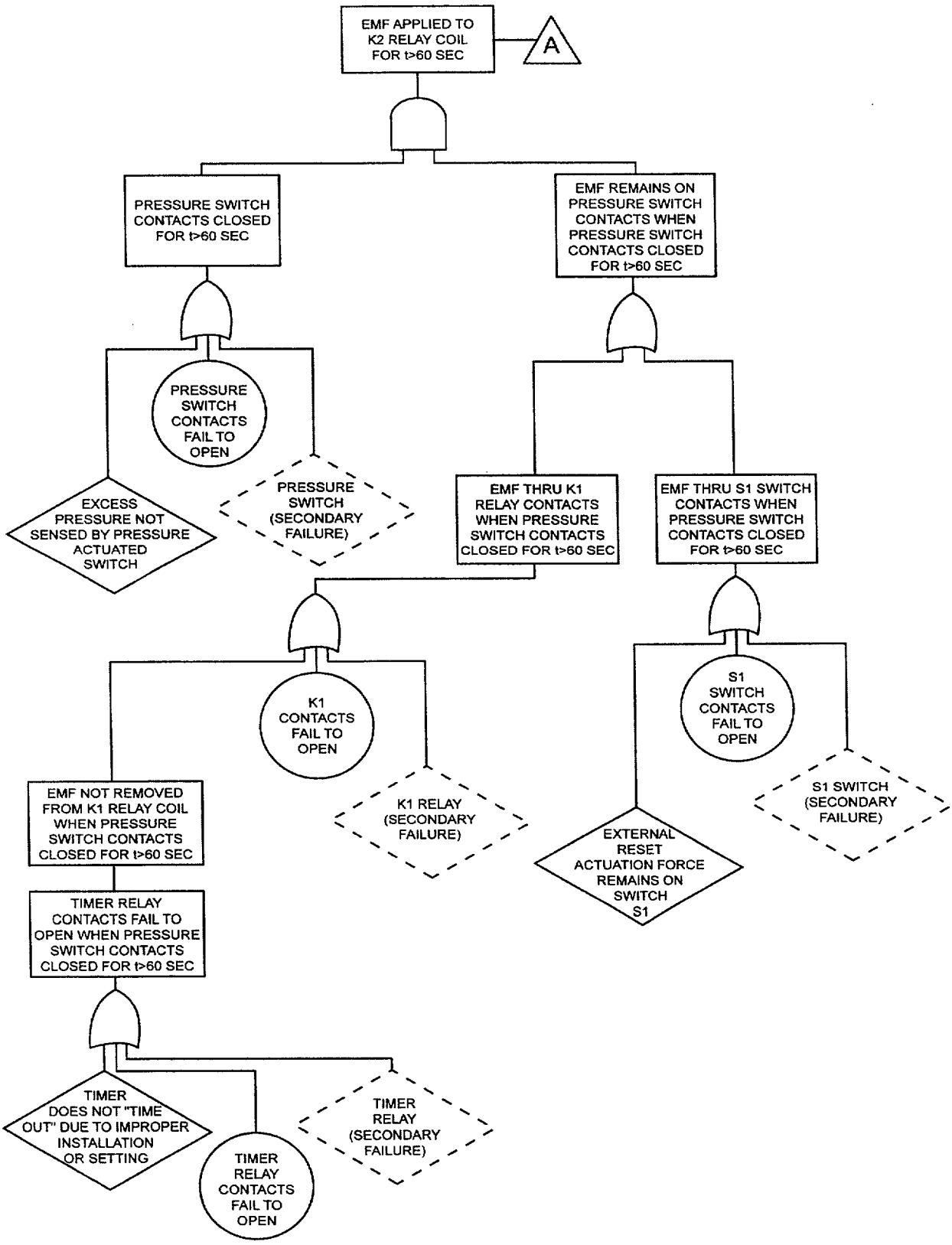
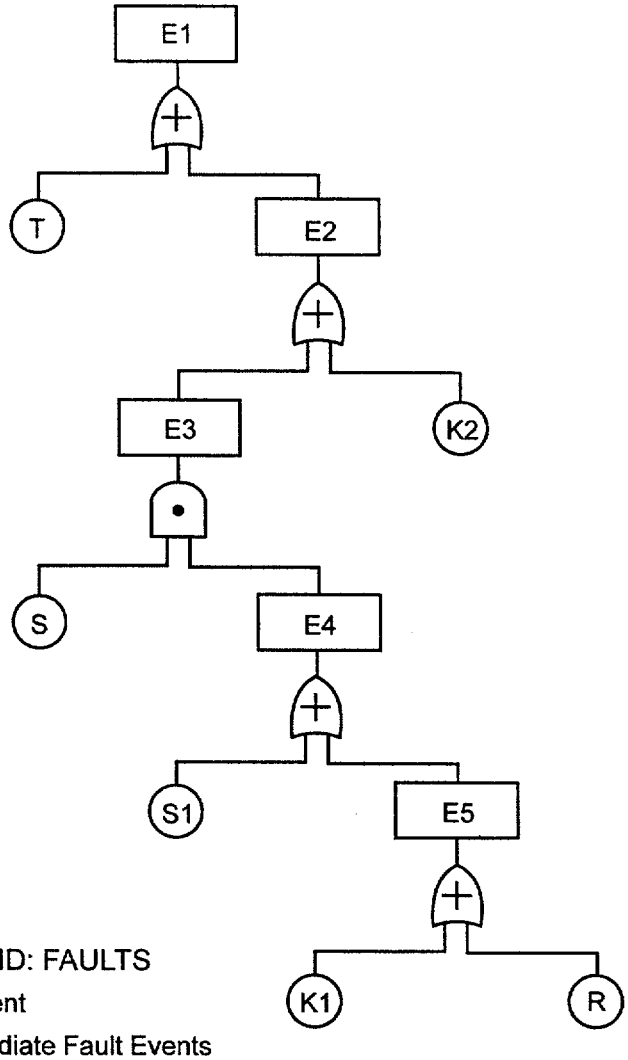


Figure 7-12. Fault Tree Example for Pressure Tank Rupture (Continued)



LEGEND: FAULTS

E1	Top Event
E2, E3, E4, E5	Intermediate Fault Events
R	Primary Failure of Timer Relay
S	Primary Failure of Pressure Switch
S1	Primary Failure of Switch S1
K1	Primary Failure of Relay K1
K2	Primary Failure of Relay K2
T	Primary Failure of Pressure Tank

Figure 7-13. Simplified Fault Tree for Pressure Tank Example

7.3 HUMAN RELIABILITY ANALYSIS

7.3.1 Purpose

This section defines the bases and methods for the application of HRA in support of the PSA for a repository. The section defines the methodology for the treatment of HAs in operational, administrative, and maintenance activities that are explicitly incorporated into the ET or FT logic models for the PSA.

7.3.2 Scope

This section presents a cursory, focused guide to the construction, application, and evaluation (both qualitative and quantitative) of HRA models. While some concepts are universal to all HRAs, the application in this section is focused on the support of the repository PSA. This section is not meant to be a textbook or exhaustive in scope. Where appropriate, reference is made to literature for additional information.

The HRA methods presented in this section provide a systematic process for identifying HAs that can affect the risk associated with preclosure operations of a repository and quantifying their probabilities.

7.3.3 Overview of Approach

An HRA is primarily an engineering discipline developed in support of PRA activities, but may involve a multi-disciplinary team. The topic of HRA is frequently called human factors in PRAs or safety reports. While HRA is related to, and works in concert with, the disciplines of Human Factors and Ergonomic Engineering, there are important differences. Human Factors analysts, who are often educated in the field of behavioral science, are engaged to provide work situations that reduce the likelihood of errors qualitatively by providing unambiguous instrumentation, logical arrangements of controls, ease of access, and ease of communications. The human reliability analyst is usually an engineer or system safety analyst who can identify potential human events that can affect safety. The human reliability analyst identifies where and how human interactions can influence the progression of event sequences, estimates the probability that a particular HA will be performed correctly and in a timely manner, and evaluates the effect on the frequencies of alternative event sequences. The HRA analyst can often estimate the probability of incorrect HAs using generic or surrogate information. In more complex instances, the human reliability analyst may be assisted by a Human Factors Specialist to identify and quantify the effects of performance shaping factors and error-forcing conditions or to prepare a detailed task analysis as a framework for quantifying the probability of performing the task correctly and timely.

The HAs of interest to PSA are operational, maintenance, or administrative actions that can ameliorate or exacerbate the probability of an unwanted event sequences. The HAs of interest are identified through the process of ET construction and the supporting FT construction. Significant HAs may be modeled as event headings in ET construction.

This section presents a discussion of the HRA techniques that are to be applied in the PSA.

7.3.4 Details of Approach

Background–Advances in HRA were initiated as part of the evolution of PRA methodology. Early PRA studies during the 1970s (e.g., the Reactor Safety Study: An Assessment of Accident Risks in US Commercial Nuclear Power Plants [NRC 1975]) demonstrated the uses of ET and FT modeling of accident sequences for complex nuclear reactor power plants, and identified instances in which human interactions with the plant systems could hinder (exacerbate) or help (ameliorate) the initiation or propagation of event sequences. The Reactor Safety Study (NRC 1975) was supported by an early version of the Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Operations (Swain and Guttmann 1983). The early PRAs also served to identify areas where HRA methodology was weak and in need of improvement to adequately model the interactions and to quantify the probability of such actions.

During the past 30 years, research and data-gathering operations sponsored by the U.S. Nuclear Regulatory Commission (NRC), the Electric Power Research Institute, the Institute of Nuclear Power Operations, and others have produced many insights into the underlying causes of undesired HAs (unsafe acts) and several methods for representing and quantifying human failure events (HFEs). The most recent attempt to improve upon HRA methodology is the ATHEANA study (NRC 2000).

Much of the HRA methodology has been developed to support PRAs for complex systems represented by NPPs, chemical process plants, and the piloting of aircraft. Although the operations of a repository are not as potentially challenging to human operators as one of the more complex systems, and as not as susceptible to catastrophic results in the event of unsafe acts, most of the HRA methods can be applied to the PSA, albeit with some simplifications.

Anatomy of an Accident–Post-event evaluations of many industrial accidents have shown that a high proportion can be attributed to some form of HFEs. Such evaluations have shown that the type of HFEs involved in many catastrophes are caused by faulty diagnosis, flawed or missing communications, failure to perceive a signal or warning, decisions taken too late, and violations of procedure or rule. Hidden (latent) HFEs (e.g., faulty maintenance, or failure to return a system or component to service) can contribute to the progression or severity of an accident.

By comparing accidents across industries and performing an evaluation of their root causes, various authors (e.g., Joksimovich et al. 1993) have defined the anatomy of an accident in terms of "the four Ms:"

- Machine–The system design with basic flaws, control characteristics, and operator friendliness
- Milieux (Media)–Operating conditions (context), commercial and regulatory pressures, natural phenomena
- Man–Operator reliability in preventing accidents and controlling systems in emergency conditions; maintenance reliability

- **Management**–Flaws in safety culture, organizational influences, quality of procedures, training, and resources provided; reactions to political and regulatory pressures.

The evolution of PRA methodology has addressed each of the four Ms sequentially. Early PRAs concentrated on the effects associated with non-human influences (i.e., Man and Milieux). The HRA research conducted over the past two decades concentrated on the human influences; first at the individual (Man) level, and most recently, on the organizational influences (Management) level.

As noted, the most recent attempt to improve upon HRA methodology was the ATHEANA study (NRC 2000). The term HFE (i.e., human failure event) was introduced in that to eliminate the element of blame, which is viewed as implicit in the older term of human error. The basic premise of ATHEANA was that many HFEs are caused by contextual, or situational, conditions that virtually guarantee that the human operator will make the wrong decision or perform an unsafe act that results in a desired plant state. While the ATHEANA study provides a framework for identifying the causal factors that underlie an HFE, it does not provide a specific representation. Instead, the study adapts some of the older techniques. Further, the ATHEANA study is oriented toward the post-accident responses of NPP operators. Such risk-significant emergency responses are not relevant to a repository.

This section describes the methods that are appropriate to the PSA.

HRA Process and Structure–The processes of HRA may be addressed (via the risk triplet) by asking: what can happen, what are the consequences, and how likely is it? These questions are applied at any point in the development of an ET or FT whenever there is a known or potential human interaction with the systems or processes. Several methods have been developed to provide a structured process for addressing these questions. This section will adapt principal elements of the SHARP process, as presented in Section 7.3.4.1.

The answers to "what can happen?" identify where potential errors of commission can initiate or exacerbate an event sequence, where errors of omission can potentially occur (in which a human fails to take appropriate action to mitigate the sequence), or where the human can ameliorate the effects of prior human errors or equipment failures by performing a recovery action. Refinements of this identification process take into account the operational context (e.g., the availability of instrumentation, the occurrence of a precursor event such as equipment failure, or prior HAs). This evaluation is similar to the dependency analysis for events in an event sequence as described in Section 7.1.

The answers to "what are the consequences?" require the knowledge of the likely system response given the HA. If a human closes a switch in the wrong system, or in the right system at the wrong time, how does the facility respond? Does this action require rapid recovery to avoid a significant release of radioactivity, or is it benign? If the consequences are deemed significant in quantifying the frequencies or radiological consequences of event sequences, then the third question will be addressed.

The answer to "how likely is it?" may be easy to answer for some well-known, generic HAs or could involve an extensive analysis. In some applications, it is efficient to perform a

conservative quantitative screening by assigning a high probability to the event, such as 1.0. If the HA is not revealed as a significant contributor to the FT top event probability, or a sequence frequency, then the HA can be eliminated through the screening process and not subjected to a detailed analysis.

There are several different methods for representation and quantification of probabilities of human errors. Many of these methods are aimed at particular types of HAs. As part of the structured approach to HRA, potential human interactions are categorized as one of three types:

- **Type A**–Type A characterizes human events that occur before the IE of an event sequence. Type A HAs are typically are related to testing and maintenance (T&M) wherein a system is left in a state of unavailability or under-capacity. Errors of commission and errors of omission can occur. This type of human interaction may be termed latent because its effect on the progression of an accident is unrevealed until the system is called upon. The potential effects of Type A human interactions on system unavailability are usually modeled in FTs.

- **Type B**–Type B characterizes human events that are caused by or contribute to an IE. Such events are not usually analyzed in PRAs for nuclear plants for which experience data exist for IEs. The human-related causes are considered to be implicit in the historical data. This implicitness also may be true for some IEs for a repository. In general, Type B events should be considered for first-of-a-kind facilities such as a repository. Such human events are usually errors of commission. Type B events are modeled in FTs to quantify the likelihood of an IE.

- **Type C**–Type C characterizes human events that occur after an IE as part of the process of mitigating an event sequence. Errors of commission and errors of omission can occur. The influence of Type C events on event sequences is modeled primarily in ETs. For some HRA quantification, it is appropriate to sub-divide Type C into:

  - **Type CP**–This subtype refers to human interactions that are procedurally driven by formal procedures (written emergency operating) or by informal procedures (learned training) that guide the human operator in performing a series of steps

  - **Type CR**–This subtype refers to recoveries of unavailable systems and of prior human errors. Such HAs may not be part of a procedure, but they rely on the knowledge of the operating crew.

This guide recommends techniques deemed appropriate for the PSA for each category.

7.3.4.1 Structured and Systematic Approach for Incorporating Human Reliability Analysis into Preclosure Safety Analysis

One approach for structuring the responses to the risk-triplet questions is termed SHARP (Hannaman and Spurgin 1984). The SHARP1 process (Wakefield et al. 1992) enhances SHARP, but this effort primarily is a rebundling of the seven steps into the first two of four

stages (the other two stages are recovery analysis and internal review). These enhancements are not deemed relevant to the purposes of this guide.

The SHARP process defined seven steps for a structured, systematic approach for incorporating HRA into a PRA. It was developed originally as a means to augment an existing PRA so as to improve its treatment of HRA. Pre-existing ETs and FTs are examined for human interaction. For the PSA of a repository, however, HAs will be addressed as part of iterative development of ETs and FTs as the design details evolve. Much of the SHARP guidance fits well. Since all PSA analyses, including HRA, will be performed and documented according to Yucca Mountain Project procedures, the SHARP Step 7 - Documentation is not addressed in this section.

Therefore, a six-step SHARP process is used as the framework for conducting the HRA portion of the PSA. The following sections define the activities of each of the following steps:

1. Identification and Logic Modeling
2. Screening
3. Task Analyses
4. Representation and Models
5. Quantification of HA Probabilities
6. Quantification of the ET or FT

7.3.4.2 Identification and Logic Modeling (Step 1)

This step may be regarded as integral to the development ET or FT logic models as described in Sections 7.1 and 7.2, respectively. In general, Type A and B human interactions will be modeled in FTs as basic events that contribute to the top event expression for SSC unavailability (Type A) or as an IE (Type B). Figure 7-14 illustrates the manner in which a Type A HA is incorporated into a system FT. Figure 7-15 illustrates the use of a Type B human interaction as a contributor to an IE. The shaded boxes in the respective figures indicate the HAs.

A Type C human interaction (after an IE) will usually be modeled in ETs, but could be modeled in an FT in the same manner as a Type A human interaction. As noted in Section 7.1, HAs may be included as one of the event headings that define the logic structure of the tree. Potential dependencies between the HA and a precursor event can be identified as described in Section 7.1. Figure 7-16 illustrates how a Type C human interaction is included in an ET. The shaded event heading in the figure indicates the HA.

Step 1 also covers situations where preliminary ET or FTs have to be modified to include HAs. For example, preliminary logic models may be high-level or functional. After design decisions are made regarding the selection of specific types of equipment to accomplish the functions (the selection of, for example, manual versus automatic controls), there will be a better understanding of where and how humans can interact with the operational systems. The logic models will be updated accordingly.

The output of Step 1 is a comprehensive list of all of the potential human interactions that affect the event sequences.

The quantification of the conditional probability of the HFE uses an appropriate method, as described in section 7.3.4.

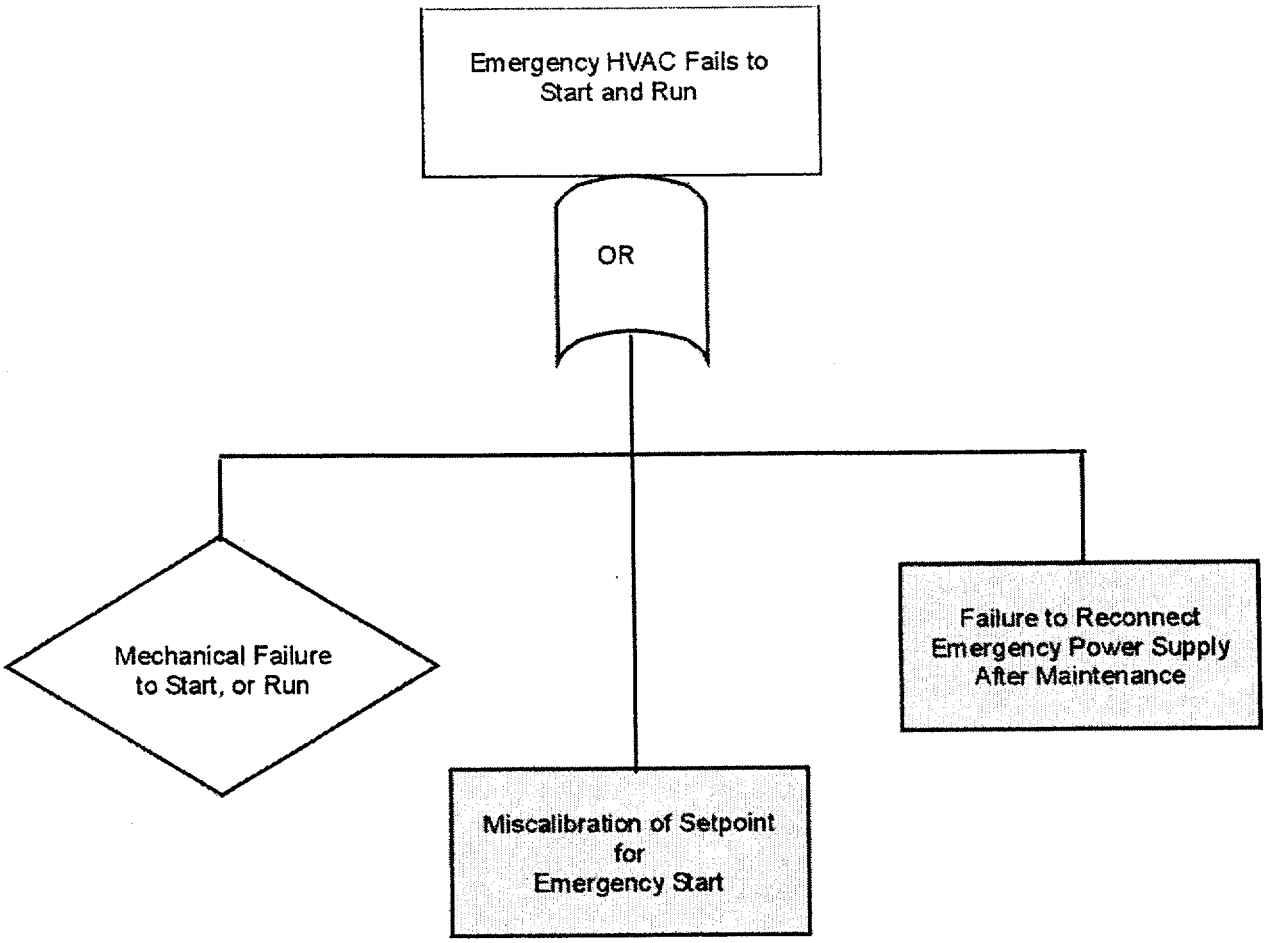


Figure 7-14. Example of Fault Tree Containing Type A Human Actions

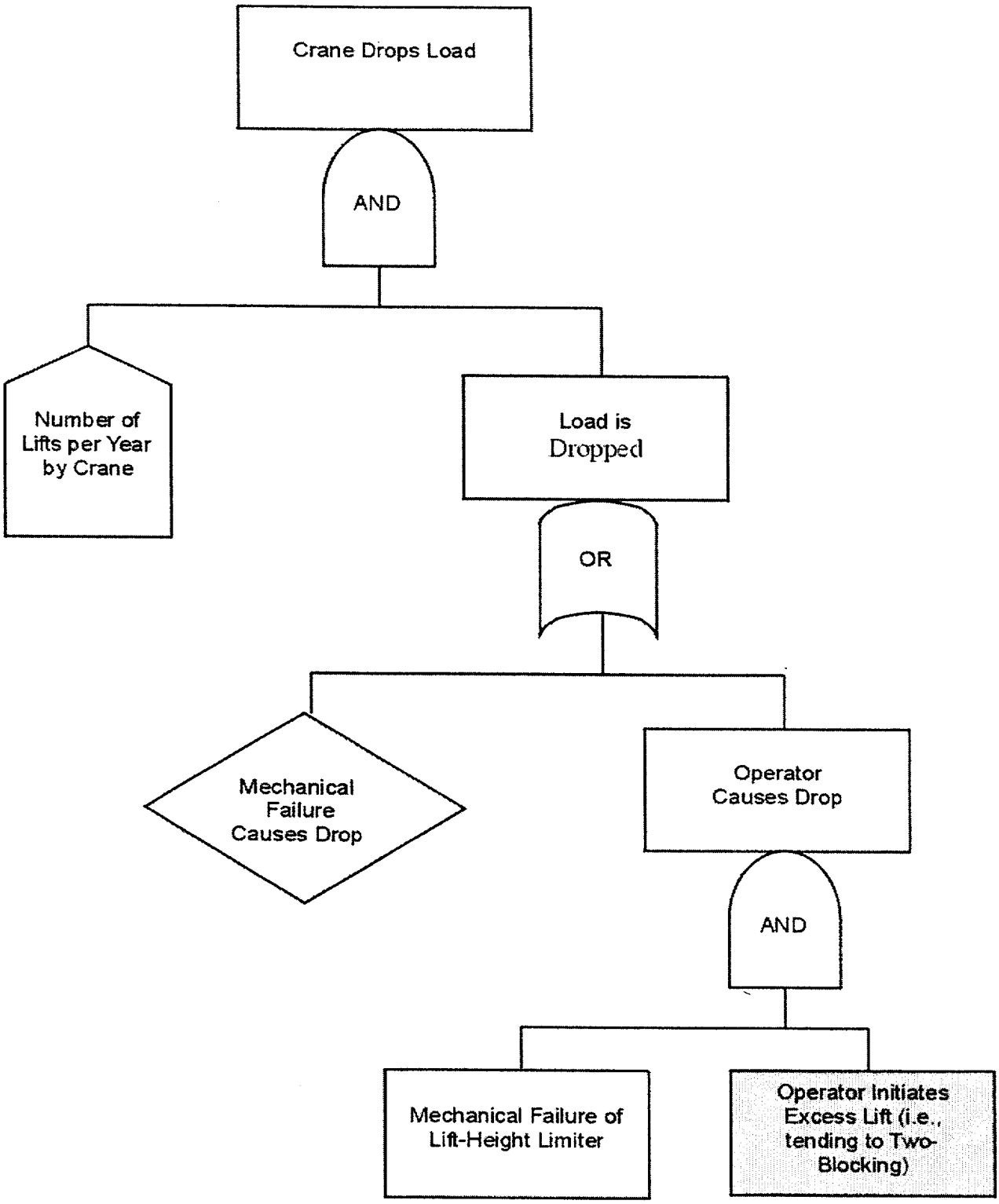


Figure 7-15. Example of Fault Tree Containing Type B Human Actions

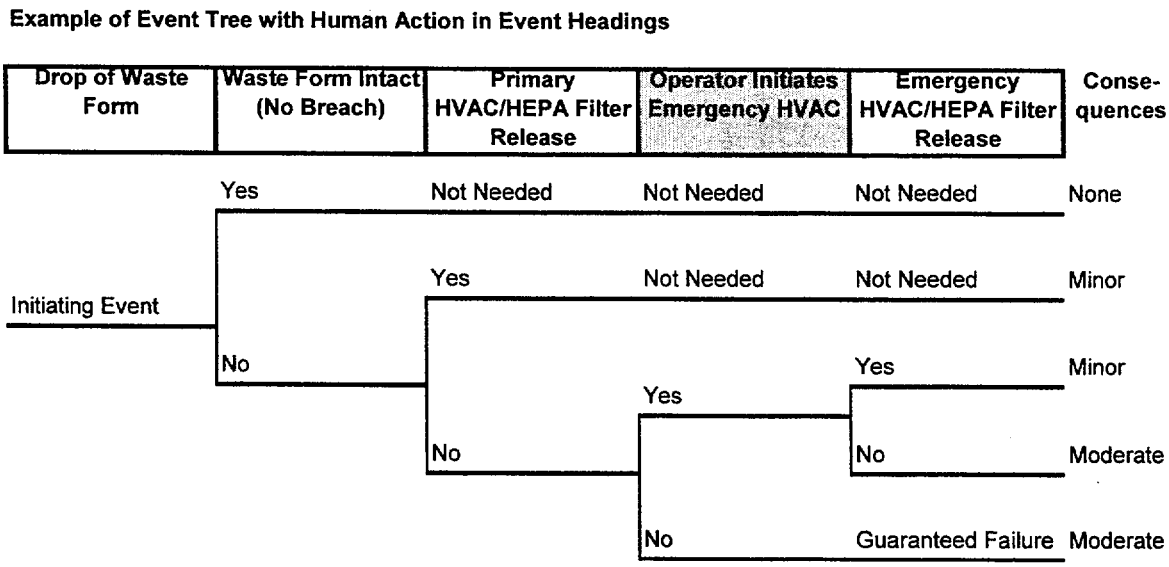


Figure 7-16. Example of Event Tree with Type C Human Action in Event Headings

7.3.4.3 Screening (Step 2)

The purpose of Step 2 is to reduce the number of HAs that require a detailed HRA. If few HAs are identified, the screening process may not be very important. Nevertheless, it is useful to survey the list of HAs to identify those of potential importance.

