BSC	Design Calculation or Analysis Cover Sheet *Complete only applicable items.*	1. QA: ~~NA~~ QA 2. Page 1

3. System	4. Document Identifier
Monitored Geologic Repository	000-PSA-MGR0-02500-000-00A

5. Title

Waste Package Misplacement Probability

6. Group

Preclosure Safety Analysis/Thermal/Structural Analysis

7. Document Status Designation

☐ Preliminary ☒ Committed ☐ Confirmed ☐ Cancelled/Superseded

8. Notes/Comments

Attachments		Total Number of Pages
Attachment A.	Results from Monte Carlo Simulation	2
Attachment B.	Beta Factor Distribution	2

RECORD OF REVISIONS

9. No.	10. Reason For Revision	11. Total # of Pgs.	12. Last Pg. #	13. Originator (Print/Sign/Date)	14. Checker (Print/Sign/Date)	15. EGS (Print/Sign/Date)	16. Approved/Accepted (Print/Sign/Date)
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ACRONYMS AND ABBREVIATIONS

Acronyms

3D	three-dimensional
BSC	Bechtel SAIC Company, LLC
CSNF	commercial spent nuclear fuel
DOE	U.S. Department of Energy
EOC	error of commission
EOO	error of omission
ETE	engineering thermal evaluation
GROA	geologic repository operations area
HEP	human error probability
HFE	human failure event
HRA	human reliability analysis
MC&A	material control and accounting
NNPP	Naval Nuclear Propulsion Program
OTE	operations thermal evaluations
PCSA	Preclosure Safety Analysis
SNF	spent nuclear fuel
TAD	transportation, aging, and disposal
TID	tamper-indicating device
WFTC	waste form tracking and checking
WHF	Wet Handling Facility

Abbreviations

°C	degrees Celsius
°F	degrees Fahrenheit
ft	feet
kW	kilowatts
m	meter

ACRONYMS AND ABBREVIATIONS (Continued)

m^3/s	cubic meters per second
%	percent
vs.	versus

1 PURPOSE

The purpose of this calculation is to determine the probability of waste package misplacement and the probability that such misplacement may result in a violation of the thermal limits for the repository.

As part of the license application, an analysis to show that the repository can accept waste streams with a range of thermal power output values is included. The postclosure analysis has been performed with a single thermal modeling basis, with an evaluation of effects on features, events, or processes from alternate thermal loads. For the purposes of waste stream evaluation, a waste stream with a thermal power average higher than has been used in the past has been selected for demonstration purposes to develop an upper bound to the thermal envelope. This selection has been made to show that a range of waste streams with different thermal characteristics could in fact be received at the repository. The acceptance of the additional waste stream is being examined using the current design and will show the ability to maintain acceptable thermal limits during normal and off-normal operations. However, since the design has not been significantly changed to accommodate these higher thermal loads, it has resulted in a reduction of margins with respect to the maximum thermal loads used in the past. Accordingly, the effects of misloading a waste package may be more pronounced than in the previous studies and is the subject of this analysis.

The considerations of misload must include the actual physical misplacement of the waste package from the planned location. Also, uncertainty in the thermal characteristics of a waste form received or loaded at the repository can contribute to the misload potential, as well as a misload at the point of loading the transportation, aging, and disposal (TAD) canister. In order to address the concerns associated with the misplacement of a waste package, it was determined that the probability of the combined errors resulting in the violation of thermal limits during preclosure or postclosure should be estimated.

Furthermore, the Naval Nuclear Propulsion Program (NNPP) has a specific need to know the probability of misplacement of a naval waste package in the repository for the purpose of feature, event, or process screening analyses. In a prior analysis performed by BSC (*Calculation of the Naval Long and Short Waste Package Three-Dimensional Thermal Interface Temperatures* (Ref. 2.2