Screening may be performed qualitatively or quantitatively on the basis of either frequency (probability) or radiological consequences.

Qualitative screening rules are to be developed to fit the purpose of the PSA. The screening rules must be tailored to fit the safety function and the system characteristics. Examples of qualitative screening rules for Type A (pre-IE) or Type B (part of IE) human interactions include:

- Analyze (retain) miscalibration events because of potential CCFs
- Eliminate from consideration mis-alignment events where there is
  - Automatic realignment on demand signal
  - Interlocks to prevent operation with mis-alignment
  - System status indicated in control panel

Examples of qualitative screening rules for Type C human interactions include:

- Eliminate the interaction if the success or failure of the action has no influence on progression of event sequence
- Retain HAs that change the state of equipment that is required to respond to (mitigate) sequence progression
- Eliminate the interaction if physical limitations prevent action (e.g., requires access to radioactive or hostile environment, or if the time required is too short for a realistic HA).

Quantitative screening is performed as a pre-test to determine the potential significance of a given HA to the unavailability of an SSC or to event sequence frequencies. Quantitative screening should be applied to Type A human interactions because these events compete with hardware and software failures in system logic models and may only serve as backups to automatic actions. A coarse screening is performed in such cases by setting the probability of the human failure alternatively to 1.0 and 0.0 (or by using a nominal value such as 0.01 or 0.001 based on similar HAs) and comparing the top event probabilities in the two cases. If the difference is judged insignificant, then that HA does not need detailed analysis.

Quantitative screening of a HA in Type B human interactions is similar to that of Type A. If non-human initiated causes dominate the initiator, then the particular Type B HA does not require detailed analysis.

Since a Type C HA is judged important enough to explicitly model in ET headings, a probability screening may not rule out the need for a detailed analysis. On the other hand, the radiological consequences of performing a particular HA (e.g., restoring offsite power within X hours) may be insignificant. In this case, that HA may also be excluded from a detailed analysis.

7.3.4.4 Task Analyses (Step 3)

This step is the initial step of detailed HRA. In the SHARP methodology (Hannaman and Spurgin 1984), this step is termed Breakdown. The objective of this step is to identify as specifically as possible the level of available detail, the tasks or actions that the particular human is required to perform, including any time restrictions. The human may be, for example, an equipment operator, a central control room operator, a T&M technician, a health physicist, or a supervisor.

There may be detailed procedures for the specific task in mature designs. In earlier stages of design, the HR analyst will have to consult with the design and operations staff to define the principle tasks to be performed, the time restraints, and the man-machine interface that will be used (including the types and locations of controls, instrumentation, or other source of information).

A human-factors evaluation is then performed to identify the conditions and contextual environment associated with each task. The conditions and context are then used to identify the specific performance shaping factors and error-forcing conditions that will be used in the representation and quantification steps.

Table 7-1 presents an example of a task analysis for a hypothetical transfer of an SNF assembly that affects the IE and the emergency response.

It may be possible to identify and take credit for recovery actions to reduce the importance of the initial HFE as part of this step or after the quantification of the FT or ET.

7.3.4.5 Representation and Models (Step 4)

The representation is the method (or logical framework) for organizing the information developed in Step 3. Selection of a representation method for a particular HA depends on the quantification method used for the Type A, B, or C human interactions. The model is the equation(s) that result from the representation. Quantification (Step 5) is the process of assigning values to the parameters used in the model.

- Representation methods include:
  - Simple success-failure
  - HRA ET
  - HRA FT
  - Operator action tree (OAT).

Quantification methods are discussed in the Step 5.

The representation and models recommended for the PSA are described in the following sections.

7.3.4.5.1 Type A

Type A HAs are typically T&M errors (leaving an SSC in an unavailable or degraded state), calibration errors (resulting in failure to actuate automatic safety functions when the conditions require), or the failure of items such as interlocks or limit switches. The methods described in Swain and Guttmann (1983) are applicable to a repository.

Figure 7-14 illustrates a simple FT that includes two Type A HAs (the FT is developed as part of Step 1). The top event is titled "Emergency HVAC Fails to Start and Run." Three causes of the top event are shown as inputs to an OR gate. One input is titled "Mechanical Failure to Start or Run." This event is shown as diamond indicating that the logic is undeveloped (see Section 7.2). One Type A HA is titled "Miscalibration of Setpoint for Emergency Start," and the other is titled "Failure to Reconnect Emergency Power Supply After Maintenance." The top event describes a probability to start or run, q_{SR}, which is termed the unavailability of the HVAC in the sequence frequency quantification. Therefore, all of the input events must be represented as probabilities.

Table 7-1. Example of Task Analysis

Part A: Task Description and Context

Task Number	Task Description	Subtask Description	Location and Environment	Indications	Time Factor	Other Factors
1	Transport block to pickup location	Move bridge, trolley, or both into position	Control Room and Manual Control	Visual – coarse position; CRT – computer-aided positioning	Normal speed for throughput	Procedures for entire operation cycle; extensive training
2	Lower block to height for engaging load			CRT – computer aided		
3	Engage load	Operate remote grapple to mate with lifting lugs on load		Panel lights for limit-switch position		Faulty lifting lugs on package may prevent full mating
4	Raise block to transport height (e.g., so bottom of load is six inches above floor)			Visual – coarse position; CRT – computer-aided height monitor		
5	Transport load (supported by cable and block) to transfer location (move bridge, trolley, or both into position)					
6	Lower block until load is supported by target location					
7	Disengage load	Operate remote grapple to release lifting lugs on load		Panel lights for limit-switch position		Faulty lifting lugs on package may prevent release
8	Raise block to transport height (repeat cycle)					

Table 7-1. Example of Task Analysis (Continued)

Part B: Identification of Influence Factors and Potential Unsafe Acts

Task Number	Task Description	Potential Influence Factors	Potential Mistakes/Slips	Consequences of Mistake/Slip	Recovery Potential
1	Transport block to pickup location	Computer positioning miscalibrated	Mis-alignment of grapple with lifting lugs	No engagement (not a safety problem)	Manual- halt operation to calibrate computer
2	Lower block to height for engaging load				
3	Engage load	Faulty lifting lugs; failure of engagement indicators, interlocks, or both	Inadequate engagement of lugs	Uneven load; single lug engaged; slap-down of load	
4	Raise block to transport height (e.g., so bottom of load is six inches above floor)	Operator distracted – too routine; computer aided height control fails or not used	Raises load higher than procedure calls for	Potential damage to load - Contingent upon subsequent drop	Lower back to normal
5	Transport load (supported by cable and block) to transfer location (move bridge, trolley, or both into position)	Operator distracted – too routine; computer aided position and speed control fails or not used			
6	Lower block until load is supported by target location				
7	Disengage load				
8	Raise block to transport height (repeat cycle)				

Note: CRT = cathode ray tube (i.e., a computer monitor).

A representation of system or component unavailability due to a Type A maintenance or calibration error accounts for several factors:

- Initial HEP (Ei)
- Probability of non-recovery of initial error by self, crew, or supervisor (R)
- Single component or multiple components
- Whether or not the system or component availability is checked or monitored between T&M intervals (announced versus unannounced unavailability)
- The fractional time that the component or system is out-of-service (or miscalibrated) between periodic T&M.

The generalized model for Type A HAs is:

$$q_{SR,} = (p_{HE} * d)/T \quad \text{(Eq. 7-15)}$$

$$p_{HE} = E_i * R \quad \text{(Eq. 7-16)}$$

where

d = mean equipment downtime (or time in a miscalibrated state), in hours, between scheduled T&M with regular interval (T) hours; E_i and R are defined above.

If the equipment outage or miscalibration is not checked or monitored between scheduled T&M, the mean downtime is equal to the T&M interval, and

$$d = T \quad \text{(Eq. 7-17)}$$

and

$$q_{SR,} = p_{HE} = E_i * R \quad \text{(Eq. 7-18)}$$

If the equipment outage or miscalibration is checked or monitored between scheduled T&M, the mean downtime is a function of the efficiency of the checking (monitoring) function. Here efficiency is defined as the probability (C_i) of detecting a prior error during the i^{th} check that occurs at an interval (H_i) within the interval (T). In this case, the mean outage (miscalibration) of the system or component is represented as

$$d = H1 + C1 * H2 + C2 * H3 + C1\ C2 * H3 + ... \quad \text{(Eq. 7-19)}$$

Values for E_i, R, and C_i are estimated from experience data (if available) or from Swain and Guttmann (1983). Table 7-2 presents examples of the form of information contained in Swain and Guttmann (1983).

The initial error, E_i, may be either an error of commission or an error of omission. Estimates of the parameters account for factors affecting the quality of T&M, such as:

- T&M procedures
- training
- use of independent checkers
- tagging system (e.g., to avoid T&M and calibration of wrong equipment)
- administrative controls
- safety culture.

The presence and quality of these factors will have to be assumed and documented for the PSA. The application in the quantification (Step 5) accounts for these factors.

7.3.4.5.2 Type B

Type B HAs are typically operational or T&M errors that cause a system or component to change state, and thereby initiate an abnormal operating condition that could propagate to a sequence of events leading to release or exposure to radioactivity.

Figure 7-15 illustrates a simple FT that includes a Type B HA (the FT is developed as part of Step 1). The top event is titled "Crane Drops Load" in a FT representation to estimate the frequency of the event. The house event represents the frequency of opportunities for the operator to err; it is titled "Number of Lift per Year."

Two causes of the intermediate event titled "Load is Dropped" are shown as inputs to an OR gate. One input is titled "Mechanical Failure Causes Drop." This event is shown as a diamond indicating that the logic is undeveloped (see Section 7.2). The other intermediate event is titled "Operator Causes Drop." These two events will be quantified as probabilities per lift.

The event titled "Operator Causes Drop" is developed through an AND gate to represent that the event can happen only if both input events occur (i.e., that "Operator Initiates Lift > Normal Height" and "Mechanical Failure of Lift-Height Limiter" occur).

A representation for the HA titled "Operator Causes Drop" is illustrated next. The information from Step 2, Table 7-1, indicates that the operation is manually controlled. Table 7-1 defines the tasks to be performed by the operator:

- Transport the block to the pickup location (move the bridge, trolley, or both into position)
- Lower the block to the height for engaging the load
- Engage the load (e.g., operate the remote grapple to mate with the lifting lugs on the load)
- Raise the block to the transport height (e.g., so that the bottom of load is six inches above the floor)

- Transport the load (supported by a cable and block) to the transfer location (move the bridge, trolley, or both into position)
- Lower the block until the load is supported by the target location
- Disengage the load (e.g., operate the remote grapple to release the lifting lugs on load)
- Raise the block to the transport height (repeat the cycle).

The analyst now asks "what can happen?" with respect to dropping the load; that is, what erroneous actions could the operator take to cause the load to drop. While there may be several opportunities for the operator to cause the drop, this illustration will examine the task titled "Raise block to transport height." This task has the potential for causing a two-blocking event that can result in the overstressing and breaking of the lifting cable(s), resulting in a load drop from a height exceeding the normal transport height.

The operator is trained to raise the load only to the normal transport height (e.g., six inches) but the controller permits the operator to raise it higher, subject to a control interruption by an interlock that prevents the raising of the load to the two-blocking height. Each time that the operator performs the routine lift (that has been performed hundreds of times previously) a probability exists that the attention of the operator can be diverted. An initial error of commission is committed by holding the lift control too long and raising the load too high.

If the operator or other crew member realizes the commission of the initial error in a timely manner, the event can be recovered (i.e., the lift can be stopped and the load lowered). If there is no height-limiting device and no recovery, then the initial error will result in two-blocking event followed by a load drop.

The FT (Figure 7-15) leads to the following model (i.e., the boolean expression for the FT events) for estimating the frequency of the IE:

$$f_{OD} = f_{LL} * q_{HL} * E_O * R \qquad \text{(Eq. 7-20)}$$

where

f_{OD} = frequency that load drops are initiated by operator error, drops per year

f_{LL} = frequency of load lifts using crane (calculated from throughput), lifts per year

q_{HL} = probability that lift-height limiter fails on demand, probability per demand

E_O = probability of initial error that the operator attempts to raise the load to excessive height probability per opportunity (probability per routine lifting operation)

R = probability that the operator fails to recover from the initial error

As in the case of a Type A HA, the parameters E_O, and R are estimated from experience data (if available) or from Swain and Guttmann (1983). Table 7-2 presents examples of the form of

information contained in Swain and Guttmann. Estimates of the hardware unavailability (q_{HL}) are obtained from experience (see Section 7.5) or through FTA (see Section 7.2).

7.3.4.5.3 Type C

Type C HAs are actions taken by an operator in response to an IE or another event. The HAs of interest are those taken to prevent an event sequence from progressing toward a worse state, actions taken to mitigate the consequences of an event sequence, or actions taken that worsen the situation. Generally, such HAs are included in the heading of the ET for a given IE. It is particularly important to show the HA in the ET headings if there are dependencies between the success of the HA and prior events in the ET or if the success or failure of the HA represents a significant turning point in the evolution of event sequences (see Section 7.1).

For example, an ET heading titled "Operator Starts Emergency HVAC" might be an important action that would prevent a significant release of radioactivity following the drop and breach of a waste form, followed by an event titled "Loss of normal HVAC." This action warrants its inclusion in an ET heading. The operator may be prompted early in the sequence to initiate the action by an alarm (e.g., radiation alarm, or loss of normal HVAC alarm), an operator, or (later) by secondary indications (e.g., radiation alarms in stack monitors). In addition there may be no secondary prompt; instead, the indication may rely solely on the attentiveness of the operator (and other staff). The success or failure of the alarm or prompts to alert the operator represent alternative conditions that affect the probability of the success or failure of the operator performing the HA. Thus, the representation of the probability of human failure must account for the dependency on the prompt.

In other cases, a Type C HA may be modeled as part of an FT for a system failure event that is represented in an ET heading. This is the case, for example, for a backup operator action to manually actuate a system that is supposed to start automatically. The ET heading represents the operation of the system; for example, a heading titled "Emergency AC power is available." The system is supposed to start automatically on the loss of voltage of the primary power supply. The system FT for the failure event titled "Emergency AC power is unavailable" would include events representing the failure of components, including the failure of the actuation function. The backup operator action titled "Operator fails to actuate emergency AC power" would be ANDed with the automatic actuation event in the FT.

The following sections present representations for the respective cases of Type C HAs.

7.3.4.5.3.1 Type C HAs in Event Tree Headings

This type of Type C HA has been the subject of a considerable amount of research and development, as well as the subject of a considerable amount of controversy.

The principal research on this HA has been directed toward a better understanding, representation, and quantification of the reliability of the operators of NPPs in preventing and mitigating severe accidents. Severe accidents for NPPs are event sequences that progress to undesired plant damage states that exceed the design basis accidents; namely, core damage and, possibly, loss of secondary containment. Because the probability of human error involves cognitive processes, this research has involved various multi-disciplinary teams of system-safety

and PRA practitioners, behavioral scientists, human-factors specialist, NPP operators and operations supervisors, and operator training personnel.

Table 7-2. Example Probabilities of Errors of Commission in Operating Manual Controls

Item	Potential Errors	HEP[a]	Error Factor
	Select wrong control on a panel from an array of similar-appearing controls:[b]		
(2)	identified by labels only	0.003	3
(3)	arranged in well-defined functional groups	0.001	3
(4)	which are part of a well-defined mimic layout	0.0005	10
	Turn rotary control in wrong direction (for two-position switches, see item 8):		
(5)	when there is no violation of population stereotypes	0.0005	10
(6)	when design violates a strong population stereotype and operating conditions are normal	0.05	5
(7)	when design violates a strong population stereotype and operation is under high stress	0.5	5
(8)	Turn a two-position switch in wrong direction or leave it in the wrong setting	[c]	

Source: Modified from Swain and Guttmann (1983, Table 20-12)

NOTES: [a] The HEPs are for errors of commission only and do not include any error of decision as to which controls to activate.

[b] If controls or circuit breakers are to be restored and are tagged, adjust the tabled HEPs according to Swain and Guttmann (1983, Table 20-15).

[c] Divide HEPs for rotary controls (Items 5 through 7) by 5 (use same EFs).

The HAs of most interest to NPP risk assessment are, typically, time-critical and are performed when the operators are under extreme stress because they understand the severity of the evolving situation. There are other Type C HAs, however, that are risk-significant for NPPs that are not as time-critical. These differences have led to different types of representations for the two classes of Type C HAs.

The hazards and operations associated with a repository do not pose demands on the operators with the severity of those associated with NPPs. In addition, the risk profile of a repository is not expected to be very sensitive to operator reliability for Type C HAs. Nevertheless, the efforts of the past three decades have led to advances in the understanding and development of alternative methods for the representation and quantification that can be applied in the PSA, where appropriate, to Type C HAs.

7.3.4.5.3.2 Operator Action Tree

The operator action tree (OAT) shown in Figure 7-17 is a generalized representation of Type C HAs. The OAT is an ET. There are two main phases of operator response that are indicated across the top of the figure: detection, diagnosis, and decision phase, as well as Manual Action. The OAT, as shown, represents both time critical and non-time critical HAs. Two ET headings comprise the detection, diagnosis, and decision phase: Cognitive Processing/Procedural Mistakes and Failure to Process Information in a Timely Manner.

The event heading titled "Cognitive Processing/Procedural Mistakes" covers all of the information gathering and diagnosis that the operator performs (e.g., through the instrumentation or through phone calls from local operators) that make the operator aware of an off-normal situation. The indications are symptoms that are indicative of an event. Operators are trained to use the symptoms to diagnose the event and initiate appropriate actions.

As shown in the OAT, the failure to diagnose the event leads to a failure to perform the Type C HA, as indicated by the "F" at the endstate. The probability of this failure is shown as p_1 in the figure. The representation, modeling, and quantification of p_1 have been the principal subjects of HRA research. Most recently, it was the primary motivation for the ATHEANA project (NRC 2000). Methods for quantifying p_1 are discussed in a following section.

The event heading titled "Failure to Process Information in a Timely Manner" means that there is a finite time window within which the manual action must be started; if not, the action is performed too late. This non-action results in a failure to perform the Type C HA, as indicated by the "F" at the endstate. The probability of this failure is shown as p_2 in the figure. Representation, modeling, and quantification of p_2 have also been subjects of HRA research (e.g., Moieni et al. 1993). If the particular HA is not time-critical, this event heading, sequence branch, and endstate are deleted from the OAT.

The event heading in the Manual Action phase of the OAT is labeled "Manipulative Slips." The term slips is used to denote that at this point, the operator knows what to do and moves to the appropriate control to execute the desired action. For various reasons, including poor ergonomic design, the operator selects the wrong control or moves it to the wrong position. In addition, p_3 includes the probability that all steps in a control action are not completed, or not completed within a required time window. The result is a failure to perform the Type C HA, as indicated by the "F" in the endstate. The probability of the slip is indicated by p_3 in the figure.

The probabilities, p_1 and p_3, (Figure 7-17) represent non-recovered mistakes and slips. For some of the Type A and Type B HAs, the final probability represents a product

$$p_i = E_i * R_i \qquad \text{(Eq. 7-21)}$$

where

E_i = probability of initial mistake (or slip) i
R_I = probability of non-recovery of initial mistake (slip) i

The probability, p_2, includes an implicit failure to recover.

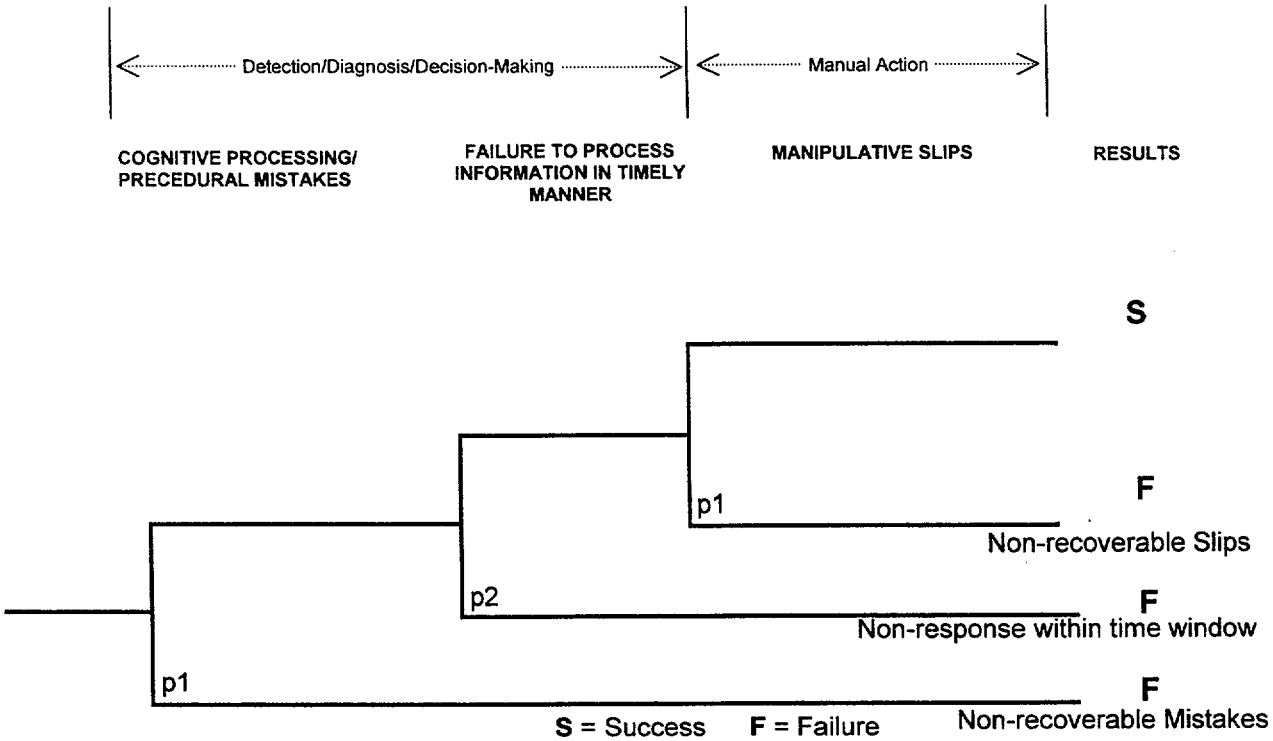


Figure 7-17. Operator Action Tree: A Generalized Representation of Type C HAs

The probability of failing to perform the particular Type C HA is the sum of the three failure branches of the OAT (labeled F):

$$p_{HA} = p_1 + p_2 + p_3 \qquad \text{(Eq. 7-22)}$$

The following sections describe the representations and models for the respective probabilities (p_1, p_2, and p_3). This is an elaboration of Step 4. These sections also describe the bases for quantifying the probabilities, which is Step 5.

7.3.4.5.3.3 Representation, Modeling, and Quantifying p_1

Several methods have been developed for defining p_1 for NPP applications (e.g., Moieni et al. 1993). This portion of the detection, diagnosis, and decision phase for NPPs typically involves the use of emergency operating procedures that the operators follow to diagnose and respond to the event. Currently, NPPs use symptom-based emergency operating procedures that support decision making with cascading IF–THEN statements. While a repository will have emergency operating procedures, it is unlikely that they will be as complex as those of NPPs.

All of the methods provide some means of identifying and quantifying the effects of causal factors (or error forcing conditions) and Performance Shaping Factors that affect the probability. Typical causal factors might be:

- Erroneous or incomplete procedures (e.g., have inadequate validation and verification)
- Inadequate training to help diagnose, or apply procedures

- Inadequate instrumentation or alarms
- Miscommunication among crew members

Alternative approaches for p_1 include:

- Swain and Guttmann (1983, Chapter 20)
- Decision tree (Moieni et al. 1993)
- ATHEANA (NRC 2000)

Most of the approaches for p_1 appear to be too complex, inappropriate, or both, for the types of operator actions expected in a repository. These alternative methods will be reviewed and adapted as appropriate to the PSA

7.3.4.5.3.4 Representation, Modeling, and Quantifying p_2

[Information for this section is under development and will be provided later.]

7.3.4.5.3.5 Representation, Models, and Quantification of p_3

The p_3 probability represents the chance of a non-recovered slip by control operators or the probability of not completing all steps in a control action within the required time window. This type of HA is generally viewed as non-cognitive and the requirements are well known to the trained operator.

Alternative representations of p_3 depend on the complexity of the manual actions to be performed. If the action is simple, such as changing the position of a single switch or controller, then a binary, success or failure, representation suffices. If the action requires multiple steps then either a HR FT or Swain and Guttmann HRA tree can be used to delineate the various steps and the conditional probabilities of the sequential steps. These representations include dependencies between steps.

The representation, modeling, and quantification must include the effects of performance shaping factors (e.g., quality of ergonomic interface of indicators, controls, communications, training, and the complexity of task) for all of the representations.

The basic source of information on quantification is the *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Operations* (Swain and Guttmann 1983). This handbook has extensive tables of generic error types. For example, the error titled "Select wrong control on a panel from an array of similar-appearing controls" (Swain and Guttmann 1983, Table 20-12; see also Section 7.2) and the recommended values for the HEP and EF for lognormal (LN) distribution are presented. See Section 7.6 and Section 9 for discussions of uncertainties and EFs.

The HEP values and EFs are given for various configurations and operating conditions. For the example previously quoted, the HEP and EF are 0.003 and 3, respectively, if controls are identified by labels only. If the control is part of a panel where controls are arranged in a well-delineated functional groups, then the HEP is given as 0.001 with an EF of 3. Further, several ancillary tables provide adjustments for various performance-shaping factors and operating

conditions. Again, for the example quoted, a footnote reads "if controls ... are to be restored and are tagged, adjust the tabled HEPs according to Table 20-15."

For a single step HA, such as an HA titled "Start emergency HVAC with Switch No. 1234," located in a well-delineated functional group with no performance shaping factors outside the nominal range, the representation and quantification are given as:

$$p_3 = \text{HEP (tabulated for conditions, adjusted for performance shaping factors) with EF} \quad \text{(Eq. 7-23)}$$
$$= 0.001 \text{ (EF = 3)}$$

The representation for multiple-step HAs is a compounding of the single action case with consideration of dependencies. That is, if the operator slips on the first action without recovery, the execution of the second and subsequent actions may be missed because the operator is executing a practiced, but erroneous, series of manipulations. The representation is an HRA tree or an HR FT, depending on the HA to be modeled.

As an example, a HRA tree is illustrated in Figure 7-18. The control action consists of two steps: "Start emergency HVAC with Switch No. 1234," which is located in a well-delineated functional group; and "Close HVAC damper between Zones 2 and 3 with switch D56." This action requires that the switch be held in the closed position until the damper completely closes. Swain and Guttmann (1983, Table 20-12, Item 10) gives this HEP as 0.003 (EF = 3).

Figure 7-18 illustrates an HRA tree for this HA. Following the convention of Swain and Guttmann (1983), the branches labeled with capital letters represent failure to execute and small letters are the success branches. If there are no recoveries, the representation for p_3 is:

$$p_3 = A + B \quad \text{(Eq. 7-24)}$$

and the quantification is:

$$p_3 = HEP_A + HEP_B \text{ (with composite EF)} \quad \text{(Eq. 7-25)}$$
$$= 0.001 + 0.003 = 0.004 \text{ (EF > 3)}$$

Where HEP_A and HEP_B are the human error probabilities for actions A and B, respectively.

If recoveries are possible at Step 1 or Step 2 (illustrated by dashed lines in Figure 7-18), the probabilities of non-recovery (R_A and R_B) are inserted into the representation as follows:

$$p_3 = HEP_A * R_A + HEP_B * R_B \text{ (with composite EF)} \quad \text{(Eq. 7-26)}$$

For example, if $R_A = 0.1$ and $R_B = 1$ (non-recoverable) the quantification becomes:

$$p_3 = (0.001)*(0.1) + (0.003) * (1.0) = 0.0031 \text{ (with composite EF)} \quad \text{(Eq. 7-27)}$$

The representation must also consider if the order of execution is important because of potential dependencies. For example, suppose the HVAC damper has to be fully closed before the emergency HVAC can be started (i.e., an interlock prohibits starting the HVAC). In this

particular example, the representation is further complicated by the dependency on the reliability of the hardware (interlock) as well as the human reliability:

$$p_3 = HEP_B + HEP_A * (1 - q_{IL}) + q_{IL}, \text{ (no recovery)} \quad \text{(Eq. 7-28)}$$

where

q_{IL} = probability of failure of interlock, failures per demand

If $q_{IF} = 0.0001$, for example, p_3 is quantified as:

$$p_3 = 0.003 + 0.001 * (1 - 0.0001) + 0.0001$$
$$= 0.0032$$

7.3.4.6 Quantification of Human Action Probabilities (Step 5)

[Information for this section is under development and will be provided later.]

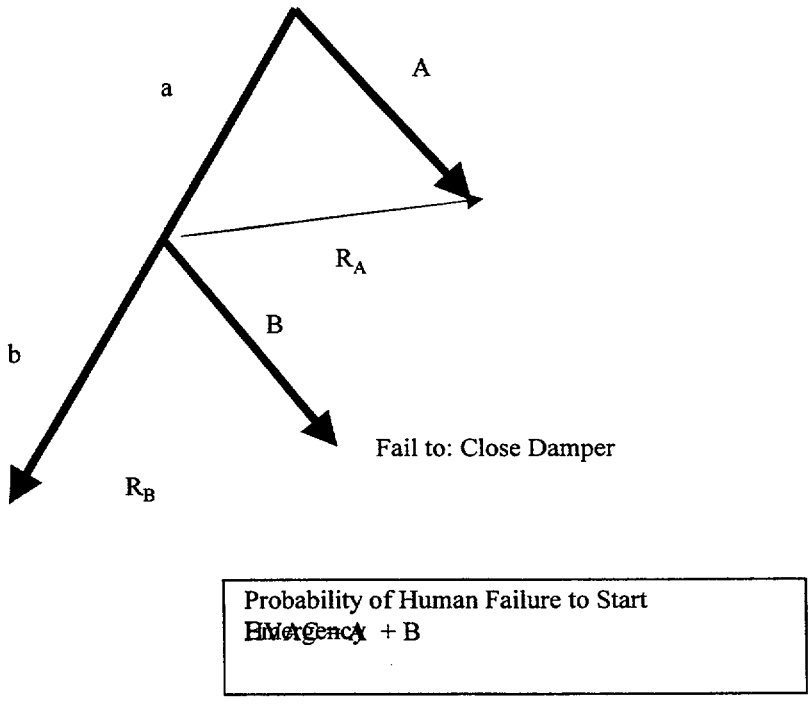


Figure 7-18. Example of Human Reliability Analysis Tree

7.3.4.7 Quantification of Event Tree/Fault Tree (Step 6)

This step is just a re-statement of the outputs of Sections 7.1 and 7.2, respectively. When all of the HA probabilities (and uncertainties) have been quantified, they are incorporated into the logic models. Quantification of the FT top event gives SSC unavailabilities, or IE frequencies, with the effects of HA. Quantification of event sequence frequencies illustrate the influence of HAs and any recovery actions that have been quantified.

7.3.5 Examples

[Information for this section is under development and will be provided later.]

7.4 COMMON-CAUSE AND DEPENDENT FAILURES ANALYSIS

7.4.1 Purpose

This guide defines the bases and methods for identifying and analyzing common-cause and dependent failures in support of the PSA. These common-cause failures (CCFs) and dependent failure analyses support event sequence analyses through applications in ETA and FTA. In addition, this section provides a link to HRA, which is an important contributor to CCFs and dependent failures.

7.4.2 Scope

This section is a guide to the identification and analysis of common-cause and dependent failures. While some concepts and methods are universal to safety and risk analyses of nuclear, chemical, and other facilities, the approaches and examples are focused on the support of a repository PSA. The guide provides methods that are expected to be acceptable to the NRC. The guide is not meant to be a textbook or exhaustive. Where appropriate, reference is made to literature for additional information. Examples of CCF applications are described in the discussions of ETA (Section 7.1), FTA (Section 7.2), and Seismic Analysis (Section 10.1).

In particular, this section will provide guidance in the following areas:

- Method(s) used to identify and screen important dependent failures in SSCs that affect preclosure safety
- Application of qualitative versus quantitative evaluations, where qualitative analysis is used to postulate, identify, and eliminate potential dependent failures through a screening process
- Quantitative methods for use when evaluating FTs, ETs, and event sequence frequencies
- Data requirements and sources
- Treatment of external events as potential common-cause IEs and how dependent failures of SSCs are conditionally linked to external hazard frequency
- Differences in approach and level of design detail and operational detail considered for the LA submittal for CA in contrast to the LA submittal to receive and possess nuclear materials
- Application of software packages (e.g., SAPHIRE, and the Microsoft Excel spreadsheet program)

7.4.3 Overview of Approach

The term common cause events refers to a specific class of dependent events that must be considered in reliability analyses of safety systems in support of a PSA or PRA. Common cause

failures are encountered when considering the causes of, and probabilities of, basic events at the component level in system logic models (e.g., FTs).

"Explicit" dependent failure is used to define those dependent events that can be directly attributed to physical phenomena and identifiable causal factors. Causal factors include inter-system dependencies that are hard-wired inter-connections; physical interactions between components or systems, such as missiles or sprays; environmental factors such as extreme temperatures or humidity; and human actions, including miscalibration of instruments or test and maintenance. The probabilities of such dependent events are quantified with appropriate equipment failure rates, test and maintenance intervals, and human-error probabilities. In some cases, physical interaction probabilities can be explicitly calculated, such as the probability of a spray or missile from the first failed component causing a failure in two or more additional components in the same or different systems.

System analysts include the explicit dependent failures in the system or plant logic models. That is, functional dependencies can be indicated in ETs to impose boundary conditions on event probabilities for events that occur later in the ET. In addition, functional dependencies of front line systems on support system are directly modeled in FTs as either basic (or undeveloped) events or as a transfer to the FT model of the support system. Likewise, cascading or propagating failures and operator actions to respond to events are modeled explicitly. Identified maintenance errors are modeled directly in the FTs.

By contrast, "implicit" dependent failures is used to define the potential occurrence of unidentified specific causal factors that can defeat the independence between redundant systems or components. Such dependencies are modeled in ET and FT logic as basic events as "pseudo-components" that are not physically present in the system design. The probabilities of such events are quantified using "implicit" or "parametric" analyses in which the failure rate information for various components is partitioned into independent and dependent rates.

Initially the plant or system logic model (e.g., FT) is developed with the basic events considered to be independent failures. Explicit intersystem dependencies are modeled as described above. Potential dependencies among components (basic events) that have not been explicitly modeled in the logic model are identified and modeled as pseudo-events in the FT models to represent CCFs. The probabilities of the CCFs are quantified with methods described in NUREG/CR–4780 (Mosleh et al. 1988). Only a brief acknowledgement of alternative methods is provided here since the simplest model for CCF analysis, the beta factor model, suffices for most preclosure safety analyses of a repository. The methods for the LA submittal for CA are presented. If deemed appropriate, this desktop guide can be revised to include more advanced methods of treating CCFs.

7.4.3.1 Definitions

The following are definitions (NUREG/CR-4780 [Mosleh et al. 1988]) of the principal terms that are used in this section.

Independent Event–This is an event in which a component state occurs causally unrelated to any other component state. Two events, A and B, are independent if and only if:

$$p(A|B) = p(A), \text{ and } p(B|A) = p(B) \quad \text{(Eq. 7-29a)}$$

such that

$$p(A \text{ and } B) = p(A) * p(B) \quad \text{(Eq. 7-29b)}$$

where

$p(x|y)$ = probability of occurrence of event x given the occurrence of event y, and

$p(x)$ = probability of occurrence of event x.

Dependent Event–This event does not satisfy the definition of an independent event. Two events, A and B, are dependent if and only if:

$$p(A \text{ and } B) = p(A) * p(B|A) = p(B)*p(A|B) \neq p(A) * p(B) \quad \text{(Eq. 7-30)}$$

and more importantly

$$p(A \text{ and } B) > p(A) * p(B) \quad \text{(Eq. 7-31)}$$

Common Cause Event–In the context of system modeling, common cause events are a subset of dependent events in which two or more component fault states exist at the same time or in a short time interval and are a direct result of a shared cause. NUREG/CR-4780 (Mosleh et al. 1988) does not attempt to provide a clear and unambiguous definition of common cause events for all purposes. It is implied that the shared cause is not another component state because such cascading failures are modeled explicitly in the system models. The common cause is termed a root cause applied at the component level.

Root Causes–Root causes ideally can be traced to an event that occurred at some prior time. There are four general types of root causes:

- Hardware and software–inherent defects
- Human errors–operations, T&M, design, construction
- Environmental–events external to the equipment but internal to the facility or operation that result in abnormal stresses in the equipment
- External–events external to the facility that result in abnormal stresses in the equipment

Coupling Mechanism–A coupling mechanism is a means by which a root cause propagates to involve multiple components or subsystems. Three broad categories of coupling mechanisms are identified:

- Functional Couplings
- Spatial Couplings
- Human Couplings

Table 7-3 describes some examples of each of these coupling mechanisms.

Table 7-3. Types of Dependent Events Based on their Impact on Preclosure Safety of a Repository

Dependent Event Type	Characteristics	Subtypes (Coupling Mechanism)	Examples
1. Common Cause IE	Causes challenge to facility design or operations, and concurrently increases likelihood that one or more prevention or mitigation SSCs will fail	Functional Spatial Human	Loss of Offsite Power Earthquake or fire Maintenance error in main control room
2. Intersystem Dependency	Causes a dependency in a joint event probability involving two or more systems	Functional Spatial Human	Two trains of instrumentation and control fail because electric power supply fails Fire in one instrument cluster causes failure in others in proximity Operator error causes loss of two or more systems
3. Intercomponent (Intrasystem) Dependency	Causes a dependency in a joint event probability involving two or more components	Functional Spatial Human	Crane cable(s) break after two-block prevention features fail Failure of one of two crane cables allows rigging to tilt and sever second cable Installation of wrong lifting fixture permits crane two blocking and break of cables

Source: Modified from NUREG/CR-4780 (Mosleh et al. 1988, Table 2-1)

Common Cause Component Group–This is a group of components (usually similar) that are considered to have a high potential of failing due to the same cause.

Defensive Strategy–A defensive strategy is a measure taken to diminish the probability and consequences of common cause failures. Operations, maintenance, design, and surveillance are areas where defensive strategies can be applied.

Explicit Analyses–Explicit analyses of dependent or CCF failures are identified from specific potential root causes and coupling mechanisms. Inter-component or inter-system dependencies are shown explicitly in logic models (e.g., ETs and FTs). Conditional probabilities of dependent events are evaluated from consideration of vulnerabilities in the target component or system and opportunities for the coupling mechanism to link the root cause (triggering event) to failure of the target.

Implicit (or Parametric) Analyses–Implicit analyses of dependent or CCF failures are used when the possibility of dependent failure is known (or suspected) to exist but specific root causes and coupling mechanisms cannot be identified or quantified. Inter-component or inter-system dependencies are shown explicitly in the system logic models (principally FTs) to represent implicit events. Conditional probabilities of dependent failure are estimated using various parametric approaches such as the beta factor method.

Parametric Analyses–See the definition of implicit analyses).

Primary (Front-Line) System–A primary system is one that provides a direct function in the handling, packaging, or transporting a high-level radioactive waste form. Of particular importance are the front-line systems important to safety that prevent or mitigate potential unwanted sequences of events. Such front-line safety systems may be slated for single-failure-proof-, or fail-safe, design principles. The HVAC/HEPA filter system in the waste handling building of the surface facility is an example of an important front-line system. Analyses of dependent and CCFs can help to provide assurance that such systems perform their intended safety functions with adequate reliability.

Support (Secondary) System–A support system is one that provides an indirect function in the handling, packaging, or transporting of a high-level radioactive waste form by providing essential support to the front-line systems. An important support system for the safety of repository operations is the electrical supply system. Virtually every operation in a repository is dependent on electric power. Although many devices can be designed to halt in a safe mode on the loss of a power supply, other devices (i.e., HVAC/HEPA filters, instrumentation, or control systems) cannot. Thus, there is an explicit coupling (dependency) between the front-line system and the support system.

7.4.3.2 Background Discussion

The analysis of common-cause and dependent failures is a subtopic of PSAs.

A CCF (sometimes called common-mode failure, although there is a distinction) can be considered to be a special case of dependent failures. Dependent failures, as a class, are so-named to distinguish them from independent failures. Independent failures are sometimes termed random failures, but this is a misnomer since dependent failures can also occur randomly in time.

Common-cause and dependent failures are important considerations in the analysis of SSCs that are intended to be highly reliable in preventing or mitigating the effects of potential hazards. Considerations of common-cause and dependent failures are important whenever redundant components or subsystems (or alternative success paths) have been provided for safety and reliability. The treatment of common-cause and dependent failures contrasts with traditional reliability analyses and single-failure-proof design approaches that implicitly assume that only independent failures can occur among two or more redundant components or subsystems.

Dependent failures result from the coexistence of two factors: a susceptibility for components to fail or be unavailable from a particular root cause and a coupling mechanism.

For example, two components located in the same room might be susceptible to failure if the humidity exceeds some level. An event such as a rupture of a hot-water or steam pipe would result in extreme humidity and induce a dependent failure of the two components. High humidity from the steam break would be the root cause of the component failure. The fact that the components are situated in the same room where there is a source of water or steam is the coupling mechanism.

Design errors can also result in dependent failures. For example, the redundant safety injection system at one NPP failed because the motor-operated valves in both of the redundant pump trains were undersized and unable to open against the pressure. The root cause was the design process and the coupling mechanism was the use of identical valves and common demand conditions in addition to the lack of adequate surveillance tests. An analogous situation could occur in a repository. For example, if the braking power of each of two redundant and diverse brake systems on the emplacement transporter was designed to be inadequate, then the effect of having a redundant backup system might be negligible. Or, the design might be such that the primary brake system fails in such a way to cause a spray or missile to induce failure of the backup system. Generally, CCFs due to system design flows are eliminated through design reviews, including fault tree analysis and quality assurance. As the design of a repository evolves, PSA specialists can help in design reviews to eliminate potential common cause failures. Potential design flaws must be evaluated implicitly as one of the non-specific common causes during the preliminary design phases.

Figure 7-19 (based on Mosleh et al. 1988) illustrates the general model for consideration of dependent failures or CCFs. A root cause interacts with each of the multiple components labeled A through N by the means of a coupling mechanism. A defense strategy may be employed to prevent dependent failures or reduce their likelihood. A defense strategy attacks any or all of the elements in the figure by eliminating or reducing the root cause, eliminating or reducing the coupling mechanism, or by making each component less susceptible to the root cause or the coupling mechanism (one means of achieving the latter might be to use diverse components). Table 7-3 illustrates several typical root causes and coupling mechanisms.

A dependent failure of two or more redundant SSCs can occur when there is a coupling mechanism that links a causal agent to the failure of the multiple SSCs. In some cases (usually termed physical interaction dependencies), the failure of one component may cause a domino effect, such that a missile, spray, excess stress, water hammer, or other mechanism induces the failure of two (or more) of the redundant components. Design and operational features can be provided to eliminate such physical interactions, once identified.

Another type of dependent failure among redundant SSCs occurs when two or more components or subsystems are dependent on the same support system. For example, if all of the fan motors in a HVAC/HEPA filter system are connected to the same power bus, all fans will fail to run if the power system fails. Design features can eliminate such dependencies or displace them a lower level (e.g., by providing redundant offsite and onsite power distribution systems).

Source: modified from NRC (1987)

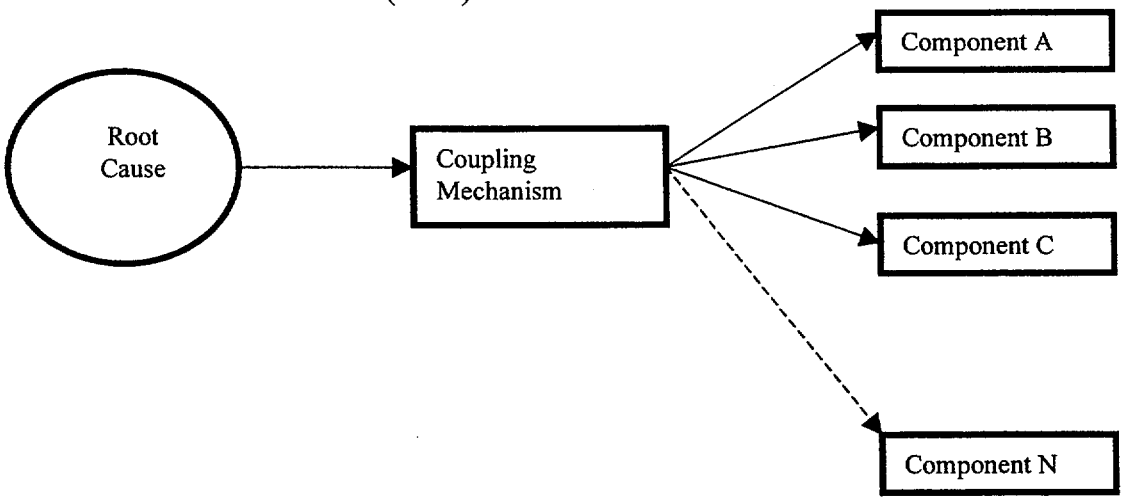


Figure 7-19. Physical Elements of Dependent Events

A CCF of two or more redundant SSCs, as noted, is a special designation for dependent failures that are caused by coupling mechanisms other than physical interactions or systemic dependencies. Such CCFs may arise from common maintenance errors, common calibration errors, inadequate design (capacity), abnormal loads, or other situations that result in multiple components (or systems) failing in response to a given demand or during a given mission time.

Insights from the PRAs of nuclear plants and quantitative risk analysis of chemical process plants, as well as events such as the Three Mile Island incident and Challenger explosion, have revealed the significance of CCFs in potential accidents. The identification and elimination of potential CCFs are now part of safety design and operations.

In addition, studies have shown that CCFs (identified or unidentified) limit the practical reliability that is achievable in engineered systems. Even with the use of redundant and diverse channels (trains), there appear to be limits on the lowest probability of failure that can be achieved. Table 7-4 summarizes s commentary in Watson (1987) on the reliability achievable with various system configurations employing varying degrees of redundancy and diversity. It is noted that the lowest limit for fully diverse and redundant systems is approximately 10^{-6} per demand. Therefore, any system analysis for active repository systems that yields a failure probability less than 10^{-6} should be challenged and reviewed to ensure that all potential causes of CCF and dependent failures have been identified. In most cases, failure causes deemed unimportant at the beginning of modeling or design evolution become dominant after all other identified causes have been defended against or designed out. This does not mean that lower probabilities are to be categorically dismissed, but only that the analysis is subject to scrutiny if major safety decisions are based on such analyses.

7.4.4 Details of Approach

The analysis of CCFs and dependent failures may take many forms. In explicit analyses, potential dependent or CCF failure models are identified from specific potential root causes and probabilities of common-cause events are evaluated from a consideration of vulnerabilities and

opportunities for coupling via spatial, functional, environmental, or human interactions. In implicit analyses (also termed parametric modeling), it is assumed that a small fraction of the total failure probability of a component or system is attributed to CCFs of indeterminate or non-specific causes. The small fraction of CCFs is included in system reliability models though parameters derived from experience data or through judgement. The well-known beta-factor method is an example of an implicit or parametric model.

Table 7-4. A Guide to Unreliability of Various System Arrangements with Consideration of Dependent Failures

System Arrangement[a]	Description and Features	Range of Unreliability Factors[b]
Single Channel System	The simplest form of a system having a single input module and single processor or output module. The lower limit of probability of failure is about 10^{-2}. Adding a redundant channel can improve the reliability to about 10^{-4} if only independent failures can occur. But the effects of CCF become apparent.	0.2 to 10^{-2}
Partly Redundant System	A system having redundancy in its input channels only might have a failure probability in a range of 5×10^{-2} to 10^{-3}. The inference is that the most significant contributors to system failure have been determined to be in the input, although redundancy could be extended to other modules for further reduction in failure probability. CCF	5×10^{-2} to 10^{-3}
Partly Diverse System	The logical development in the quest for higher system reliability is to reduce the CCF probability by introducing diversity into those parts of the system where redundancy was previously considered, as in the Partly Redundant System, and to introduce redundancy where there was none previously. In this example, the input modules apply diverse designs while the processor or output applies redundant modules. One arrangement could be isolated channels where the channel fails if either its input or its processor or output fails. Alternatively, cross ties may be included to permit either input channel to connect to either process/output channel. It is cautioned that such cross ties may themselves introduce other CCF paths. The Partly Diverse System is capable of a failure probability in a range of 10^{-2} to 10^{-4}.	10^{-2} to 10^{-4}
Fully Diverse System	For further reduction in system failure probability, the independence between redundant channels must be improved by using diverse designs for input modules and for processor/output modules, and eliminating any cross ties between the channels. Systems have evolved to provide a failure probability in a range from 10^{-3} to less than 10^{-5}.	10^{-3} to $< 10^{-5}$
Two Diverse, Redundant Systems	The final stage in this example of system design evolution is to provide diverse input channels each being two-fold redundant in addition to redundant and diverse processor/output modules (i.e., four input channels, two each connected to one of two redundant and diverse processor/output modules). For practical reasons it is unlikely that more than two-fold redundancy can be applied to each subsystem. There are, therefore, completely diverse and separate systems throughout and would be expected to provide an overall system failure probability in a range of 10^{-4} to 10^{-6}.	10^{-4} to 10^{-6}

Source: Modified from Watson (1987, Figure 9)

NOTES: [a] Examples are primarily active electronic systems that have input, and processing/output modules.
[b] Per Watson (1987, Figure 10).

7.4.4.1 Explicit Modeling of Dependent Failures in Event Trees and Fault Trees

When specific mechanisms or linkages can be identified among components, subsystems, or systems, dependent failures can, and should be, modeled explicitly in ETs or FTs. More details on how such dependencies are modeled are provided in Sections 7.1, 7.2, and 10.1. An overview is presented in the following paragraphs.

Table 7-3 lists types of dependent events, their characteristics, principal coupling mechanisms, and examples relevant to repository operations.

7.4.4.1.1 Explicit Dependencies in Event Trees

The framework of the ET is used to display the frequency of the initiator and the conditional probabilities of each enabling event in a sequence. The frequency of each event sequence is calculated as the product of the initiator frequency and the probabilities of branch nodes that appear in the event sequence. The ET permits analysis of the dependencies between the IE and enabling events, dependencies between enabling events, or both. This means that if there are sequence-dependent couplings between events, there may be different probability values for a given enabling event in different sequences.

A dependent event in an ET has to be inserted into the tree after (to the right of) a precursor event upon which it is dependent. In extreme cases of dependency, the occurrence of the precursor event may guarantee the occurrence of the dependent event; that is, there is complete dependence between the events.

Figure 7-20A and 20B illustrate how dependent failures can alter the structure of ETs and affect the outcomes of event sequences. Figure 7-20A illustrates a simple (baseline) ET containing only independent events. The IE is a drop of a waste form that causes a release inside the hot cell. When the HVAC/HEPA filter system functions properly, the filtered release is small. This is indicated by a "Yes" under the event heading titled "HVAC/HEPA Filters Release" leading to Sequence No. 2. If the HVAC/HEPA filter fails (by independent failure), as represented by the "No" branch, the release is large, as represented by Sequence No. 3. Because this failure is independent of the IE, the frequency of Sequence No. 3 is equal to the frequency of the IE multiplied by the independent failure probability of the HVAC/HEPA filter.

Figure 7-20B, by contrast, illustrates the case in which the initiator is a fire inside the hot cell. In this example, it is assumed that there is a dependency between the initiating event (fire) and the HVAC/HEPA filter system. In this case, there is no "Yes" (or success) branch under the heading titled "HVAC/HEPA Filters Release," which leads to Sequence No. 3 and a large release. Note that the sequence numbers are different in Figures 7-20A and 20B.

The origin of the fire is not defined in this example. In addition, the probability of success or failure of a fire suppression system is not modeled in this example. See Section 10.1 for a discussion of such ETs.

Such a fire could induce a drop of a load as another type of dependent failure that could occur together with the dependent failure of the HVAC/HEPA filter. This event sequence would result in a simpler ET and a higher frequency of release.

Similarly, events may be dependent on the availability of a support system. In an ET having an IE titled "loss of offsite power," an event heading might be titled "backup power system is available." Subsequent events that are dependent on having AC or DC electrical power are shown in various event headings. For example, the HVAC/HEPA filter requires AC power for its fan motors, but the control and instrumentation systems may require DC electric power to perform their safety functions. Unless provided with fail-safe features, devices such as cranes, manipulators, and transport vehicles may be dependent on the availability of electric power.

In a loss-of-offsite-power ET, in the "no" branch after the heading titled "backup power system is available," no branching node would be shown under the event heading titled "HVAC/HEPA filter operates" to indicate a "guaranteed failure" because the HVAC/HEPA filter is dependent on the AC and DC power. In the "yes" branch, by contrast, a branching node would be included to represent the independent failure of the HVAC/HEPA filter system when AC and DC power are available. The other examples would be similarly modeled.

Dependencies on key HAs can be modeled in an ET in the same manner. If an operator is supposed to take an action to prevent or mitigate a potentially unsafe situation (e.g., activate a filtration system, a backup power supply, or close an isolation barrier), the branching nodes under the event headings in the ET are developed to show these dependencies. The dependencies may be complete, giving a guaranteed failure (as in the examples previously mentioned), or result in conditional probabilities that are higher than the independent failure probability for the heading event.

The analyst must justify the conditional probabilities assigned in such circumstance.

7.4.4.1.2 Explicit Dependencies in Fault Trees

To a certain degree, accounting for explicit dependencies in FT modeling is almost automatic if the analyst is thorough. The top-down decomposition of the top event to subsystems, components, and basic events leads to the identification of virtually all of the explicit dependencies.

For example, in an FT for a multi-train HVAC/HEPA filter system, the analyst resolves the failure of one of the trains (an event titled "HVAC/HEPA filter Train A fails to start and run") through an OR gate that includes as inputs: failure of the motor to start and run, failure of HEPA filter element, and failure of the fan. These inputs represent failures within the hardware of the primary system. Other events that could cause Train A to be unavailable (e.g., Train A out of service for maintenance, No electric power available to Train A, or Operator fails to actuate Train A) must be included to complete the FT. These inputs are examples of explicit dependencies that are incorporated into the logic model for the system.

In a multi-train system (such as the HVAC/HEPA filter system in the example), several of the modeled dependencies may be found to be CCFs. For example, if Train A and Train B (and other trains) all depend on a single train of electric power, then loss of the power supply would result in a loss of all HVAC/HEPA filters. In FT analyses, such dependencies might be identified through inspection in a simple system. Otherwise, in the determination of the minimal cutsets for the system failure, the singlet representing the failure of the electric power supply would be identified automatically through the boolean algebra.

7.4.4.1.3 Common-Cause Initiating Events

The IEs such as earthquakes, floods, fires, and loss of offsite power (previously discussed) can be important contributors to the risk of a facility unless design provisions prevent dependent failures. These topics are addressed in more detail in their respective sections of this guide. This section provides an overview of IEs and dependent failures using an earthquake as an example. Section 10.1 Seismic Analysis, illustrates the applications of seismic ETs that account for

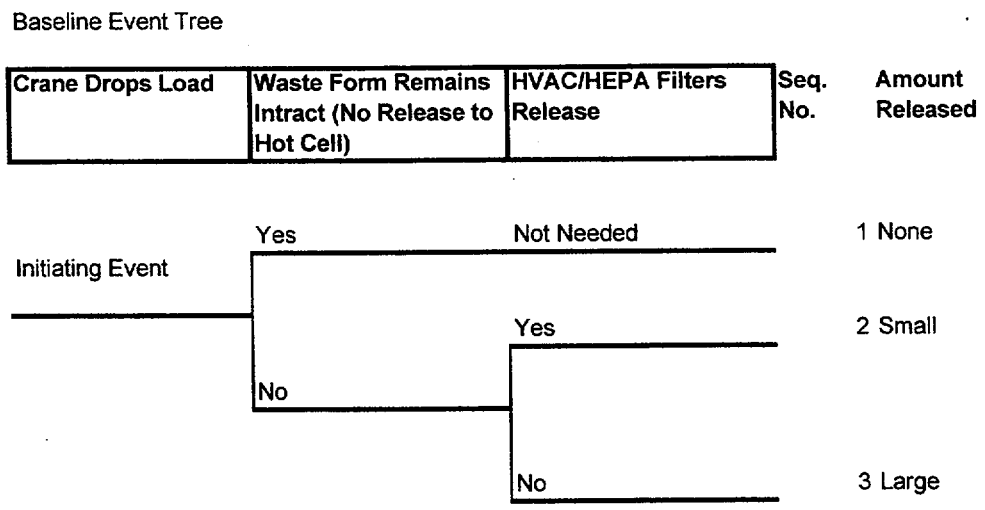


Figure 7-20A. Baseline Event Tree Without CCFs

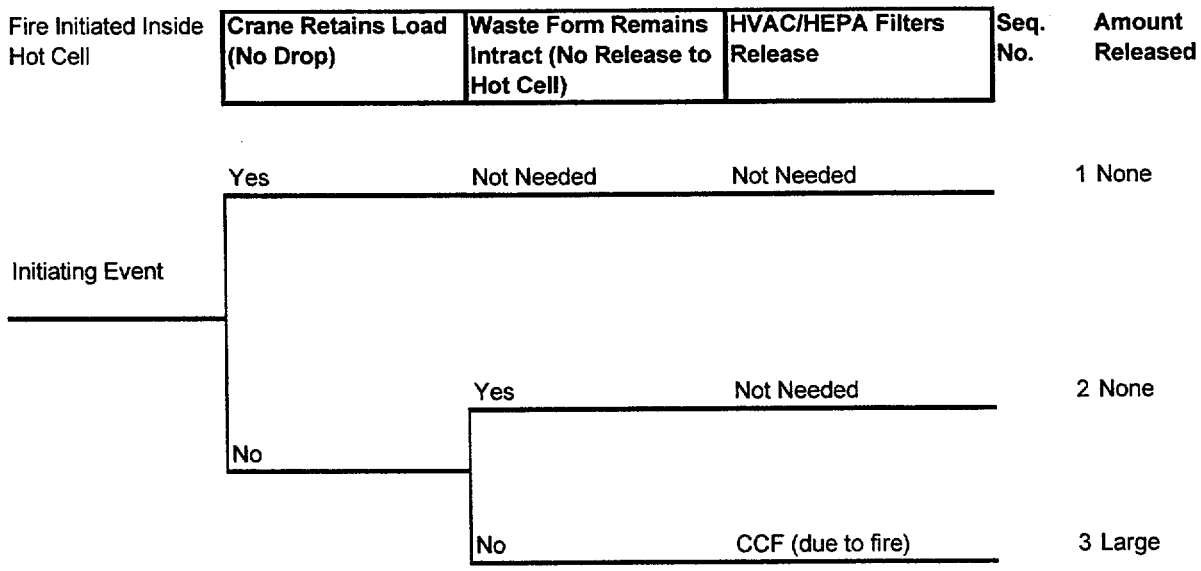


Figure 7-20B. Event Tree with Fire-Initiated Common-Cause Failure of a Heating, Ventilation, and Air-Conditioning, and High-Efficiency Particulate Air Filter System

dependent failures after a common-cause initiator (i.e., an earthquake that exceeds the seismic design criteria of the SSC).

An initial model of a seismic ET for a fuel handling facility, for example, could include headings that represent all of the undesirable interactions and consequences that might occur as a result of an earthquake of any unspecified magnitude. The IE would be labeled "strong earthquake occurs at site." Consequently, potentially dependent events that could be included as ET headings

include crane drops transport cask, manipulator drops fuel assembly, crane falls onto spent fuel racks, hot cell walls are breached, hot cell walls collapse, or HVAC/HEPA filter fails to function. An ET would be used to display the possible event sequences that might occur unless design features prevent some or all sequences from being credible. The seismic ET can be used for qualitative analyses or applied further in deterministic or probabilistic evaluations (see Section 10.1).

In a deterministic analysis, the seismic ET would be modified to account for success criteria and design features that withstand design-basis earthquakes up to a given magnitude. Two design basis earthquakes have been defined for a repository: the Frequency Category 1 (FC-1) earthquake (1×10^{-3} per year with a magnitude to be specified) and a Frequency Category 2 (FC-2) earthquake (1×10^{-4} per year with magnitude greater than that of FC-1).

Two new ETs are created by modifying the initial tree. One tree (the FC-2 ET) would define the IE as "earthquake of magnitude greater than FC-1 but less than FC-2 occurs." The other tree would label the IE as "earthquake less than FC-1 occurs."

All of the event headings that represent an SSC that is designed to withstand the FC-2 earthquake without a loss of a safety function would have branches representing the independent failure of the SSC in a deterministic application of the FC-2 ET. By contrast, all of the event headings that represent an SSC that is designed to withstand only the FC-1 earthquake would not have branching nodes, thus representing guaranteed failure. The ET thus eliminates many of the possible sequences from the initial ET.

All of the event headings that represent an SSC that is designed to withstand the FC-2 earthquake without loss of safety function would be considered to be a guaranteed success with respect to the seismically induced failures in a deterministic application of the FC-1 earthquake ET. In this ET, however, all of the event headings that represent an SSC that is designed to withstand either the FC-1 earthquake or those designed for the FC-2 earthquake would have branching nodes representing potential independent failures. Any SSC not designed to withstand at least the FC-1 earthquake is assumed to be a guaranteed failure without any branching nodes.

Finally, a third ET is created that has the IE titled "earthquake exceeding design basis occurs at site." All of the possible seismic-induced failures of SSCs would be treated as guaranteed dependent failures in a deterministic application. The number of event sequences would be significantly reduced, perhaps collapsing the tree to one sequence: a severe earthquake occurs and all SSCs fail dependently.

Section 10.1 also describes the application of seismic ETs with CCFs in probabilistic analyses such as seismic PRA or seismic margins analysis.

7.4.4.2 Use of Software

Dependent events and CCFs are readily handled in both ETs and FTs with computer programs such as SAPHIRE. A Microsoft Excel spreadsheet can be used to draw ETs that include dependent events and can be used to quantify event sequences. The ETs and CCFs of basic events can be handled with an FT computer program such as CAFTA.

7.4.4.3 Implicit (or Parametric) Modeling and Quantification of Common-Cause Failure

A CCF analysis can be applied to systems containing several levels of redundancy and diversity, including systems having various success criteria (e.g., 1 out of 2, 2 out of 3, and so on).

The simplest example for introducing CCF analyses is illustrated in Figure 7–21A. This figure presents a reliability block diagram for a system having two-fold redundancy. The success criterion is one out of two: if either component A or B is available, the system safety function is achieved. Figure 7-21B illustrates the FT logic model for the system assuming that all failures of A and B are independent. The top event (failure of safety function) will occur when A and B fail, as represented by the AND gate. The probability of the top event is given as:

$$p_S = p_A * p_B \quad \text{(Eq. 7-32)}$$

If $$p_A = p_B = 0.01 \quad \text{(Eq. 7-33)}$$

then $$p_S = 0.01 * 0.01 = 0.0001 \quad \text{(Eq. 7-33)}$$

The potential for CCF is introduced into the reliability block diagram by inserting a pseudo-component that is in series with the representations of the physical components (or systems), A and B, as shown in Figure 7-22A. The pseudo component is labeled CCF_{AB}. Figure 7-22B illustrates the FT logic model for the system in the reliability block diagram. The top event (failure of safety function) will occur when A and B fail independently OR if they fail by a CCF. The top event is resolved into an OR gate having event CCF_{AB} as one input and the event titled "independent failures of A and B" as the other input. The probability of the top event is given as:

$$p_S = p_{A,I} * p_{B,I} + p_{CCF} \quad \text{(Eq. 7-35)}$$

where $p_{A,I}$ and $p_{B,I}$ are the probabilities of independent failures of A and B, respectively.

The expression in Equation 7-35 is valid for any appropriate values of the parameters $p_{A,I}$, $p_{B,I}$, and p_{CCF}. A determination of the value of p_{CCF} is required, but not easily achieved.

The beta-factor method is applied here to quantify the probability of the top event to illustrate the basic approach that is recommended for the PSA.

7.4.4.3.1 Beta Factor Approach

The beta factor method assumes that a fraction β of the reported failures of components is due to CCFs with the remainder due to independent failures.

If

$$p_A = p_B = p_{Tot} \quad \text{(Eq. 7-36)}$$

where p_{Tot} is the total failure probability of either component A or B, taken alone, then the probability of both components failing due to CCF is defined as

$$p_{CCF} = \beta * p_{Tot} \quad \text{(Eq. 7-37)}$$

and the probability of independent failure is

$$p_{A,I} = p_{B,I} = (1 - \beta) * p_{Tot} \quad \text{(Eq. 7-38)}$$

A typical value (e.g., a rule of thumb often used in screening analyses) is to assume $\beta = 0.1$. Using this value in the example gives the following equations:

$$p_{CCF} = \beta * p_{Tot} = 0.1 * 0.01 = 0.001$$

$$p_{A,I} = p_{B,I} = (1 - \beta) * p_{Tot} = (1 - 0.1) * 0.01 = 0.9 * 0.01 = 0.009$$

$$p_S = p_{A,I} * p_{B,I} + p_{CCF} = 0.009 * 0.009 + 0.001 = 0.000081 + 0.001$$

The contribution from the CCFs dominates the system failure probability. This is a typical result from the beta factor approach when β is 0.1 or higher. For the two-fold redundancy case, it may be shown that CCFs dominate the system failure probability until $\beta \approx p_{Tot}$. In this example, if $\beta \rightarrow 0.01$, then the factor $\beta p_{Tot} \approx 0.0001$ and is approximately equal to the term $P_{A,I} * P_{BI}$ for the probability of independent failures. In other cases, if the independent component $P_{A,I} = P_{BI} = 0.001$, then a B = 0.01 would dominate the system failure probability. It should be noted that the beta factor method gives essentially the same numerical result for any redundancy of two or higher. More complex, multi-parameter models may be used, as described in Section 7.4.4.3.7.

The beta factor method is perhaps the most useful technique for including CCFs in the PSA, especially for the LA submittal for CA, when complete design detail is not yet available. Moreover, the beta factor is suitable when only two-fold redundancy is used. The value chosen for beta may be less than, or more than, the generic beta of 0.1. The analyst must determine whether design, operational controls, and environmental controls affect the susceptibility and opportunity for CCFs and justify an appropriate beta factor or factors.

7.4.4.3.2 Using the Beta Factor with Component Failure Rate and Event Frequencies

The development of the methodology in Sections 7.4.3 and 7.4.3.1 used the probability of a system or component failure as the parameter of interest. The same development can be based on a failure rate using the beta factor. The original development of the beta factor was based on component failure rates because experience data (from which beta is derived) are expressed in terms of failure rate (either in units of time or per demand).

These results demonstrate that even a small contribution from CCFs can seriously degrade the reliability of a safety system. Designer and safety analysts must be cautioned against overconfidence and complacency when redundancy or single-failure proof designs are specified. The CCFs associated with these designs must be controlled.

Experience data are expressed in one of the following forms:

Demand Based–K failures are observed in N challenges (demands) on components in records or test data. In this basis, data analysis would estimate the failure rate (or probability per demand). The failure rate, also termed the component unavailability, is calculated as:

$$q = K/N \text{ failures per demand} \quad \text{(Eq. 7-39)}$$

CCF Contribution, Beta Factor Estimation:

The analysts examine the database(s) to identify what fraction of all recorded failures can be attributed to CCFs. It is determined that a portion k_{CCF} of the K failures are attributed to CCFs. This defines the beta factor as:

$$\beta_q = k_{CCF}/K \quad \text{(Eq. 7-40)}$$

So that

$$q_I = (1 - \beta_q)\, q \quad \text{(Eq. 7-41)}$$

$$Q_{CCF} = \beta_q\, q \quad \text{(Eq. 7-42)}$$

where

q_I = probability of independent failures, per demand

Q_{CCF} = Probability of CCF failure, per demand

In the demand-based case, q is a probability; therefore, the development in Sections 7.4.3 and 7.4.3.1 apply directly.

CCF Contribution, Beta Factor Estimation:

The analysts examine the database(s) to identify the fraction of all recorded failures that can be attributed to CCFs. It is determined that a portion m_{CCF} of the M failures are attributed to CCFs. This defines beta as:

$$\beta_\lambda = m_{CCF}/M \quad \text{(Eq. 7-44)}$$

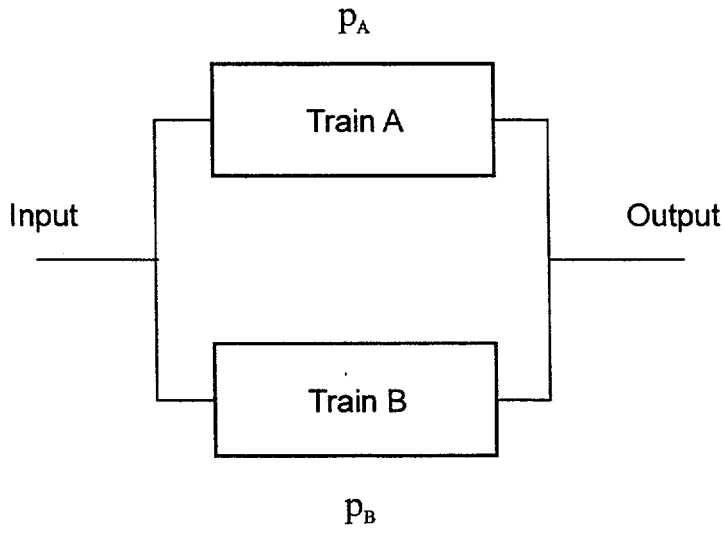
The failure rate for independent failures becomes:

$$\lambda_I = (1 - \beta_\lambda)\,\lambda \quad \text{(Eq. 7-45)}$$

and the expression for the failure rate for CCFs is:

$$\lambda_{CCF} = \beta_\lambda\, \lambda \quad \text{(Eq. 7-46)}$$

A. Reliability Block Diagram of Redundant System



B. Fault Tree Logic Model of Redundant System

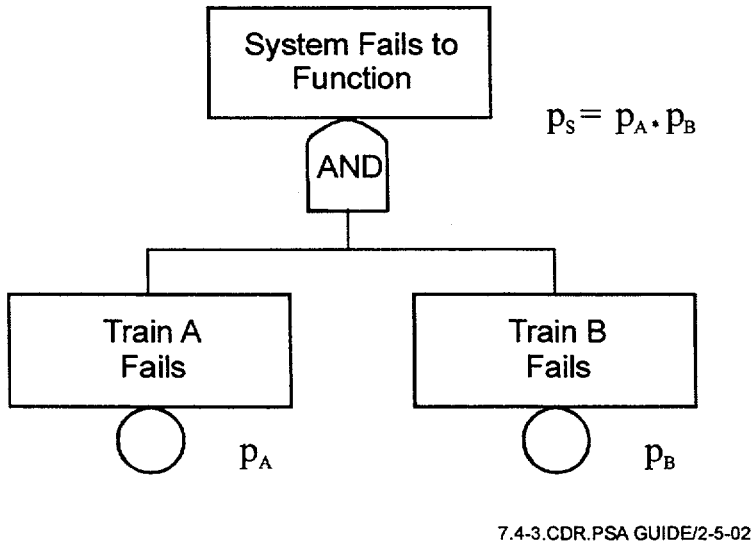


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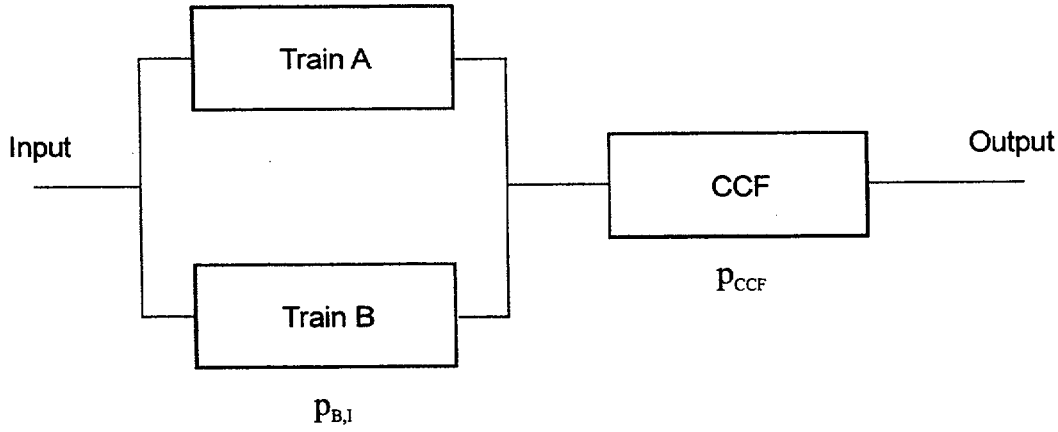
Figure 7-21. Illustration of Logic Models for Independent Failures

A. Reliability Block Diagram of Redundant System with Pseudo Series Element CCF



B. Fault Tree Logic Model with CCF of Redundant System

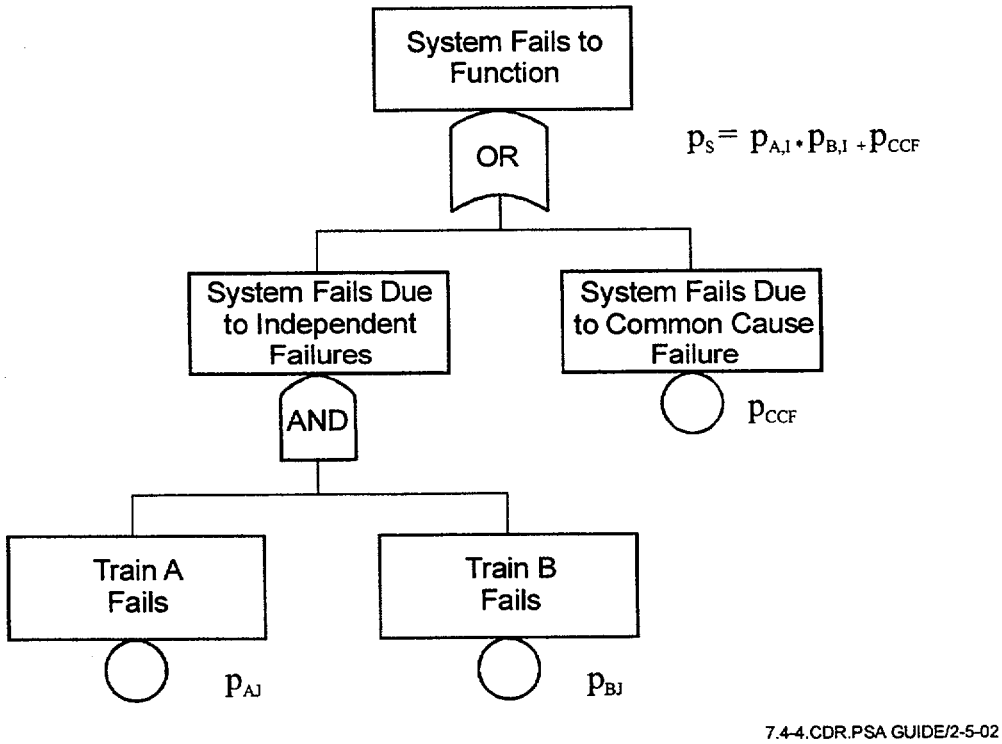


Figure 7-22. Illustration of Logic Models for Common Cause Failures

The unavailability of a component or system in the exponential reliability model is expressed as:

$$P_F = 1 - \exp(-\lambda t_M) \quad \text{(Eq. 7-47)}$$

Here t_M is the mission time and P_F is the probability that that the component or system will not perform its safety function for at least a time t_M when it is needed. The expression for P_F is usually approximated as

$$P_F \approx \lambda\ t_M \quad \text{(Eq. 7-48)}$$

and P_F is the probability of failure for all causes (i.e., the total of independent and common cause failures) for the mission time, t_M.

The independent failure and CCF contributions to the component or system unavailability can be separated using Equations 7-45 and 7-46.

The probability of independent failure is

$$P_{F_I} \approx \lambda_I\ t_M \approx (1-\beta_\lambda)\lambda\ t_M \approx (1-\beta_\lambda)P_F \quad \text{(Eq. 7-49)}$$

and the probability of CCF is:

$$P_{FCCF} \approx \lambda_{CCF} * t_M \approx \beta_\lambda\ t_M \approx \beta_\lambda * P_F \quad \text{(Eq. 7-50)}$$

Rate Based–M failures are observed in exposure (operational or test) time T for components in records or test data. In this basis, data analysis would estimate the failure rate (in units of numbers of failures per unit time, also termed the component failure frequency) as:

$$\lambda = \text{M/T failures per hour} \quad \text{(Eq. 7-43)}$$

7.4.4.3.3 Other Methods for Common-Cause Failure quantification

When diversity is also present in addition to redundancy and in cases where three-fold or higher redundancy is used, other methods such as the Multiple Greek Letter or the alpha factor should be used. If the need arises, the analyst should consult a source such as NUREG/CR-4780 for instructions.

7.4.5 Steps in Performing Dependent Failure Analysis for a Repository

The following steps are presented to guide the analyst. The steps are based on those presented in NUREG/CR-4780 (Mosleh et al. 1988) but are less detailed since some of the steps are not relevant to the preclosure safety of a repository. The first two steps are general systems analysis tasks that are performed in conjunction with ET and FT analyses.

7.4.5.1 Step 1–System Logic Model Development

System Familiarization–The specific system or operation of a repository is examined for preclosure safety issues. The analyst becomes familiar with the design, environment, and

operational characteristics of the system. This step is a common starting point and common activity for the entire PSA. For dependent failure analysis, attention must be given to the following points:

- The results of external and internal event hazards analyses are used to develop event sequence descriptions (e.g., using ET logic models) and FT logic models of SSCs that are relied upon for prevention or mitigation of particular sequences of events.
- The analyst must understand the intended function of each front-line SSC, what it is composed of (i.e., construction, kinds of components), what kinds of procedures will govern its operation, and its requirements for T&M.
- The analyst must also understand which support systems are required for proper functioning of each frontline SSC (i.e., does it require electrical power, cooling water or air, temperature or humidity control?).
- The analyst should consider the location of each SSC in relation to other operations that may pose hazards of spatial interaction.

Problem Definition–In this step, the analyst translates information from the familiarization step into specific considerations and constraints that will influence the logic model development. Particular points to be considered include:

- Specific success (performance) criteria that are defined for each SSC that prevents or mitigates an undesired sequence
- Boundaries of the specific system being considered (i.e., what it includes and what it does not)
- Dependencies between frontline (primary) system and support systems or functions (for complex systems, a support matrix may be constructed to define direct and indirect dependencies between primary, secondary, and tertiary systems and components or HAs)
- Ground rules imposed on the analyses to focus on the problems of interest (e.g., coarse modeling and conservative rules might be applied to preliminary analyses, and them more detailed modeling and more realistic rules might be applied in later analyses)
- Identify those root causes of dependent failures that will be explicitly modeled (e.g., earthquakes, fires, T&M, human errors).

The last point is important; in later modeling of implicit (parametric) dependencies care must be taken to not introduce double counting.

Logic Model Development–Explicit dependencies are incorporated into ET or FT logic models. Implicit (or parametric) dependencies are treated in FT models that permit the analyst to relate (decompose) a system state (such as HVAC/HEPA filter system is unavailable) to lower,

component level states. The dependent failure events are then treated as one cause of component failure alongside independent component failure events.

7.4.5.2 Step 2–Identification and Screening of Common-Cause Failure Component Groups

The objectives of this step include qualitative and quantitative screening to:

- Identify the groups (or types) of components to be included in, or excluded from, the CCF analysis
- Prioritize the groups to allocate resources and time
- Provide engineering arguments to aid data analysis
- Provide engineering insights for later formulation of CCF defense alternatives

Qualitative Analysis–The analyst searches for common attributes and mechanisms of failure that can lead to common cause events. This step relies on past experience and an understanding of system and component behavior in the intended operational environment for signs of potential dependence among redundant components as well as consideration of defenses that may be included in the design. If necessary, a root-cause analysis is performed to substantiate and improve the initial identification of potential CCFs.

Quantitative Screening–This step is applied in the CCF analysis of complex systems to identify dominant contributors to system unavailability or event sequence frequencies. In this step, conservative values are assigned to each basic event in the system FT for both independent and CCF modes. If several potential CCFs are associated with a given system, this step will help to identify the dominant contributors and to prioritize further analyses.

7.4.5.3 Step 3–Common Cause Modeling and Data Analysis

A CCF model that best fits the situation being modeled is then selected. NUREG/CR-4780 (Mosleh et al. 1988) several methods are presented. For most repository analyses that involve two-fold redundancy, the beta-factor method is the recommended approach. However, the appropriate beta factor must be applied.

The analysis of appropriate CCF factors is similar to the general problem of parameter estimation and selection, as discussed in Section 7.4. If information sources are available for systems or components similar to those of a repository and are located in an environment similar to a repository application, the analyst should attempt to extract CCF factors. Otherwise a generic beta factor should be used. Although a beta factor of 0.1 is a good value for use in preliminary analyses of high quality components, the analyst should consider whether a smaller or larger value is more suitable for the quality of component, the environment, and the degree of uncertainty in the root causes and coupling mechanisms for the CCFs.

Table 7-5 (based on Table 3-7 of NUREG/CR-4780 [Mosleh et al. 1988]) lists generic beta factors for several components used in nuclear reactor plants. The generic factor ranges from

0.03 for various pumps to 0.22 for various safety and relief valves. The average value is 0.1 for all components.

7.4.5.4 Step 4–System Quantification, Sensitivity Analysis, and Interpretation of Results

After all of the CCF elements in the system logic model have been assigned appropriate CCF parameters (e.g., an appropriate beta factor) and parameters have been assigned to all independent failure modes and explicit dependencies (such as human error probabilities or T&M unavailability), the probability of system failure is quantified (e.g., using the SAPHIRE code). This step identifies the key contributors to system unavailability. These contributors are expected to be one or more CCF events. The initial results may point to potential recovery actions that can reduce the impact of the CCFs and identify defenses against the CCFs.

At this stage, it may be desirable to perform a sensitivity analysis by varying the beta factors in the various CCF elements to gain insight into the significance of uncertainty in the CCF parameters.

The analyst should also perform a review of the results at this point to determine if the system unavailability factor appears to be extraordinarily small or large.

7.4.5.5 Step 5–Reporting/Documentation

Although the dependent failure/CCF analysis is an integral part of the event sequence analyses, it is important that the analyst clearly document this portion of the analyses with respect to assumptions, modeling approximations, and parameter selection.

NUREG/CR-4780 (Mosleh et al. 1988, Section 3) presents a detailed explanation of the activities in Steps 1–5.

7.4.6 Examples of Application

An example application of a CCF analysis was developed to examine the likelihood of having an uncontrolled descent of a waste-package transporter train during travel to the subsurface. An FT analysis was performed to examine the reliability of the brake system(s) of the WP transporter train. The most recent analysis is reported in *Subsurface Transporter Safety Systems Analysis* (CRWMS M&O 2000) based on FT models developed in *Application of Logic Diagrams and Common-Cause Failures to Design Basis Events* (CRWMS M&O 1997). The logic model made extensive use of CCF modeling.

The train was theoretically comprised of two locomotives and a shielded waste-package transporter car. Each vehicle had air-actuated tread brakes and hydraulic actuated disk brakes. Each of the vehicles had elements of redundancy within each of the respective brake systems. The actuation of the transporter brakes was controlled by the counterpart brake system on the primary locomotive. Thus, one mode of failure of transporter brakes was dependent on failure of the locomotive brake actuation system. This dependency was modeled explicitly in the FT analysis. Actuation of the brakes, however, could be initiated from either locomotive or from a central control room.

The beta factor method in this analysis was used at three levels: intra-vehicle (i.e., among redundant components on either of two locomotives or the transporter), inter-locomotive (i.e., among redundant and like components on both locomotives), and inter-vehicle (among redundant and like components on both locomotives and the transporter car).

The standard generic beta factor of 0.1 was used for the intra-vehicle level. This beta factor was applied to mechanical and electronic components in redundant configurations. Thus, the two channels of brake actuation signals were modeled as two paths of independent failures in series with one path of CCF. Redundant air-brake system components were modeled similarly.

Table 7-5. Generic Beta Factors

Component	Generic Beta Factor[a]
Reactor Trip Breakers	0.19
Diesel Generators	0.05
Motor Operated Valves	0.08
Safety or Relief Valves	
Pressurized Water Reactor	0.07
Boiling Water Reactor	0.22
Check Valves	0.06
Pumps	
Safety Injection	0.17
Residual Heat Removal	0.11
Containment Spray	0.05
Auxiliary Feedwater	0.03
Service Water	0.03
Chillers	0.11
Fans	0.13
All [b]	0.10 [b]

Source: Modified from NUREG/CR-4780 (Mosleh et al. 1988)

NOTES: [a] Based on classification of 3000 events from experience data. Dependent failure types were classified. Generic common cause events included potential as well as actual events. See Table 3-7 and the explanation in NUREG/CR-4780 (Mosleh et al. 1988, Section 3).

[b] Average of all component beta factors.

A second level of CCF was introduced using a beta factor of 0.01 (using the argument that the probability is less likely than the intra-vehicle situation) to allow for the possibility that there may be mechanisms for CCF among components on the two locomotives (e.g., root causes of common erroneous maintenance, calibration, and installation). Similarly, a third level beta factor of 0.001 was used to allow for CCFs among components on all three vehicles. By using three beta factors that differ by orders of magnitude, the issue of double counting of some of the failure modes is less important.

The analysis indicated, as expected, that use of diverse and redundant brake systems on multiple vehicles reduce the probability of failure by independent failures or intra-vehicle CCFs. The assumed inter-vehicle CCFs are seen to be potentially significant contributors (even when a beta factor of 0.001 was used). The insights gained from such analyses indicate that programmatic controls should be put into place to eliminate or reduce the likelihood of such CCFs. The

numerical results must not be taken too literally or used to infer that brake systems cannot be made sufficiently reliable.

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7.5 TECHNICAL INFORMATION

7.5.1 Introduction

This section defines the bases and methods for gathering and quantifying technical information that is used in the quantification of FTs and ETs. The technical information needs for ET and FT quantification consist generally of IE frequencies, failure rates and probabilities, CCF parameters, HEP, mission times, repair times, inspection intervals, and demand rates. This section also describes the methods for quantifying the uncertainty factors in the parameters based on concepts described in Section 9. Because of the precise use of the term "data" on the Yucca Mountain Project, this section uses the term "technical information" for the sources of information described.

This section will concentrate on the bases and methods for gathering and quantifying failure rates and probabilities for hardware and software along with associated mission times, repair times, inspection intervals, and demand rates. Information for common-cause and dependent failures, and for HEP, are presented in Sections 7.3 and 7.4, respectively.

This section also includes methods for combining various sources of generic databases and for combining generic databases with repository-specific information. The bases for estimating uncertainty factors in parameters are described, as well as reference to the concepts presented in Section 9.

7.5.2 Overview of Approach

Other sections of this guide present methods for modeling and analyzing ETs, FTs, CCFs, and human errors. All of those models require numerical quantities of various types of inputs. Most of these parameters will be used to quantify the probabilities of basic events in FT models or the probabilities of event headings in ETs. Another application of the information is for use in quantifying the frequency of IEs (i.e., the frequency is expressed as probability per unit time). The fundamental parameters, however, are in the form of failure rates (i.e., number of failures per unit time) and failure probability on demand (e.g., number of failures per number of trials). Other parameters include T&M intervals. This section describes the techniques for producing the parameters and sources of information upon which to base the parameters.

This section will follow the presentation in Section 5 of the *PRA Procedures Guide* (NRC 1983) for the following elements:

- Selection and Use of Event Models
- Information (Data) Gathering
- Estimation of Model Parameters
- Uncertainties in Information and Event Probabilities
- Documentation

The *PRA Procedures Guide* (NRC 1983, Section 5.6.2) also provides a brief discussion of the evaluation of dependent failures and the estimation of parameters for a shock model for the treatment of dependent failures. This material is not applied as a recommended model in this

PSA guide. The methods for identifying and modeling dependent failures are described in Section 7.4. For example, the principal approach for CCF analysis in the PSA is the beta-factor method described in Section 7. For initial scoping analyses, a beta factor of 0.1 is often used. For more refined analyses, however, the beta factor should reflect generic information on similar components in operating conditions similar to a repository. The evaluation of the parameters and the uncertainty for modeling dependent failures is essentially the same as that described in this section for treating failure-on-demand and constant failure rate information.

The Selection and Use of Event Models refers to the mathematical expression used to quantify a specific failure probability, the unavailability of SSC, or the frequency of an initiator. In many cases, the mathematical expression will be time-based to express the probability that a given failure will occur within some mission time or the probability that a particular SSC will be unavailable because it is out of service for T&M or inspection. Each of these time-based situations has a rigorous mathematical formula for calculating the desired probability. Furthermore, each of the rigorous expressions is often approximated by simpler mathematical expressions.

For example, the exponential formula is used to calculate the probability that a component will not be available for a mission time, T, when the failure rate, λ, is constant in time. The probability is expressed as $q = 1 - \exp(-\lambda * T)$. When λ, T, or both are small, the expression is approximated as $q \approx \lambda * T$. The exponential and other models are described in Section 7.5.3.

Information (Data) Gathering involves the selection and acquisition of generic databases, generic event data, and repository-specific event data, when available. Because a repository is a first-of-kind and will not have any operational experience prior to licensing, repository-specific data will not be available. Therefore, the PSA must rely heavily on generic information, principally information from generic databases developed for PRAs, but also from experience data for equipment and systems similar to those that will be used in a repository. However, for some parameters, site-related information such as the frequency of natural phenomena, nearby hazardous activities, and historical information is available for components used in the Exploratory Studies Facility (ESF) (e.g., ground support).

Estimation of Model Parameters is the process of assigning a value to each of the parameters. If generic databases are used, the parameters of interest are already in the proper form (e.g., a failure rate and its uncertainty). Therefore, the estimation may involve adjustment factors to alter the generic failure rate to account for repository-specific conditions (such as operational environments or quality assurance program). In some cases, there may be several pieces of generic information (and their uncertainty ranges) that are combined in specified ways to arrive at the best values for repository application.

Otherwise, the parameters have to be derived from event data. The number of observed failures must be divided by the number of trials or the length of exposure time. The associated uncertainty factors are also derived.

The Bayesian approach is the generally accepted method for parameter estimation in PRAs. It is based on subjective probabilities applied with empirical information. In many reliability analyses, however, the classical or Frequentist approach is used. When enough information is

available, the two approaches give essentially the same numerical results. The Bayesian approach has some advantages, however, when less information is available (e.g., when the number of observed failure events is zero).

Uncertainties in Information and Parameters are the sources of uncertainty that are accounted for, and propagated in, the event sequence quantification (as described in Section 9). The uncertainty derives from issues such as the amount of information (e.g., number of trials), variability between sources (e.g., the failure rate for similar components vary significantly between two or more compilations), and the potential inaccuracies in the reported values. The uncertainty distributions (i.e., probability density functions PDFs) ascribed to basic parameters such as failure rates and repair times are propagated throughout the event models, resulting in PDFs for the event probabilities that are input to the ET and FT analyses.

The following sections provide the details of each of the five elements.

7.5.3 Details of Approach

This section provides the essential methods and sources that are expected to be applied in the PSA. It is not intended to be exhaustive. In some cases, the analyst may find a need for alternative approaches that can be found in PRA and reliability literature.

7.5.3.1 Selection and Use of Event Models

Section 7.2, FTA, describes the event models most likely to be used in a PSA, but the mathematical formulas are repeated here for clarity. The analyst must determine the appropriate model to apply to a particular basic event. These models are summarized in Table 7-6. PRA or FTA programs, such as SAPHIRE (Russel et al. 1994), include these event models as options for quantifying basic event probabilities.

Except for quantifying IE frequencies, the purpose of an event model is to quantify a probability (that ranges from 0 to 1.0). The probability evaluation may be time-based or demand-based. Component or system faults are characterized as one of the following probabilities:

- Failure on demand – probability of failure per demand
- Standby failure – probability of failure on demand after a given non-operational period, usually given as time-between-inspections
- Operational failure – probability of failing to run or operate (provide required function) during a specified time period (i.e., the mission time)

In addition to the failures of equipment or software due to random causes, failures may be caused by:

- Human errors in T&M that leave the equipment or software in a disabled state
- Human errors during operation that cause a loss of the safety function

Such events are treated probabilistically by methods described in Section 7.3

Table 7-6. Sources of Facility-Specific and Operations-Specific Experience Information

Parameter	Information Requirements	Potential Sources[a]
Probability of failure on demand	Number of failures Number of demands	Repository and ESF inspection and T&M reports Surrogate and generic reports
Standby failure rate	Number of failures Time in standby	Same as above
Operating failure rate	Number of failures Time in operation	Same as above
Repair-time distribution parameters	List of kinds of repairs (principally on-line) of interest to PSA Repair times	Preliminary hazards and event sequence analyses Sources as above
Unavailability due to T&M	List of kinds of T&M of interest to PSA Frequencies and length of T&M	Preliminary hazards and event sequence analyses Sources as above
Recovery	List of kinds of recovery actions of interest to PSA Recovery times	Preliminary hazards and event sequence analyses Sources as above
Human errors	Lists of HAs of interest to PSA Number and categories of errors Number of opportunities Recovery	Preliminary hazards and event sequence analyses Detailed HRA for PSA Sources as above

NOTE: [a] When available, parameters should be estimated from repository, ESF, or other Yucca Mountain specific sources. Otherwise, the best available and applicable surrogate sources should be used. Surrogate sources represent operations, equipment, and environments similar to a repository.

Finally, there may be cases where a system or subsystem is taken out of service for scheduled maintenance. The unavailability may be modeled in the system FTA. The unavailability for this case is a function of a scheduled maintenance interval and the expected time duration for the maintenance.

The symbol used for the probability in discussions, tables, or qualitative FTA is very often a "p." However, in many cases the symbol "q" is used to connote the probability of failure (per demand), or the probability of unavailability (i.e., the probability of being unavailable when needed or unavailable for the time required).

The value of "q" may be derived directly from demand-based experience data or indirectly from time-based (or rate/frequency) experience data, as described in the following sections.

7.5.3.1.1 Time-Based Event Models

Unless special cases dictate the use of a different model, it will be assumed that all time-based failures are governed by a failure rate that is constant in time. This produces the well-known exponential failure model, which is expressed as

$$q(t) = 1 - \exp(-\lambda t) \qquad \text{(Eq. 7-51)}$$

where

q(t) is the probability that the component or system will fail within a time, t; and
λ is the constant failure rate.

A graph of q(t) is illustrated in Figure 7-23.

The PDF for q(t) is given as

$$f(t)dt = \lambda \exp(-\lambda t)\, dt \qquad \text{(Eq. 7-52)}$$

where

f(t)dt is the probability of a component or system failing within a time interval dt about t.

Using the PDF, the mean-time-to-failure is evaluated as

$$\underline{t} = \int_{\circ}^{\infty} \lambda t \exp(-\lambda t)\, dt = 1/\lambda \qquad \text{(Eq. 7-53)}$$

This is an important relationship that is used in parameter estimation. The mean-time-to-failure is the inverse of the constant failure rate λ in an exponential model.

There is an uncertainty distribution (i.e., a PDF) associated with the parameter λ that will result in an uncertainty distribution for q(t). If the 5th percent lower bound and the 95th percent upper bound are expressed as $\lambda_{LB \text{ and}}$ λ_{LB}, the corresponding expressions for the event probability are:

$$q_{LB}(t) = 1 - \exp(-\lambda_{LB}\, t) \qquad \text{(Eq. 7-54)}$$

$$q_{UB}(t) = 1 - \exp(-\lambda_{UB}\, t) \qquad \text{(Eq. 7-55)}$$

These probabilities are illustrated in Figure 7-23. The methods for quantifying $\lambda_{LB \text{ and}}$ λ_{LB} are described in Section 7.5.3.3. Several time-based event models are derived from the exponential failure model (Equation 7-51), as defined in the following section.

Operational Unavailability (No-repair Model)–The unavailability of a component or system in the exponential reliability model without repair is:

$$q(t_M) = 1 - \exp(-\lambda\, t_M) \qquad \text{(Eq. 7-56)}$$

where t_M is the mission time. The term $q(t_M)$ is the probability that that the component or system will not perform its safety function for at least a time t_M when it is needed. The longer the mission time, the higher the probability of the failure event modeled in the ET or FT.

Because the failure rate for highly reliable components is usually small, (i.e., such that $\lambda\, t_M < 0.1$) the expression for $q(t_M)$ can usually be approximated as:

$$q(t_M) \approx \lambda\, t_M \qquad \text{(Eq. 7-57)}$$

This event model is applied to the failure-upon-demand of standby components that are not inspected or repaired. It is often applied to failure-to-run of a normally operating system or to a standby system after successful starts-upon-demand.

Standby Unavailability (With-Repair or Renewal, Unannuciated)–This unavailability applies to a system or component that is on standby, but whose condition is not known between periodic inspections or tests (i.e., failures are unanunciated). If a system is found to be failed or not performing to specification, the system or component is repaired. It is assumed that after repair, the component or system becomes good-as-new with a failure rate of λ_S, and the failure probability between inspections/tests follows the exponential function. This function is presented in Equation 7-51 (in Equation 7-51, λ is replaced by the standby failure rate of λ_S).

The average unavailability of a system that is on standby but is periodically inspected, tested, and repaired, is given by:

$$q(\tau) \approx \lambda_S \tau/2 \qquad \text{(Eq. 7-58)}$$

Here τ is the inspection or test interval.

Figure 7-24 illustrates the time behavior of the exponential function between inspection intervals of varying length (calculated with Equation 7-56) and the corresponding average unavailability (calculated with Equation 7-58). The figure illustrates how the average unavailability increases with the inspection or test interval. In addition, the maximum failure probability can be significantly higher than the average unavailability and occurs just before the inspection or test.

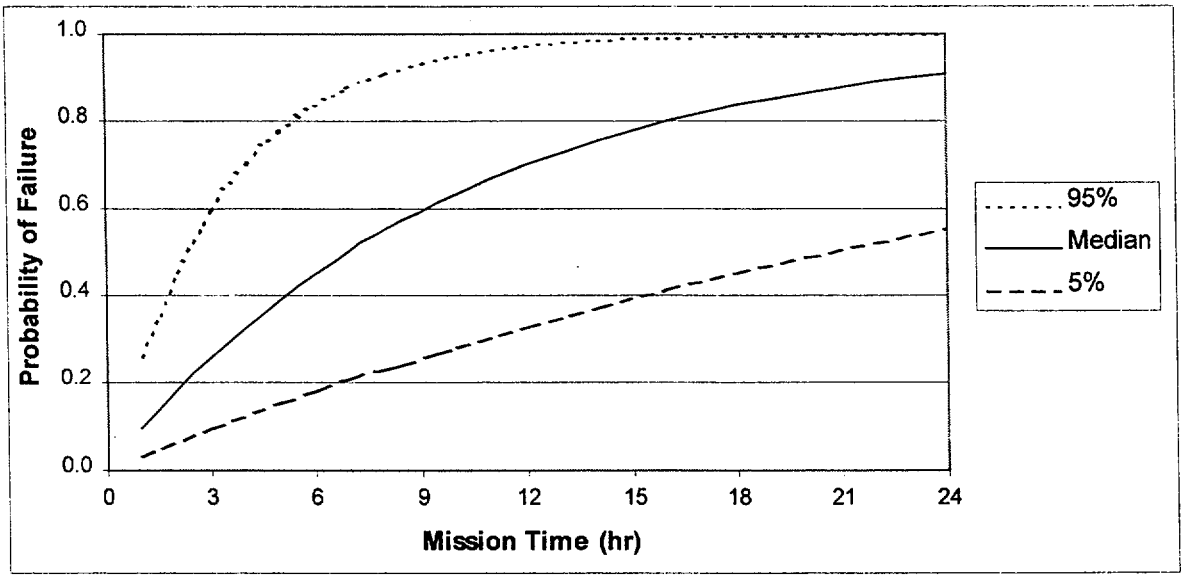

Figure 7-23. Exponential Probability of Failure

Standby Unavailability (With-Repair or Renewal, Annuciated)–This unavailability applies to a system or component that is on standby, but whose condition is known continuously due to instrumentation or some performance characteristic that indicates when the item is unavailable. The event model becomes that of the operational unavailability. Here it is assumed that repair or restoration begins immediately and that normal operations continue without having the item available.

The average unavailability of a system that is on standby but is periodically inspected, tested, and repaired, is given by:

$$q(\tau) \approx \lambda T/(1 + \lambda T) \qquad \text{(Eq. 7-59)}$$

Here T is the average total time to respond to the failure indication, repair, and return the item to service.

As above, if λT is small compared to unity, the expression is approximated as:

$$q(\tau) \approx \lambda T \qquad \text{(Eq. 7-60)}$$

Recovery within Required Time–This case represents an event that is represented in a logic model as an intersection (AND logic) with a primary failure (unavailability) event. It may be applied to failures during mission time, to failures to start-and-run on demand, and to IEs such as loss-of-primary power source.

In many instances, the exponential function (Equation 7-51) is applied as an exponential repair model, given as:

$$p_R(t_C) = 1 - \exp(-t_C/\tau_R) \qquad \text{(Eq. 7-61)}$$

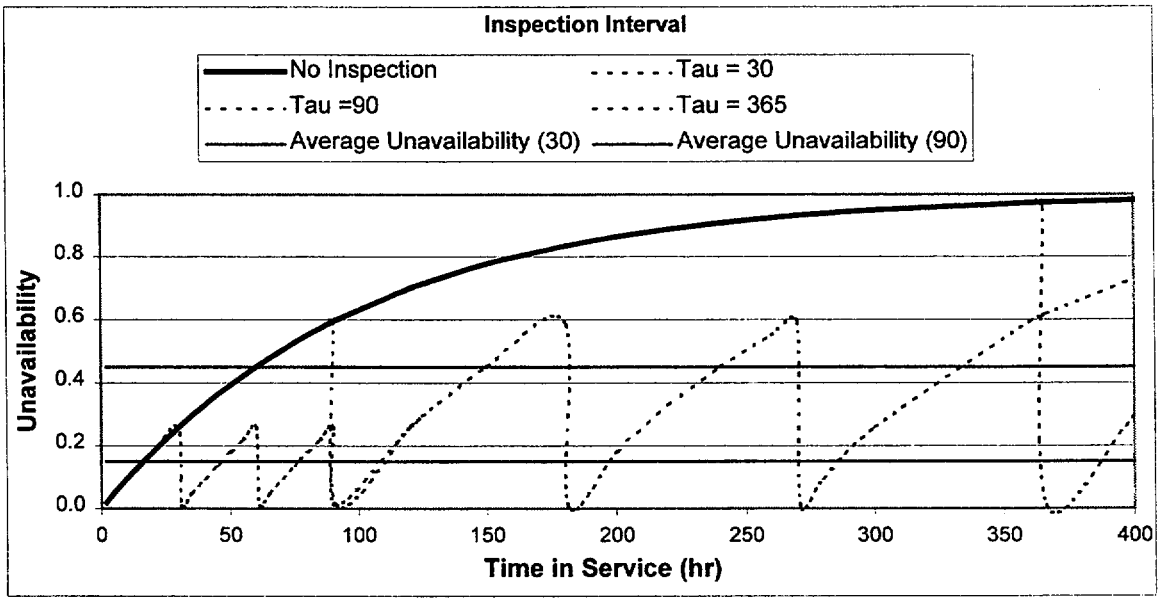

Figure 7-24. Unavailability with Inspection and Test

where

τ_R is the mean-time-to-restore

$p_R(t)$ is the probability that the unavailable item is recovered (returned to functionality) within a required time t_C.

Figure 7-25 illustrates the behavior of this function for a range of τ_R. It is observed that the probability of successful restoration for a given required time, t_C, is closer to 1.0 for small values of τ_R. In quantifying an event for an ET or FT application, a value of t_C is specified, based on safety functional requirements. If t_C were 1.0 hours, the probability of success would be 0.982 for a mean-time-to-restore τ_R of 0.25 hours, but only 0.632 for τ_R of 1.0 hours.

This failure probability is applied in the event sequence modeling. For the examples cited previously, where t_C is 1.0 hours, the probability of failure is small (0.018 [1-0.982]) for a mean-time-to- restore τ_R of 0.25 hours, but 0.3680 for τ_R of 1.0 hours.

The joint probability of having the item unavailable to provide its safety function is the product of the primary failure probability and the probability of non-recovery in the required time. If the primary failure probability is $q_P = 0.01$ and τ_R is 0.25 hours, then the joint probability is calculated as:

$$q = q_P * p_R(t_C) = 0.01 * 0.018 = 0.00018$$

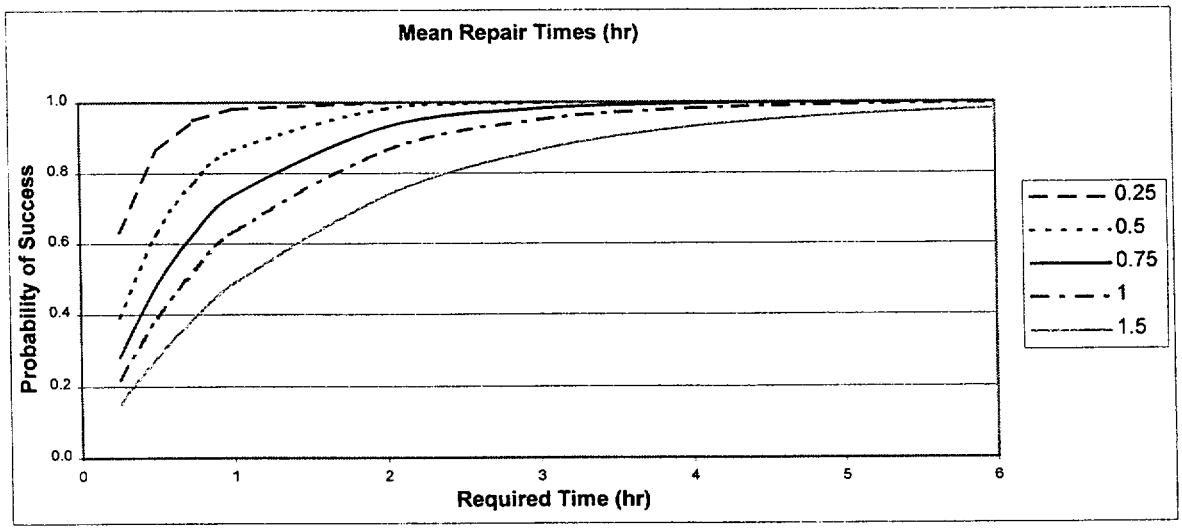

Figure 7-25. Probability of Restoration – Exponential Repair Model

Estimates of the mean-time-to-restore, τ_R, are developed for each situation, where required. This parameter is also subject to uncertainty analysis. The LN distribution has been shown to be a good representation of the repair and restoration times.

7.5.3.1.1.1 Specifying Mission Times and Allowable Recovery Time

The analyst must specify a mission time when the non-repairable time-based model is used. The specification must be defensible to the NRC as being adequate for a specific safety function. The specified mission time may be based on an engineering analysis or dictated by a regulatory requirement or precedent. However, the mission time may be somewhat arbitrary a long as the performance is shown to meet 10 CFR Part 63 requirements. For example, requiring that the Waste-Handling Building HVAC/HEPA filter system (for the inner-most zone) must function for at least 24 hours following a release of radioactivity from a breached waste form may be based, initially, on the qualitative argument that most of the important filtration will have occurred. Should offsite doses indicate that a longer operational period is required, however, the mission time would have to be extended.

The analyst must provide similar justification for allowable recovery times for repairable systems. The logic is similar to the specification of a mission time, but asks the complementary question of "how long can we be without this safety function before the 10 CFR Part 63 performance criteria cannot be met?" Using the example of the HVAC/HEPA filter system, it may be allowable for components of the secondary or tertiary zones to be out of service for many hours without compromising the negative pressure that ensures that airflow is inward toward the primary zone. The allowable time would set the limit on the recovery time in the repairable event model.

7.5.3.1.1.2 Specifying Time between Tests or Inspections

The probability of a failure-on-demand of standby SSCs is assumed to increase between inspections or tests, at which time they are restored to good-as-new. The probability of failure on demand must be low enough to ensure that a repository can meet the risk-informed performance requirements. It may be required to specify a shorter inspection interval or developing a more reliable standby system having a lower standby failure rate. This activity may be iterative.

The analyst may initially specify a reasonable typical interval such as one year, three months, one month, or a week, depending on how important it is to ensure the availability of a given system or component. If the risk-informed performance is demonstrated to meet the requirements of 10 CFR Part 63, then the specified interval may become part of the licensing specifications. If the performance is unacceptable, then shorter testing and inspection intervals may be explored or alternative designs (e.g., having more redundancy or diversity) may be considered.

7.5.3.1.2 Demand-Based Event Models

The failure-on-demand event model, as described in the *PRA Procedures Guide* (NRC 1983), is also termed the constant-failure-rate-per cycle model in the *Fault Tree Handbook* (Vesely et al. 1981).

The failure-on-demand model applies to a component or system that is in a dormant state until the instant there is a demand for it. This concept applies to standby components, as described previously. The failure-on-demand model also applies to structural and passive components that may never be challenged during their operational lifetime or are not amenable to testing, inspection, or refurbishing after the initial installation or construction. The weld on a WP is an example of such a component.

However, the constant-failure-rate-per cycle model may be applicable for operating or standby equipment that may be required to perform several, repeated operations (demands) for which there is a fixed probability of failure per demand.

For point estimates of event probabilities in an ET or FT analysis, the failure on demand is simply the value of the constant probability for a given situation, calculated as:

$$q_D = p_D = r/n \qquad \text{(Eq. 7-62)}$$

where p_D is derived from tests or event reports for r failures in n trials. The expression for q_D is a limiting case (for $r \geq 1$ failure) of the binomial probability distribution.

The demand-based event model should be applied to events that are modeled as a one-time demand in the PSA ET and FT analyses. This quantity is subject to considerations of uncertainty.

When the event involves a cycling of a system or component during some operational time span (or mission time), the expected number of cycles (demands) during the time interval is important. If N cycles are expected during a mission time T and the probability of failure per demand is p_D, then the probability of failure during T is estimated as:

$$q_T = N * p_D \qquad \text{(Eq. 7-63)}$$

This expression may be evaluated as a probability (pure number) or as a frequency (probability per unit time), depending on the application.

If the system or component is used during the response (mitigation) as part of an event sequence, or as a basic event in an FT, the probability form is used. The event modeling will specify the number of demands that will be expected. For example, a pressure relief damper may be required to cycle N times during a hot cell purging operation following a drop and breach of an SNF assembly. The value of N may be derived from considerations of the pressure equalization between the Waste Handling Building zones or be based on a performance-time requirement. The probability of failure, then, is $q_T = N * p_D$.

The frequency form is used if the system or component failure could be an IE of an event sequence. Event modeling will specify an operational frequency for demands (e.g., N is the number of lifts per year of SNF assemblies). If p_D represents the probability per lift of dropping a SNF assembly, then the frequency of dropping SNF assemblies becomes $f_T = N * p_D$ drops per year (here, f_T is used in place of q_T).

7.5.3.1.2.1 Binomial Distribution

The binomial distribution is a discrete form of a PDF:

$$b(x;n,p) = \binom{n}{x} p^x (1-p)^{n-x} \qquad \text{(Eq. 7-64)}$$

This expression gives the probability that exactly x number of failures will be observed in n independent trials, given a constant probability per trial, p. The parameter needed in this model is p. The expression for b(n;n,p) is a built-in function in the Microsoft Excel spreadsheet program.

The binomial form of the cumulative probability function is often used in ET and FT analysis. It is expressed as:

$$B(r;n,p) = \Sigma \binom{n}{s} p^s (1-p)^{n-s}; \text{ sum from } s = 0 \text{ to } s = r \qquad \text{(Eq. 7-65)}$$

This expression gives the probability that x, the number of failures observed in n independent trials, will be less than or equal to r, given a constant probability per trial, p. The statistical average of the binomial distribution is np and the variance is np(1-p). The expression for B(r;n,p) is a built-in function in the Microsoft Excel spreadsheet program.

If the binomial PDF is taken to the limit as n goes to infinity for the product, m = np is constant and finite, given the Poisson distribution that is expressed as:

$$p(x) = [m^x/x!] \exp(-m) \qquad \text{(Eq. 7-66)}$$

This expression represents the rare event approximation for a small number of failures in a large number of trials. It gives the probability that exactly x number of failures will be observed in a large number (effectively infinite) of independent trials having a small probability per trial, p. The parameter needed in this model is m = np. The expected number (mean) is m, and the variance is also m. The probability that $x \leq r$ is the summation of Equation 7-66 over x, from 0 to r. The Poisson distribution of Equation 7-66 is the basis for the exponential failure models, described below.

The Poisson distribution is a good approximation for the binomial, even for rather large values of p and small values of n. As an example, the *Fault Tree Handbook* asks "what is the probability of finding exactly one defective unit in a random lot of 10, given p = 0.1?" The exact value using the binomial distribution is 0.3874; the Poisson formula gives 0.3679. This estimation may be adequate for many probability estimates in light of other uncertainties. When the lot size is increased to 20, the respective values are 0.2702 and 0.2707; thus, an excellent agreement.

It is further noted that for most event tree and fault tree analyses, the probability of interest is that for exactly 0 failures. Setting x = 0 in Equation 7-66 gives:

$$p(0) = \exp(-m) = \exp(-np) \qquad \text{(Eq. 7-67)}$$

The available failure event data are given as time-based data, (i.e., a failure is observed to occur with an average interval of τ hours). Expressed another way, if the mean arrival interval of failures is τ a number R failures would be expected in some time interval T, where $R = T/\tau$). Since m, (Equation 7-66) is the number of failures, replacing M with $R = T/\tau$, gives:

$$p(0) = \exp(-R) = \exp(-T/\tau) = \exp(-\lambda T) \qquad \text{(Eq. 7-68)}$$

Here $\lambda = 1/\tau$ is a constant failure rate. This expression is observed to be the exponential event model, thus demonstrating the similarities between the demand-based and time-based event models. Equation 7-68 gives the probability of having exactly zero failures in the time T. The probability of having at least one failure is a time period, T, is given by $P_F = 1\text{-}p(0) = \exp(-\lambda T)$.

7.5.3.1.3 Dependent and Common Cause Failures

A more complete discussion of dependent failures and CCFs is presented in Section 7.4.

In developing FT models that include redundant components or subsystems, it is generally recognized that the joint probability of the concurrent failure of two or more redundant components may not be the product of independent failure probabilities. That is, the failures of the individual components or subsystems may be dependent (i.e., coupled). This possibility is modeled in the FT when the construction rules are applied. Similarly, events in a sequence may no be independent (i.e., the success or failure of one system may influence the probability of failure of a system [component, or human] that occurs later in the sequence).

The probabilities of the dependent or CCFs are quantified using demand-based or rate-based parameters, as appropriate for the event being quantified. Dependencies are explicitly modeled in ETAs and quantified by sequence-dependent probabilities (see Section 7). Potential CCFs are identified and quantified in FTAs. It is expected that most CCF quantification will apply the beta factor method (see Section 7.4).

7.5.3.1.4 Initiating Event Frequency

When the purpose of information analysis in an FTA is to quantify the frequency of an event sequence (or accident scenario), the frequency of the IE has to be scaled to match the operational load of the system. For example, the IE definition may be "crane drops SNF canister" and the quantification may require "F_D drops per year." The operational throughput of the system may be Z canisters per year. Demand-based and rate-based data can be used to calculate the frequency of the IE, as follows:

Demand-Based Data–Experience data indicate that the probability of dropping any given canister during a lift is Q_D drops per lift (i.e., more precisely defined as the probability of a canister drop per lifting operation). If the frequency of lifting canisters is Z per year, then the frequency of the postulated IE is calculated as:

$$F_D = Z * Q_D \text{ (drops per year)} \quad \text{(Eq. 7-69)}$$

Rate Based Data–Experience data show that the rate of dropping any given canister during operational time is λ_D drops per hour (e.g., this rate might be derived from related information like a crane failure rate). In this situation, the exposure time (or mission time) must be defined for each lift operation to derive the probability of a drop per lift. The estimated time that each canister is suspended in a vulnerable condition during each operation is T_L minutes. The probability of canister drop per lift is derived as:

$$Q_D = \lambda_D * T_L \text{ (drops per lift)} \quad \text{(Eq. 7-70)}$$

The time units must be converted, as appropriate, from hours to years.

Proceeding in the same manner as in the demand-based case, the frequency of the postulated IE is calculated as:

$$F_D = Z * Q_D \text{ (drops per year)} \quad \text{(Eq. 7-71)}$$

7.5.3.1.5 Human Error Probabilities or Rates

Many basic events in ET or FT models represent human errors in operations or maintenance. Special techniques have been developed for estimating the probabilities of various kinds of human errors. The events are sometimes called HAs to include positive effects (recoveries or interventions) as well as to recognize that the basic causes of an undesired event involving a human may be situational and not a true human error. HRA is the process of analyzing situations where human errors (or human recovery actions) may occur and quantifying the probability of those actions. Section 7.3 describes an approach for support of the PSA.

7.5.3.2 Information (Data) Gathering

A repository is a first-of-a-kind facility. Therefore, there is no facility-specific operational experience to draw from to support the PSA for the LA submittal for CA. Therefore, the estimates of event probabilities or failure rates will be based on surrogate experience or generic information. Since the operational portions of the facility will employ many systems and components that are common in general industry, mining, and the nuclear industry, there are many potential sources of information that can be applied in the PSA. This section identifies some of the known sources and describes the kind of information that is available in each. Guidance is provided on how to employ such information in the PSA development.

This section does not proffer a single, definitive database as a mandatory input to the PSA, however. The establishment, maintenance, and configuration control of such a database should be established outside of this Guide.

The two primary categories of information are operational experience and tabulated generic data.

7.5.3.2.1 Operational Experience

Operational experience provides raw data on the number, modes, and causes of failures of systems, components, and software and a baseline that quantifies the time-in-service or number of demands represented in the reporting. A failure rate (or failure probability) of a given failure mode is derived from the ratio of the number of failures during the operational time (or number of demands). While it is relatively easy to find reports on the number and modes of failures in reports from many industries (i.e., to quantify the numerator), it is usually difficult to determine the baseline (i.e., to quantify the denominator). The analyst must often make assumptions on the baseline, estimating the time-in-service or number of demands based on throughput rates of the surrogate facility, preferably with input from operating personnel at that facility.

In many instances, the analyst will have to adjust the raw information to make it applicable to a particular repository operation. For example, if information is available on commercial railway locomotive derailments per mile traveled, and the causal breakdown shows that 25 percent are due to bad weather, the analyst might reduce the raw number by 25 percent as an estimate for subsurface transporter locomotives to account for the fact that there is no weather underground.

In applications of surrogate data, the analyst must provide a rationale to support selection of the source and how the information is applied.

Representative sources of operational information sources are described in the following paragraphs.

- **Exploratory Studies Facility**–The ESF experience can be applied where appropriate. For example, records on ground support system installation, maintenance, and inspections may provide bases for estimating the reliability of the repository ground support system.

- **U.S. Department of Transportation, Federal Railway Association**–Statistics and analysis of causal factors of accidents on commercial railways may provide bases for estimating derailment, brake failure, and human error rates.

- **British Mining Locomotive Data (U.K. Health and Safety Executive)**–Statistics and analysis of causal factors of accidents on commercial mining locomotives may provide bases for estimating derailment, brake failure, and human error rates.

- **U.S. Nuclear Regulatory Commission**–The NRC maintains databases of licensee event reports for cranes, fuel handling equipment, instrumentation and controls, electrical distribution, emergency diesel generators, HVAC systems, and other systems that will be used in a repository.

- **Waste Isolation Pilot Project**–Experience information accumulated on this project should be examined and incorporated into event probability estimates.

- **Institute of Nuclear Power Operations**–Performance information has been collected for many years, but for confidentiality, the Institute and the participating utilities closely

hold the information. Some summary information has been published, but access to compiled reliability databases has been restricted. Available information should be examined for applicability to the PSA for a repository.

List of other specific sources. [Information for this section is under development and will be provided later.]

7.5.3.2.2 Tabulated Generic Data

There are many tabulations of generic information that can be used for PSA. A bibliography of generic data sources is provided in Appendix 7A. The following paragraphs describe some of the principal databases.

- **Savannah River Site Generic Data Base** (Blanton and Eide 1993)–This document describes a project for improving the component failure rate database at the Savannah River Site. It provides a representative list of components and failure modes, approximately 75 percent of which are based on actual events. Many sources of generic data are noted, but a major generic source was NUCLARR (see below), but also incorporated data from the INEEL chemical processing plant. A Bayesian approach was used for estimation. The information was aggregated to obtain generic failure rate distributions (given as mean and EF of LN) for each component failure mode. EF is the ratio of 95 percent upper bound to median (50 percentile).

- **Savannah River Site Human Error Rate Database** (Benhardt et al. 1994)–A counterpart of the Savannah River Site component database. This report tabulates HEP for 35 representative HAs in Savannah River Site safety analyses: 16 are based on generic information, and 19 are based on site-specific information.

- **IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems** (IEEE 1998)–This document provides a limited summary of equipment reliability data (see also IEEE 1984).

- **NUCLARR, NUREG/CR-4639** (INEEL 1989)–This database, sponsored by the NRC, is a compilation of event data extracted from many PRA and individual plant examinations. Not all of the information is independent, especially some of the generic information that is replicated in several studies. The entries are categorized as 1, 2, and 3 to indicate the degree of independence and quality so the user may reject some entries, or use them with caution or weighting. Access to the NUCLARR database requires a subscription.

- **Eide and Calley** (1993)–This paper presents a comprehensive tabulation of generic component failure rates developed for light-water reactor PRAs. NUCLARR was used, so that most of the failure rates are based on actual plant experience. Failure rates and their EFs are given for several failure modes of each component. The EFs are the ratio of the 95^{th} percentile to the 50^{th} percentile. NUCLARR has automatic aggregation routines to pool information from different sources. Table 7-7 illustrates the format of the information in that paper.

- **Eide et al.** (1993)–This paper presents failure rates for fluid system components to support internal flooding PRAs for NPPs. The basic information was gathered from licensee event reports reported in Nuclear Power Experience. Rupture probabilities and leakage frequencies were estimated using Bayesian update with a noninformative prior. Component exposure times were estimated if they were not explicitly given in the information base.

- **IEEE Guide to the Collection and Presentation of Electrical, Electronic, and Sensing Component Reliability Data for Nuclear-Power Generating Station** (IEEE 1984)–This document contains failure rate point values and intervals for electronic, electrical, and sensing components. The values reported were elicited from about 200 experts and pooled using geometric averaging. Some of the information is based on operational and test information, but the user cannot tell which information has this basis versus that based purely on expert opinion.

- **Rome Air Force Base, NPRD-2, Nonelectronic Parts Reliability Data** (Arno 1981)–This document is intended to complement MIL-HNBK-217F (DOD 1991) by providing information on mechanical, fluid, and air-handling system components. For example, the table includes failure modes and rates for vehicle brakes in various applications. The tables provide rates (mean and confidence interval) for various failure modes, and where available, it provides raw data (number of failures and number of trials or operational time).

- **AIChE Guidelines for Process Equipment Reliability Data with Data Tables** (AIChE 1989)–This source contains information on components used in non-nuclear facilities. Tables include failure rates for different modes of failure and the lower bound, mean, and upper bound.

- **MIL-HDBK-217F, Military Handbook Reliability Prediction of Electronic Equipment** (DOD 1991)–This document is a compilation of baseline failure rates for a wide variety of electronic components, and it includes adjustment factors to account for the environment, duty or load, quality factor, and similar items. This document should be considered a prime source of information for the PSA because it is applied widely in government-supported activities.

- **Waste Isolation Pilot Project Safety Analysis**–Research database for potential use. [Information for this section is under development and will be provided later.]

- **Reactor Safety Study** (WASH 1400) (NRC 1975)–This work was compiled in the mid-1970s. It has tabulations of component and system failure rates and probabilities applicable to NPPs. The tabulations include data on pumps, valves, and reactor protection systems, which are not relevant to PSA; however, information on electrical components and instrumentation may be applicable. Parts of this report are still quoted and are embedded in some of the other generic databases (e.g., NUCLARR [INEEL 1989]). For PSA, preference should be given to more recent sources, provided they are applicable and reliable.

Component/Failure Mode	Recommend- ed Failure Rate, Mean	Error Factor, 95/50	NUCLARR Component Failure Information				NUCLARR Source
			Sources	Failures	Demand	Hours	
Mechanical Components							
Valve - Motor Operated							
Fail to open/close	3.0E-03 /d	5	13	480	141474		Category 1
Spurious operation	5.0E-08 /h	10	4	1		2.00E+07	Category 1
Plug	5.0E-09 /h	10		0		1.24E+08	Category 2
Internal leakage							None
Interanal rupture	1.0E-07 /h						Other
. .	. .	.	.	.	.	.	.
. .	. .	.	.	.	.	.	.
. .	. .	.	.	.	.	.	.
Pump - Motor Driven							
Fail to start	3.0E-03 /d	5	17	137	48459		Category 1
Fail to run	3.0E-05 /h	10	16	216		7.46E+06	Category 1
. .	. .	.	.	.	.	.	.
. .	. .	.	.	.	.	.	.
. .	. .	.	.	.	.	.	.
Electrical Components							
Battery							
Failure	1.0E-05 /h	5	6	8		9.44E+05	Category 1
Battery charger							
Failure	1.0E-05 /h	5	7	29		1.62E+06	Category 1
Switch-General							
Failure to open/close	1.0E-05 /d	5					Other
Spurious operation	1.0E-06 /h	10					Other
Switch-Limit							
Failure to open/close	3.0E-05 /d	5	1	0	12550		Category 1
Spurious operation	1.0E-06 /h	10	1	7		8.10E+06	Category 1
. .	. .	.	.	.	.	.	.
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Table 7-7. Example of Generic Component Failure Rates Database

- **Government Industry Data Exchange Database** (GIDEP)–Primarily oriented toward aerospace and defense industries. Generic failure rate information is similar to that presented in the Rome Air Force Base (Arno 1981) and MIL-HDBK-217F (DOD 1991) documents. Subscribers pay no fees, but must contribute data.

- **Plant-Specific PRAs and Individual Plant Examinations**–Every PRA and individual plant examination submitted to the NRC contains a tabulation of basic event data. These will be a mixture of generic and plant-specific information. If other generic sources do not support a particular facet of the PSA, the analyst may have to use this source.

- **Foreign Databases**–Component failure rate data have been compiled by foreign nuclear programs such as those in France and Sweden.

7.5.3.3 Estimation of Model Parameters

This section describes the methods for quantifying parameters needed to quantify the event probabilities and frequencies using the models described in Section 7.5.3.1. Two general classes

of methods are described that are known, respectively, as classical (or Frequentist) estimation and Bayesian (or subjectivist) estimation.

The classical approach relies on statistical theories that equate probability to the frequency of observed outcomes, usually invoking hypothetical runs of many trials. The classical approach has been applied in traditional reliability engineering. The classical approach has limitations in trying to estimate the probability of events that have never been observed, but which are believed to be possible.

The Bayesian approach is probability based, not statistical based. In this concept, probability is related to the state of knowledge or degree of belief of the analysts, hence the notion of subjectivity. The method is not entirely subjective in applications, however, since there is a robust theoretic foundation for incorporating empirical evidence into the estimation of event probabilities. Notably, there is a technique for Bayesian updates of facility-specific reliability databases. Further, Bayesian concepts are applied in the pooling, or aggregating, of information from several sources. Although the approach was fostered in the development of PRA methods, it has been adapted in modern reliability engineering.

Both the classical and Bayesian methods provide for estimating the uncertainties or in the model parameters. These are termed confidence intervals in classical estimation, and probability intervals or error factors in Bayesian estimation. In all cases, the intervals represent the range about the point estimate of a given parameter where the integral of the PDF is the fraction α of possible values reported from a large number of observations (i.e., the interval is expected to include the true value of the parameter with probability of 100α percent. The respective limits on the confidence interval are calculated as the area in the upper and lower tails of the particular PDF. The intervals are expressed as the value of the parameter that represents the upper $100(1-\frac{\alpha}{2})$ percent and lower $100(1-\frac{\alpha}{2})$ percent values of the parameter.

The following sections are based, in large measure, on the *PRA Procedures Guide* (NRC 1983).

7.5.3.3.1 Classical Parameter Estimation

The classical approach is presented for point estimates and confidence intervals for the binomial, Poisson and LN distributions. The information requirements for quantifying each distribution are also presented.

7.5.3.3.1.1 Binomial Distribution

The fundamental parameter is p, the probability of failure on demand (unitless) (see Section 7.5.3.1). It is derived from test or experience information as follows:

Point Estimate: $p^* = f/n$ (Eq. 7-72)

where information needs are:

f = number of observed or recorded failures in n demands or trials

n = number of recorded demands or trials in reporting period.

Confidence Interval: The exact method for interval estimation for the binomial distribution is to use the expression B(f;n,p) for the cumulative distribution solving for p_U and p_L, respectively, that give the upper and lower 100(1 - α) percent confidence limits:

$$\alpha = B(f;n,p_U) = \sum \binom{n}{s} p_U^{\,s} (1 - p_U)^{n-s}; \text{ sum from } s = 0 \text{ to } s = f \qquad \text{(Eq. 7-73)}$$

$$\alpha = B(f;n,p_L) = \sum \binom{n}{s} p_L^{\,s} (1 - p_L)^{n-s}; \text{ sum from } s = f \text{ to } s = n \qquad \text{(Eq. 7-74)}$$

These expressions may be solved using standard tables or by using built-in formulas in a spreadsheet (e.g., the Microsoft Excel spreadsheet program).

For small f and large n, the interval may be approximated using:

$$P_U(1 - \alpha) = [\chi^2 (2f + 2, \alpha)]/2n \qquad \text{(Eq. 7-75)}$$

$$P_L(1 - \alpha) = [\chi^2 (2f, 1-\alpha)]/2n \qquad \text{(Eq. 7-76)}$$

where χ^2 (m, γ) is the value of the Chi-Squared distribution for the 100 γ-percentile for m degrees of freedom. The interval between $P_L(1-\alpha)$ and $P_U(1-\alpha)$ constitutes a confidence interval. For example, $2\alpha = 0.1$, the range constitutes a 90% confidence interval and $\alpha = 0.05$ in Equations 7-75 and 7-76,

These expressions may also be solved using standard tables or by using built-in formulas in a spreadsheet (e.g., the Microsoft Excel spreadsheet program).

7.5.3.3.1.2 Poisson Distribution

The fundamental parameter is λ, the probability of failure per unit time (see Section 7.5.3.1). It is derived from test or experience information as follows:

Point Estimate: $\lambda^* = f/T$ (Eq. 7-77)

where the information needs are

f = number of observed or recorded failures (or an IE) in a time interval T.

T = time duration in reporting period.

Confidence Interval: The interval estimation for the Poisson distribution is to solve for λ_U and λ_L using the following expressions:

$$\lambda_L(1 - \alpha) = [\chi^2 (2f + 2, 1 - \alpha)]/2T \quad \text{(Eq. 7-78)}$$

$$\lambda_U(1 - \alpha) = [\chi^2 (2f, \alpha)]/2T \quad \text{(Eq. 7-79)}$$

where

χ^2 (m, γ) is the value of the Chi-Squared distribution for the 100 γ-percentile for m degrees of freedom

These expressions may also be solved using standard tables or by using built-in formulas in a spreadsheet (e.g., the Microsoft Excel spreadsheet program). Note that these expressions are similar to the above approximate interval estimate for p in the binomial case, except that T replaces n.

7.5.3.3.1.3 Lognormal Distribution

Parameter estimation for the LN distribution is different than the prior two in two respects: 1) it describes a transformed variable rather than the fundamental parameter of interest, and 2) it requires two-parameters, the sample mean, μ^*, and the sample variance and σ^{2*}. Further discussions of the properties of the very important LN distribution are provided in Section 9, Uncertainty Analysis.

The fundamental parameter might be an observable quantity like a repair time for some component or system, τ, which is to be estimated from experience records.

In this example, the Information Needs are N independent observations such as of repairs time, say $t_1, t_2, \ldots t_N$. The transformed variable is $x_i = \ln(t_i)$; i = 1,2, ... N.

The parameters of the PDF of the transformed variable x_i are calculated as follow:

$$\mu^* = \Sigma\, x_i/N \text{ sum for i = 1 to n, for the sample mean} \quad \text{(Eq. 7-80)}$$

$$\sigma^{2*} = \Sigma\, (x_i - \mu^*)^2 / (N-1), \text{ sum for i = 1 to n, for the sample variance} \quad \text{(Eq. 7-81)}$$

Confidence Intervals: Because the distribution requires two parameters, confidence intervals are calculated for μ and σ^2.

For μ, the upper and lower 100 $(1 - \alpha)$ percent confidence limits are:

$$\mu_L = \mu^* - t(n-1,1-\alpha)[\sigma^*/n^{0.5}] \quad \text{(Eq. 7-82)}$$

$$\mu_U = \mu^* + t(n-1,1-\alpha)[\sigma^*/n^{0.5}] \quad \text{(Eq. 7-83)}$$

where t(d,γ) is the γ-percentile of Student's t distribution with d degrees of freedom.

For σ^2, the upper and lower 100 $(1 - \alpha)$ percent confidence limits are:

$$\sigma^2_L = [(n-1)\,\sigma^{2*}]/\,\chi^2\,(n-1,\,1-\alpha) \qquad \text{(Eq. 7-84)}$$

$$\sigma^2_U = [(n-1)\,\sigma^{2*}]/\,\chi^2\,(n-1,\,\alpha) \qquad \text{(Eq. 7-85)}$$

where χ^2 (m, γ) is the value of the Chi-Squared distribution for the 100 γ-percentile for m degrees of freedom.

These expressions involving χ^2 and Students τ distributions may also be solved using standard tables or by using built-in formulas in a spreadsheet (e.g., the Microsoft Excel spreadsheet program).

7.5.3.3.2 Bayesian Parameter Estimation

The Bayesian approach also yields point estimates and interval estimates to represent the range where the analyst is confident that the true parameter lies. Its basis is different than the classical estimation, however, in that it permits incorporation of analysts' belief and information not contained in observed data. Such belief and information are incorporated by assigning a probability distribution, termed the prior distribution that describes the analyst's belief about the parameter. The prior describes the best estimate point value, uncertainty range, and an assumed shape (e.g., normal, LN, or binomial). In cases where the analyst has no information or weak belief in the value of a parameter, the Bayesian approach permits use of a noninformative prior (see discussion below). By applying evidence that exists (e.g., test results, experience data from surrogate systems, or facility-specific experience data), a posterior probability distribution is generated using the Bayes theorem (NRC 1983). The posterior distribution yields a revised (updated) estimate of the best estimate (median or mean) and the uncertainty ranges.

As will be shown, the Bayesian approach uses an integration over the joint distribution of the prior distribution and a likelihood function. It has been shown that the integration can be performed in closed form if the priors are represented by conjugate distributions, and each primary distribution has a natural conjugate (see *PRA Procedures Guide* [NRC 1983, Section 5] for more information). When the prior distribution is not described by a standard probability distribution, it is usually approximated with a discrete (rather than continuous) distribution, where a summation over the joint distribution of prior and likelihood function is used.

After a summation of concepts that are common to all Bayesian estimates, this section provides the methods for applying the approach to point estimates and confidence intervals for the binomial, Poisson (including exponential), and LN distributions. The information requirements for quantifying each distribution are also presented.

7.5.3.3.2.1 Basic Elements of Bayesian Estimation

Bayesian Point and Interval Estimation–The prior distribution summarizes the uncertainty in a parameter based on judgement or generic information sources. Similarly, the posterior distribution summarizes the uncertainty in the facility-specific or surrogate information.

Two commonly used values of point estimates are used, the mean and the median, which are based on the properties of PDFs. For example, if a failure rate λ is the parameter of interest, and its uncertainty is describes by a PDF $f(\lambda)$, the respective point estimates are calculated as follows:

$$\mu_\lambda = \int_0^\infty \lambda f(\lambda) d\lambda, \text{ is the mean} \qquad \text{(Eq. 7-86)}$$

while the median is the solution to the integral equation:

$$F(\lambda) = \int_0^\lambda f(t)\, dt = 0.5 \qquad \text{(Eq. 7-87)}$$

where $F(\lambda)$ is the CDF.

The point estimate definitions are applied to both the prior and the posterior distribution, as needed.

The Bayesian interval estimate also uses the probability distribution for the parameter. The range of integration is set so that the range includes the desired probability that the range contains the true value. If the desired probability is given as $(1 - \gamma)$, the respective upper (λ_U) and lower (λ_L) interval limits are calculated as follow:

$$\int_0^{\lambda_u} f(\lambda) d\lambda = \gamma/2 \qquad \text{(Eq. 7-88)}$$

$$\int_{\lambda_L}^\infty f(\lambda) d\lambda = \gamma/2 \qquad \text{(Eq. 7-89)}$$

The interval definitions are applied to both the prior and the posterior distribution, as needed.

If the desired probability of success $(1 - \gamma)$ is 0.90, then $\gamma = 0.10$, so $\gamma/2 = 0.05$.

The application of the point and interval calculations is demonstrated below for the parameter of the binomial, Poisson, and LN distributions.

7.5.3.3.2.2 Steps in Bayesian Estimation Approach

The *PRA Procedures Guide* (NRC 1983) identifies the following steps for applying the Bayesian approach to information processing. These steps are listed here in abbreviated form as applicable to the PSA.

- Identify sources and forms of generic information to be used in generating an appropriate prior distribution
- Select a prior distribution family if none has been specified in the generic information

- Define a particular prior distribution from parameters derived from generic information by reducing or combining, as appropriate
- Plot the prior distribution and characterize it: mean, median, variance, and summary percentiles (e.g., upper and lower 95 percent limits)
- If generic estimates are to be used, generate from the prior
- If facility, or application-specific estimates are required, additional sub-steps are used:
  - Obtain specific information
  - Identify appropriate form for the likelihood function
  - Apply the Bayes theorem to generate the posterior distribution
  - Plot posterior on same graph as prior to observe effect of specific information (e.g., shift in central measure, change in distribution shape)
  - Characterize posterior distribution: mean, median, variance, and summary percentiles (e.g., upper and lower 95 percent limits)

7.5.3.3.2.3 Defining Prior Distributions

Unless a noninformative prior is selected, a prior distribution is developed from generic information. When estimating a parameter such as the failure rate of a given component, the analyst usually has available generic information consisting of engineering knowledge about the design, construction, expected performance, and expected operating environment associated with the component, and the past performance and reliability of similar components. Section 7.5.3.2 describes some of the sources of generic information. When little or no generic prior information is available, a noninformative prior may be used.

In many instances, a natural conjugate distribution is used in Bayesian estimation to permit closed form integration. For a given likelihood function, such as the exponential, a natural conjugate function has the property that the posterior and prior distributions are member of the same family of distributions (i.e., a LN prior distribution on λ yields LN posterior distribution on λ).

Sometimes in practice, a particular distribution may be mapped into its conjugate by moments matching, and after the Bayesian integration over the conjugate and likelihood function, the posterior distribution is mapped back to its conjugate (Blanton and Eide 1993).

Generic information may be obtained from single or multiple sources. Sufficient information to generate the distribution parameters of the priors. For example, at least two independent pieces of information are required to generate the parameters needed to define a LN prior distribution for λ. Thus, pairs of information like a) upper and lower limits, b) mean and variance, or 3)

median and EF must be defined by the analyst. The information may be derived from tabulated failure rates, reported experience, or expert judgement.

For much of the PSA analysis, tabulated data that have been applied in various PRA studies or in MIL-HDBK-217P (DOD 1991) will suffice, particularly when there is a clear match between a repository component or system and a component or system represented in the tabulation. In other cases, the analyst may not be able to clearly establish the direct applicability of one or more tabulated items and must resort to multiple information sources. Such sources are combined using one of the methods described in the following section.

7.5.3.3.3 Pooling and Combining Information from Multiple Sources

Since the PSA will be based in large measure on surrogate information, there may be instances where two or more sources provide event data or failure rates for systems or components that are judged to be representative of those in a repository. For purposes of event probability estimation, a single prior distribution is needed. Numerous methods are available, but the *PRA Procedures Guide* (NRC 1983) describes three processes for pooling multiple information sources to arrive at a single distribution. One process, termed the mixture method is judged to be too cumbersome for PSA application, so two of the methods are presented here.

The first, based on a geometric mean, is simple to apply and is believed to be sufficient for the PSA for the LA for construction authorization. This method is noted to underestimate the uncertainties. The second method, a two-stage Bayesian, has been applied in numerous PRA studies. It is based on developing a prior distribution that is grounded in generic information before updating the distribution with facility-specific information. Since a repository will have little specific information to apply, this method is not developed in detail in this edition of the PSA Guide.

Martz and Waller (1978) examined several methods of pooling information sources. They concluded that simple averaging techniques are satisfactory when a small number of sources are to be pooled, but more sophisticated methods are required when 15 or more sources are to be combined.

7.5.3.3.3.1 Geometric Mean Method

If there are M sources of information for a failure rate λ_i and each source provides a point estimate and interval estimate, the composite values for the prior distribution are calculated as geometric means, as

$$\langle\lambda_0\rangle = \left(\prod_{i=1,m} \lambda_{0,i}\right)^{1/M}; \text{ where } i = 1\ldots m \text{ for the composite point value} \qquad \text{(Eq. 7-90)}$$

$$\langle\lambda_{LB}\rangle = \left(\prod_{i=1,m} \lambda_{LB,i}\right)^{1/M}; \text{ where } i = 1\ldots m \text{ for the composite lower bound} \qquad \text{(Eq. 7-91)}$$

$$\langle\lambda_{UB}\rangle = \left(\prod_{i=1,m} \lambda_{UB,i}\right)^{1/M}; \text{ where } i = 1\ldots m \text{ for the composite lower bound} \qquad \text{(Eq. 7-92)}$$

where $\lambda_{0,I}$ is the point value from the i^{th} information source

$\lambda_{LB,i}$ and $\lambda_{UB,i}$, respectively, are lower and upper bounds of the i^{th} information source

With the composite point estimate treated as a mean or median, as deemed appropriate for the assumed family of the prior distribution, the available experience data (evidence) can be applied to derive the posterior distribution, as described in Section 7.5.3.3.4.1

7.5.3.3.3.2 Two-Stage Bayesian Method

[Information for this section is under development and will be provided later.]

7.5.3.3.4 Applications of Bayesian Estimation to Event Quantification

For PSA purposes, important techniques for parameter estimation have been extracted from reference material. The first application is for estimating failure-on-demand probabilities, and the second is for estimating constant failure rates. The presentations give the mathematical formulas for distribution parameters when noninformative and conjugate distributions are used.

7.5.3.3.4.1 Bayesian Estimation of Failure-on-Demand Probabilities

The binomial distribution, given in Equation 7-64 in Section 7.5.3.1.2, gives the probability of observing exactly r failures in n trials, given a probability of failure per trial of p. That equation is used as the likelihood function. The purpose of the Bayesian estimation is to determine the best estimate for p and its uncertainty distribution.

The first case is application of a noninformative prior. The form of noninformative prior given in Section 5.5.2.3.2 of the *PRA Procedures Guide* (NRC 1983) is

$$[q\,(1-q)]^{-0.5}/\pi;\ \text{for}\ (0 \le q \le 1) \qquad \text{(Eq. 7-93)}$$

where it may be shown that

Prior mean: $q_0 = 0.5$
Prior median: $q_{0,0.5} = 0.5$
Prior variance: $\sigma_0^2 = 0.125$

and the 100(1 - γ) percent (e.g., 95 percent) symmetric probability is a function of the F-distribution with a and b degrees of freedom, $F_{1-\gamma/2}(a,b)$, as follows:

Prior lower bound: $$q_{0,L} = 0.5/[0.5 + 0.5\,F_{1-\gamma/2}(1,1)] \qquad \text{(Eq. 7-94)}$$

Prior upper bound: $$q_{0,U} = 0.5\,F_{1-\gamma/2}(1,1)/[0.5 + 0.5\,F_{1-\gamma/2}(1,1)] \qquad \text{(Eq. 7-95)}$$

The posterior distribution is shown to have the form of a beta distribution as follows:

$$[\Gamma(n+1)/\Gamma(r+0.5)\Gamma(n-r+0.5)]\,[q^{\,r-0.5}(1-q)]^{n-r-0.5};\ \text{for}\ (0 \le q \le 1) \qquad \text{(Eq. 7-96)}$$

where $\Gamma(x)$ is the gamma function.

The parameters of the posterior distribution are the following:

Posterior mean: $\underline{q} = (r + 0.5)/(n + 1)$ (Eq. 7-97)

Posterior median: $q_{0.5} = (r + 0.5)/[(r + 0.5) + (n - r + 0.5)F_{0.5}\,(2n - 2r + 1, 2r + 1)]$ (Eq. 7-98)

Posterior variance: $\sigma^2 = (r + 0.5)(n - r + 0.5)/[(n + 1)^2\,(n + 2)]$ (Eq. 7-99)

and the $100(1 - \gamma)$ percent symmetric probability is a function of the F-distribution with a and b degrees of freedom, $F_{1-\gamma/2}\,(a,b)$, as follows:

Posterior lower bound:

$$q_L = (r + 0.5)/[(r + 0.5) + (n - r + 0.5)F_{1-\gamma/2}\,(2n - 2r + 1, 2r + 1)] \quad \text{(Eq. 7-100)}$$

Posterior upper bound:

$$q_U = [(r + 0.5)F_{1-\gamma/2}\,(2r + 1, 2n - 2r + 1)]/[(n - r + 0.5) + (r + 0.5)F_{1-\gamma/2}\,(2r + 1, 2n - 2r + 1)] \quad \text{(Eq. 7-101)}$$

The noninformative prior is very useful when the available performance records show zero failures for a finite number of trials. In this instance, the classical estimation must assert at least one failure has occurred, or the estimation interval on p becomes indeterminant (see Section 7.5.3.4.1).

The second application assumes a beta prior that is derived from information available prior to the analysis. Such prior information may be derived from generic sources. The beta prior has the form:

$$[\Gamma(n_0)/\Gamma(r_0)\Gamma(n_0 - r_0)]\,[q^{r_o - 1}\,(1 - q)\,]^{n_o - r_o - 1};\ \text{for } (0 \le q \le 1) \quad \text{(Eq. 7-102)}$$

where the values of n_0 and r_0 are the parameters of the assumed beta prior distribution, but may also be interpreted as information derived from the prior information, where n_0 represents the number of trials, and r_0 the number of failures. $\Gamma(x)$ is the gamma function.

The parameters of this distribution are:

Prior mean: $\underline{q_0} = r_0 / n_0$ (Eq. 7-103)

Prior median: $q_{0,\,0.5} = r_0/[r_0 + (n_0 - r_0)\,F_{0.5}\,(2n_0 - 2r_0, 2r_0)]$ (Eq. 7-104)

Prior variance: $\sigma_0^2 = r_0\,(n_0 - r_0)/n_0^2\,(n_0 + 1)$ (Eq. 7-105)

and the $100(1 - \gamma)$ percent symmetric probability is a function of the F-distribution with a and b degrees of freedom, $F_{1-\gamma/2}\,(a,b)$, as follows:

Prior lower bound: $q_{0,L} = r_0/[r_0 + (n_0 - r_0)\,F_{1-\gamma/2}\,(2n_0 - 2r_0, 2r_0)]$ (Eq. 7-106)

Prior upper bound: $q_{0,U} = r_0\,F_{1-\gamma/2}\,(2r_0, 2n_0 - 2r_0)]/[(n_0 - r_0) + r_0\,F_{1-\gamma/2}\,(2r_0, 2n_0 - 2r_0)]$ (Eq. 7-107)

Posterior mean: $\underline{q} = (r + r_0)/(n + n_0)$

Posterior median:

$$q_{0.5} = (r + r_0)/[(r + r_0) + (n - r + n_0 - r_0)\, F_{0.5}\,(2n - 2r + 2n_0 - 2r_0,\ 2r + 2r_0)]$$

Posterior variance:

$$\sigma^2 = (r + r_0)\,(n - r + n_0 - r_0)/[(n + n_0)^2\,(n + n_0 + 1)]$$

and the $100(1 - \gamma)\%$ symmetric probability is a function of the F-distribution with a and b degrees of freedom, $F_{1-\gamma/2}(a,b)$, as follows:

Posterior lower bound:

$$q_L = (r + r_0)/[(r + r_0) + (n - r + n_0 - r_0)\, F_{1-\gamma/2}\,(2n - 2r + 2n_0 - 2r_0,\ 2r + 2r_0)]$$

Posterior upper bound:

$$q_U = [(r + r_0)\, F_{1-\gamma/2}\,(2r + 2r_0, 2n - 2r + 2n_0 - 2r_0)]/[(n - r + n_0 - r_0) + (r + r_0)\, F_{1-\gamma/2}\,(2r + 2r_0, 2n - 2r + 2n_0 - 2r_0)].$$

The third application assumes a LN prior distribution on q. This distribution is often used for failure rates, especially for low rates like 10-6 per demand or unit time. The LN is so named because the random variable represented by the distribution, x, is the logarithmic transform of a random variable of interest (i.e., the failure rate per demand, q). Thus, $x = \ln(q)$ is the random variable, and x is assumed to follow a normal (or Gaussian) distribution. All the well-known statistical properties and tabulations of the normal distribution can then be applied. The transformation between moments of the transformed variable and the failure rate are shown below.

The LN distribution requires two parameters, μ and σ, the mean and standard deviation of a normal distribution on *x*. These distribution parameters are derived from the assumed LN distribution on *q*, as follows.

The analyst estimates or specifies two symmetric percentiles for the interval containing q with a given probability, $1 - \gamma$, where $0 < \gamma < 0.5$ (usually, γ is 0.1 or 0.05). The respective percentiles are labeled q_γ (or q_L, lower bound) and $q_{1-\gamma}$ (or q_U, upper bound), and are symmetrical, giving:

$$p(q < q_\gamma) = p(q > q_{1-\gamma}) = \gamma \qquad \text{(Eq. 7-108)}$$

The median value of q is the geometric mean of the interval limits, that is:

$$q_{0.5} = (q_\gamma\, q_{1-\gamma})^{1/2} \qquad \text{(Eq. 7-109)}$$

and the EF is defined as:

$$EF = (q_{1-\gamma} / q_\gamma)^{1/2} \qquad \text{(Eq. 7-110)}$$

and a useful property of the EF is its relationship to the median, as follows:

$$EF = (q_{0.5}/ q_{\gamma}) = (q_{1-\gamma} / q_{0.5}) \quad \text{(Eq. 7-111)}$$

The parameters of the associated LN distribution, μ and σ, become:

$$\mu = \ln (q_{0.5}) \quad \text{(Eq. 7-112)}$$

$$\sigma = \ln (EF) / z_{1-\gamma} \quad \text{(Eq. 7-113)}$$

where $z_{1-\gamma}$ is the $100(1-\gamma)^{th}$ percentile of a normal (Gaussian) distribution. Values of $z_{1-\gamma}$ are tabulated in virtually all statistics books and can be obtained from the normal distribution function that is built into the Microsoft Excel spreadsheet program.

The moments of the fitted LN are derived from the parameters as follow:

Mean: $$q = \exp(\mu + \sigma^2/2) \quad \text{(Eq. 7-114)}$$

Mode: $$q_{Md} = \exp(\mu - \sigma^2) \quad \text{(Eq. 7-115)}$$

Median: $$q_{0.5} = \exp(\mu) \quad \text{(Eq. 7-116)}$$

Variance: $$\sigma_q^2 = [\exp(2\mu + \sigma^2][\exp(\sigma^2) - 1] \quad \text{(Eq. 7-117)}$$

The variance σ_q^2 is for the distribution of the failure rate q, while σ^2 is the variance of the transformed random variable $x = \ln(q)$.

The evidence in the form of r failures in n trials is incorporated into the Bayesian analysis. Since the LN does not allow a closed-form integral solution, numerical integration is used (see Section 5.5.2.3.4 of the *PRA Procedures Guide* [NRC 1983]).

An alternative method, applied at the Savannah River Site (described in Blanton and Eide [1993]), converts the prior LN into a beta distribution, applies the specific evidence (number of failures, r, and number of trials, n) in the Bayesian integration, which in turn produces a beta posterior distribution. The beta posterior distribution is then converted to a LN.

7.5.3.3.4.2 Bayesian Estimation of Constant Failure Rates

The methods for estimating constant failure rates are very similar to those for failure-on-demand with two primary differences. First, the likelihood function is the Poisson distribution, rather than the binomial. Second, the natural conjugate for the Poisson distribution is the gamma distribution, rather than the beta distribution. A third difference, demonstrated below, is the form of the noninformative prior that is recommended.

The method is aimed at deriving a best estimate and probability interval for a constant failure rate, λ, given information on the number of failures, r, in a given test-time duration, T. The failure on demand uses r and the number of trials, n, rather than the time.

The likelihood function for constant failure rates is the Poisson distribution, expressed as:

$$L(E|\lambda) = (\lambda T)^r \exp(-\lambda T)/r! \quad (r = 0, 1, 2, ...) \qquad \text{(Eq. 7-118)}$$

The estimation methods are presented for three cases using different prior distributions: noninformative, gamma, and LN.

The first case is the application of a noninformative prior. The form of noninformative prior given in Section 5.5.2.4.2 of the *PRA Procedures Guide* (NRC 1983) is:

Prior density: $f_0(\lambda) = \lambda^{-0.5}$ (an improper distribution) $(\lambda > 0)$ (Eq. 7-119)

Posterior density: $f(\lambda) = [T^{r+0.5}/\Gamma(r + 0.5)]\ \lambda^{r-0.5} \exp(-\lambda T)\ (\lambda > 0)$ (Eq. 7-120)

Posterior mean: $\underline{\lambda} = (2r+1)/2T$ (Eq. 7-121)

Posterior median: $\lambda_{0.5} = \chi^2_{0.5}\ (r + 0.5)/(2T)$ (Eq. 7-122)

where $\chi^2_{1-\gamma}(x)$ is the $100(1 - \gamma)$ percent (e.g., 95 percent) percentile of a chi-square distribution.

The symmetric probability interval is given by

Posterior lower bound: $\lambda_L = \chi^2_{\gamma/2}\ (2r + 1)/(2T)$ (Eq. 7-123)

Posterior upper bound: $\lambda_U = \chi^2_{1-\gamma/2}\ (2r + 1)/(2T)$ (Eq. 7-124)

The noninformative prior is very useful when the available performance records show zero failures for a finite time at test. In this instance, the classical estimation must assert at least one failure has occurred, or the estimation interval on λ becomes indeterminant. In the noninformative prior, the analyst asserts that the probability of failure per demand is somewhere in the range of (0,1) with equal likelihood, giving the prior mean of 0.5 as the best estimate (i.e., the analyst asserts that the item is equally likely to succeed or fail in any given trial.) The effect of 0 failures in n trials is to adjust the denominator so that the posterior gives the probability of 0.5 that the device will fail in n + 1 trials.

The second application assumes a gamma distribution prior that is derived from information available prior to the analysis. Such prior information may be derived from generic sources. The gamma prior has the form:

$$f_0(\lambda) = [\beta_0\alpha_0/\ \Gamma(\alpha_0)]\ \lambda^{\alpha_0 - 1} \exp(-\beta_0 \lambda);\ (\text{for } \lambda > 0) \qquad \text{(Eq. 7-125)}$$

where the parameter α_0 (shape factor) can be interpreted as the prior number of failures in β_0 prior total operating time (β_0 is the scale factor).

The parameters of the gamma distribution are:

Prior mean: $$\underline{\lambda}_0 = \alpha_0 / \beta_0 \quad \text{(Eq. 7-126)}$$

Prior median: $$\lambda_{0,0.5} = \chi^2_{0.5}\,(2\alpha_0)/(2\beta_0) \quad \text{(Eq. 7-127)}$$

Prior variance: $$\sigma_0^2 = \alpha_0 / \beta_0^2 \quad \text{(Eq. 7-128)}$$

where $\chi^2_{1-\gamma}(x)$ is the 100(1 - γ) percent percentile of a chi-square distribution.
The prior 100(1 - γ) percent (e.g., 95 percent) symmetric probability interval is given by:

Prior lower bound: $$\lambda_{0,L} = \chi^2_{\gamma/2}\,(2\alpha_0)/(2\beta_0) \quad \text{(Eq. 7-129)}$$

Prior upper bound: $$\lambda_{0,U} = \chi^2_{1-\gamma/2}\,(2\alpha_0)/(2\beta_0) \quad \text{(Eq. 7-130)}$$

The posterior distribution is also a gamma distribution given as:

$$f(\lambda) = [(\beta_0 + T)^{\alpha 0 + r} / \Gamma(\alpha_0 + r)]\, \lambda^{\alpha 0 + r - 1} \exp[-(\beta_0 + T)\,\lambda];\ (\text{for } \lambda > 0) \quad \text{(Eq. 7-131)}$$

The parameters of the posterior distribution are:

Posterior mean: $$\underline{\lambda} = (\alpha_0 + r)/(\beta_0 + T) \quad \text{(Eq. 7-132)}$$

Posterior median: $$\lambda_{0.5} = \chi^2_{0.5}\,(2\alpha_0 + 2r)/(2\beta_0 + 2T) \quad \text{(Eq. 7-133)}$$

Posterior variance: $$\sigma^2 = (\alpha_0 + r)/(\beta_0 + T)^2 \quad \text{(Eq. 7-134)}$$

and the prior 100(1 - γ) percent symmetric probability interval is given by:

Posterior lower bound: $$\lambda_L = \chi^2_{\gamma/2}\,(2\alpha_0 + 2r)/(2\beta_0 + 2T) \quad \text{(Eq. 7-135)}$$

Posterior upper bound: $$\lambda_U = \chi^2_{1-\gamma/2}\,(2\alpha_0 + 2r)/(2\beta_0 + 2T) \quad \text{(Eq. 7-136)}$$

The third application assumes a LN prior distribution on λ. The presentation in Section 7.5.4.3.4.1 applies by replacing q with λ in all of the expressions. As noted above, there are two difficulties in using this prior, and the Bayesian integration cannot produce a closed form posterior distribution. Numerical solutions are required.

An alternative method, applied at the Savannah River Site (described in Blanton and Eide [1993]), converts the prior LN on λ into a gamma distribution, applies the specific evidence (number of failures, r, and time on test, T) in the Bayesian integration, which in turn produces a gamma posterior distribution. The gamma posterior distribution is then converted to a LN.

7.5.3.3.4 Uncertainties in Information and Event Probabilities

Section 9 provides a full discussion of treatment of uncertainties in event sequence quantification, including the propagation of uncertainties through the sequence frequencies. Part of the uncertainty stem from uncertainties in the probabilities and frequencies of events. This

section (Section 7.5) discusses the sources of uncertainties contained in the information sources and its application in estimation of parameters and event probabilities.

The *PRA Procedures Guide* (NRC 1983) identifies two categories of uncertainties in event probabilities: modeling uncertainty and information (data) uncertainty. These sources are evaluated differently, as described below.

- **Modeling Uncertainty**–No physical occurrence exactly fits a mathematical model such as having a constant failure rate, adherence to a Poisson time to failure, or failure on demand fitting a binomial with constant probability per demand. In Bayesian estimation, the selection of the prior distribution is another source of modeling uncertainty. So, the selection of the event model by the analyst introduces uncertainty. Different values for the point estimate, the PDF family, and different 90 percent confidence interval can result with different event models. Such uncertainty is evaluated with a sensitivity analysis. The event probability is re-evaluated with alternative models.

- **Information Uncertainty**–Uncertainty in estimated event probabilities and their associated distribution parameter arise from several sources: 1) amount of information (number of trials, duration, number of failure events), 2) diversity of information sources when pooling (i.e., various kinds of equipment, vendors, applications and environments) 3) accuracy of information sources (i.e., quality of tests or record keeping), and 4) applicability to repository facilities.

  The uncertainty due to the amount of data is treated explicitly in the event estimation techniques described in Section 7.5.3.3. The amount of data affects the variance, the mean, and the confidence (classical) or probability (Bayesian) interval. The greater the number of trials (or duration), the tighter the distribution of the estimated parameters and event probabilities.

  The uncertainties in the diversity or accuracy of information (which may be forced on the analyst if sufficient and relevant information is not available) can be alleviated by the application of the pooling procedures described in Section 7.5.3.3.3, but this requires analyst's judgement. If all sources are judged equally representative of the system or component of interest, all information is weighted equally and the uncertainties in the respective source are propagated through the pooling formulas to give composite mean, medium, variance, and intervals that reflect the overall uncertainty. Otherwise, the analyst may want to assign weights to the various sources in proportion to their respective applicability or accuracy.

  Likewise, if multiple sources are judged equally accurate, the equal-weight pooling can be used.

  The uncertainty in the applicability of a particular information source to an event in the PSA for a repository is also treated by analyst judgement. In some instances, this may require increasing an estimated event probability derived from a given source to account for repository operating environment or duty. In other instances, the probability may be

decreased for the same reasons, or to take credit for quality assurance, expected tests, and inspections. For example, crane failure rates derived from general industrial sources may be judged to be too high for repository cranes that are designed to nuclear industry standards. The analyst must decide on whether to increase (decrease) the point estimate, the upper or lower uncertainty bounds, or both, to account for the application. Section 9 provides guidance to the analyst on such treatment of uncertainties.

7.5.3.3.5 Documentation of Parameters and Event Probabilities

To support the PSA for LA, the analyst must provide a clear, auditable record. For each event identified in the PSA event sequence analyses, an event probability (or frequency) will be tabulated.

The tabulation will be annotated to point to, for each event probability, the following:

- Event Model Used
- Information Source(s) Used
- Calculation File for Estimation of Model Parameters and Event Probability
- Treatment and Bases for Uncertainties.

Such documentation will be prepared and checked in accordance with the applicable procedure.

7.5.3.4 Examples of Parameter Estimation – Contrast of Classical and Bayesian Methods

This section presents several simple applications of the estimation methods described in Sections 7.5.4.3.1 and 7.5.4.3.2. Examples are presented for both a failure-on-demand and constant failure rate models using both classical and Bayesian approaches. For the latter, applications of noninformative and other prior distributions are illustrated.

The basic information assumed is either repository-specific (or ESF-specific) performance records or representative surrogates (e.g., records of events related to failures of spent fuel handling equipment at NPPs). Two basic information sets are used in the examples below:

Failure on Demand–Crane drop of load - 0 failures in 47,400 lifts (surrogate information; Lloyd 2001).

This information will be augmented with alternative information in the demonstration of pooling information.

Constant Failure Rate–Failure of steel sets in ESF ground support system; experience gives 0 failures in 9200 steel-set years (BSC 2001).

7.5.3.4.1 Estimation of Parameters - Failure on Demand

Classical Estimation–(see Section 7.5.3.3.1).

Point Estimate: $p^* = f/n$ (Eq. 7-137)

where

f = number of observed or recorded failures in n demands or trials,
n = number of recorded demands or trials in reporting period.

For small f and large n, the 5th to 95th percentile interval ($\alpha = 0.05$) may be approximated using the following:

$$p_U(1 - \alpha) = [\chi^2 (2f + 2, 1 - \alpha)]/2n = [\chi^2 (2f + 2, 0.95)]/2n \quad \text{(Eq. 7-138)}$$

$$p_L(1 - \alpha) = [\chi^2 (2f, \alpha)]/2n = [\chi^2 (2f, 0.05)]/2n \quad \text{(Eq. 7-139)}$$

Basis: Crane drop of load (0 failures in 47,400 lifts) or:

f = 0
n = 47,400

Initial Trial: Insert information into formulas:

$p_I^* = f/n = 0/47{,}400 = 0$, which is not credible, while
$p_U = 6.3 \times 10^{-5}$, and
p_L is indeterminant, that is, $\chi^2 (0, 0.05)$ cannot be determined.

Second Trial: Assume that there will be a failure on the next demand, so adjust input to:

$f' = f + 1$, and $n' = 47{,}400 + 1$

using Equations 7-75 and 7-76 the estimation gives:

$$p^* = f'/n' = 1/47{,}401 = 2.1 \times 10^{-5} \text{ (point estimate)}$$

and the 90% confidence interval is given by

$$p_U = [\chi^2 (2f' + 2, 0.05)]/2n' = [\chi^2 (4, 0.05)]/94802 = 9.49/94802 = 1.0 \times 10^{-4}$$

$$p_L = [\chi^2 (2f', 0.95)]/2n' = [\chi^2 (2, 0.95)]/94802 = 0.71/94802 = 1.08 \times 10^{-6}$$

Now, the point estimate p* is more useful (i.e., not equal to 0) and appears more credible (i.e., no equipment is perfect), and the point estimate falls within and interval that has a very low lower bound and a conservative upper bound.

Bayesian Estimation–(see Section 7.5.3.3.4.1).

The first case is application of a noninformative prior:

$$[q (1 - q)]^{-0.5}/\pi; \text{ for } (0 \le q \le 1) \quad \text{(Eq. 7-140)}$$

The evidence gives:

f = 0, number of observed or recorded failures in n demands or trials, and
n = 47,400, number of recorded demands or trials in reporting period. Using Equation 7-97 to 7-101 the Bayesian estimation gives:

Posterior mean: $\underline{q} = (f + 0.5)/(n + 1) = (0.5)/47{,}401 = 1.05 \times 10^{-5}$ (Eq. 7-141)

Posterior median: $q_{0.5} = (f + 0.5)/[(f + 0.5) + (n - f + 0.5)F_{0.5}\,(2n - 2f + 1, 2f + 1)]$ (Eq. 7-142)
$= (0.5)/[(0.5) + (47{,}400 + 0.5)F_{0.5}(94801, 1)$
$= 2.32 \times 10^{-5}$

and the 90 percent symmetric probability is a function of the F-distribution with a and b degrees of freedom, $F_{1-\gamma/2}\,(a,b)$, as follows:

Posterior lower bound:

$$q_L = (0.5)/[(0.5) + (47400.5)F_{0.05}\,(94801, 1)] \quad \text{(Eq. 7-143)}$$
$$= 4.15 \times 10^{-8}$$

Posterior upper bound:

$$q_U = [(f + 0.5)F_{0.05}\,(1, 94801)]/[(47400.5) + (0.5)F_{0.05}\,(1, 94801)] \quad \text{(Eq. 7-144)}$$
$$= 4.05 \times 10^{-5}$$

The noninformative prior is very useful when the available performance records show zero.

The Bayesian approach shifts the estimation toward lower points values and intervals. This result may be viewed as a better result given that no failures were observed. By selecting the noninformative prior, the analyst says "The probability of failure, q, is between 0 and 1. I am confident that q can not be 0, because nothing is perfect, and I am confident that it can not be approaching 1.0, because then there would be many observed failures." Using the evidence of zero failures for the large number of trials gives a point estimate that is approximately half of the classical estimate with one assumed failure (the Bayesian approach does not require this arbitrary assumption). Moreover, the upper 95th percent limit is 4.05×10^{-5} versus 1.0×10^{-4} from the classical estimation. The lower 5th percent limit is 4.15×10^{-8}, which can be regarded as approaching 0 versus the larger value of 1.08×10^{-6} from the classical approach.

7.5.3.4.2 Estimation of Parameters – Constant Failure Rate

[Information for this section is under development and will be provided later]

7.5.3.4.3 Estimation of Parameters – Pooling Information

Table 7-8 presents crane failure on demand rates as derived from three different sources. The Bayesian approach with noninformative prior was applied, independently, to each set of the raw information to get the posterior parameters shown in the table. These three set of parameters were processed this way to simulate how the analyst might find different sets of processed data

(e.g., in the generic databases described in Section 7.5.3.2.2). The purpose here is to demonstrate the result of combining tabulated information sources. When the source provides the raw information, it may be more appropriate to apply a successive Bayesian update, as shown below.

For demonstration information is pooled using the geometric mean (see Section 7.5.3.3.3.1)

$$\langle q0 \rangle = (\Pi\ q0,i)1/M; \text{ for the composite point value} \quad \text{(Eq. 7-145)}$$

$$\langle q_{LB} \rangle = (\Pi\ qLB,i)1/M; \text{ for the composite lower bound} \quad \text{(Eq. 7-146)}$$

$$\langle q_{UB} \rangle = (\Pi qUB,i)1/M; \text{ for the composite upper bound} \quad \text{(Eq. 7-147)}$$

Where $q_{0,i}$, $q_{LB,i}$, and $q_{UB,i}$ are the point value, lower bound, and upper bound, respectively from the i^{th} information source.

In this example, M = 3.

Using the mean values in Table 7-8 gives the following composite parameter estimates:

$$\langle q_0 \rangle = [(1.44 \times 10^{-5})\ (4.97 \times 10^{-5})\ (1.05 \times 10^{-5})]^{1/3} = 1.96 \times 10^{-5}$$

$$\langle q_{LB} \rangle = [(8.6 \times 10^{-6})\ (3.80 \times 10^{-5})\ (4.15 \times 10^{-5})]^{1/3} = 2.38 \times 10^{-6}$$

$$\langle q_{UB} \rangle = [(2.14 \times 10^{-5})\ (6.27 \times 10^{-5})\ (4.05 \times 10^{-5})]^{1/3} = 3.79 \times 10^{-5}$$

Table 7-8. Crane Failure Demand Rates

Source	Failures	Trials	Posterior Using Noninformative Prior		
Event: Drop of Load by Crane			**Mean**	**Lower 5%**	**Upper 95%**
Newport News (CRWMS M&O 1998, Attachment X)	13	939,000	1.44E-5	8.60E-6	2.14E-5
NUREG-0612 (NRC 1980)	43	8.75E+5	4.97E-5	3.80E-5	6.27E-5
Lloyd (2001)	0	47,400	1.05E-5	4.15E-8	4.05E-5

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7.6 EVENT SEQUENCE FREQUENCY BINNING

7.6.1 Purpose

This guide defines the bases and methods for applying the results of ET sequence quantification to categorize (or bin) credible event sequences as Category 1 or Category 2 according to the definitions of 10 CFR 63.2. Potential radiological consequences of the event sequences are then subject to the performance criteria of 10 CFR 63.111. Event sequences that are not Category 1 or Category 2 are categorized as BC2 and are not subjected to performance criteria. Since there are various degrees of uncertainty associated with the quantification of event sequence frequencies, this guide recommends means for dealing with uncertainty factors in categorizing sequences.

7.6.2 Scope

This section provides guidance on interpreting and using the results of ET analyses performed in accordance with Section 7.1, and considerations of uncertainties per Section 9. This section does not describe ET construction or analysis.

7.6.3 Overview of Approach

The results of ET analyses, in addition to the graphical display of the alternative sequences (or scenarios) that can result following a particular IE, include calculations of the frequency (or annual probability of occurrence) of all sequences that are modeled. The sum of the frequencies of all sequences equals that of the IE frequency.

The endpoint of each pathway through the ET represents a particular state of the system being analyzed. Each endpoint state has a measure of radiological consequence (or performance) associated with it; in most instances, the radiological consequences are nil (all consequences prevented or mitigated) or very small (mitigation features are effective). The 10 CFR Part 63 is a risk-informed, performance-based rule that imposes performance objections according the FC of each event sequence that results in radiological exposure or releases. The Category 1 and Category 2 event sequences form the bases for defining the 10 CFR 63.2 design basis for a repository, and in classifying the SSCs important to safety that are associated with prevention and mitigation of events that make up the various event sequences.

For event sequences that are below the threshold FC-2 event sequences (i.e., BC2 event sequences), there are no radiological performance requirements in 10 CFR Part 63. However, the SSCs that are credited in the frequency analyses of BC2 event sequences may be subject to classification as important to safety.

Since there are various degrees of uncertainty associated with the quantification of event sequence frequencies, it is necessary to deal with uncertainty factors in categorizing sequences. That is, a point estimate (or best estimate) of an event frequency may result in a value that is slightly below the threshold of Category 2. Should this sequence be declared to be a BC2 or Category 2 event sequence in view of the degree of uncertainty in the frequency analysis? Or, another sequence may be slightly below the breakpoint between Categories 1 and 2. Should this sequence be categorized as Category 1 or Category 2 in view of the degree of uncertainty in the

frequency analysis? This guide provides a basis for answering such questions. The treatment of uncertainties differs for analyses performed in support of LA submittal for CA versus the analyses for the support of a LA to receive and possess nuclear materials.

7.6.4 Details of Approach

7.6.4.1 Fundamental Screening Criteria

Event sequence Category 1 and Category 2 are defined by 10 CFR 63.2 (see Sections 2 and 3). If a100-year period before permanent closure is used as a basis, then frequency bounds can be defined for the respective event sequence categories as

$$\text{Category 1: } f(\text{event sequence}) \geq 1 \times 10^{-2} \text{ per year} \qquad \text{(Eq. 7-148)}$$

$$\text{Category 2: } 1 \times 10^{-2} > f(\text{event sequence}) \geq 1 \times 10^{-6} \text{ per year}$$

This guide will use these definitions as Fundamental Screening Criteria in the context of event sequence frequency binning.

It is noted, however, that other preclosure time periods may be defined for all or portions of operations, but the principles described herein are to be applied to those time bases, nevertheless. See Section 3.4 for a discussion of preclosure time periods.

This guide is based on quantitative evaluations of event sequence frequencies. Alternative approaches using qualitative arguments could be considered, if they satisfy all the requirements of 10 CFR Part 63 for performing a PSA. Such alternative approaches are not addressed.

7.6.4.2 Screening Criteria with Consideration of Uncertainties

Section 9 describes methods for identifying sources of uncertainty in event sequence modeling and Section 7.5 discusses uncertainty in probabilities of basic events that are input to FTA (Section 7.2) and HRA (Section 7.3).

In formal analysis of uncertainties, results of event sequence quantification are expressed in the form of a probability distribution. The complementary cumulative probability distribution represents the probability (between 0 and 1) that the frequency (of a given sequence of events) is less than or equal to a particular value. The point estimates derived in preliminary sequence quantification will fall near the middle of the distribution, often being the true median (i.e., the frequency corresponding to a probability of 0.5).

The PSA that supports the LA for construction authorization will categorize event sequences based on the mean value of the sequence frequencies. The mean is a probability-weighted measure of an event-sequence frequency over the range and distribution of uncertainties. Section 9 describes the general treatment of uncertainties and illustrates the significance of the mean as a measure of the true value of an event-sequence frequency. If the mean is less than the threshold frequency for Category 1 event sequences, the sequence is designated Category 2. If the mean is less than the threshold frequency for Category 2 event sequences, the sequence is designated Beyond Category 2.

7.6.4.3 Beyond Category 2 Event Sequences: Quantitative Screening

7.6.4.3.1 Application of Fundamental Screening Criteria

This category (bin) of event sequences is addressed first because the quantitative approach supplements the hazards analyses for event sequence screening. The fundamental criterion for screening out a potential event sequence is the following:

A BC2 event sequence consists of an IE and one or more additional events whose joint frequency is less than 1×10^{-6} per year.

This is expressed mathematically as:

> If f(sequence) is less than 1×10^{-6} per year,
> then the sequence is considered to be BC2.

where

> f(sequence) = frequency of the event sequence.

If, however, f(sequence) = 1×10^{-6} per year, the test fails and the sequence must be included as a Category 2 event sequence. The test is applied to the frequencies of every sequence modeled in an ET.

7.6.4.3.2 Consideration of Uncertainties in Beyond Category 2 Event Sequences: Screening and Stopping Rules

Stopping Rule–10 CFR 63.112(d) requires that the PSA include the technical basis for either inclusion or exclusion of specific, naturally occurring and human-induced hazards in the safety analysis.

This has been interpreted to mean that the NRC expects the PSA to tabulate those sequences that have been declared BC2 and to provide the bases. To avoid having an infinitely long list of sequences to pedigree that includes sequences of extremely small frequencies, it is necessary to define a lower limit on sequence frequency to be documented. This is termed a stopping rule. The definition and application of the stopping rule must be compatible with considerations of uncertainties. The following is the stopping rule recommended for use in use in preliminary documentation of the PSA:

> No event sequence having a mean frequency less than 1×10^{-8} per year will be included in the list of BC2 event sequences.

No uncertainty analysis will be applied in executing the stopping rule. This stopping rule provides two orders of magnitude below the Category 2 lower threshold, which is a wide margin.

Note that the stopping rule can be applied during ET construction and preliminary quantification as a means of simplifying the ETs. Tree branches that are readily seen to be on the order of 10^{-8} per year can be pruned from the tree.

As design evolves and uncertainties are reduced, or formal uncertainty analyses are applied, the cutoff frequency for the mean sequence frequency may be raised to 1×10^{-7} per year.

7.6.4.3.3 Identifying Controls Credited for Prevention or Mitigation of Beyond Category 2 Event Sequences

Except for event sequences that are below 1×10^{-8} per yr (i.e, per the stopping rule), the events comprising each of the documented BC2 event sequences must be examined to identify items important to safety.

The primary evaluation assesses the effect on sequence frequency for each event in the sequence, other than the IE, when the event probability is set equal to 1.0. If the recalculated mean sequence frequency is greater than the Category 2 threshold (10^{-6} per year) for any one item (e.g., an SSC, or a specific HA), then a coarse estimate of potential consequences is made. If the consequences appear to exceed the regulatory limits, then the item represented by that event may be subject to classification as an potential item important to safety and appropriate controls (e.g., quality assurance controls). If the consequences appear to be within regulatory limits for Category 2, then no such classification is necessary (see Section 12 for the discussion of the classification process).

When the event probability within an event sequence is set equal to 1.0 for a given item and the recalculated mean sequence frequency remains below the Category 2 threshold (10^{-6} per year) with sufficient margin, then no further action is required.

7.6.5 Examples of Application

[Information for this section is under development and will be provided later.]

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APPENDIX 7A

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WIPP Safety Analysis.

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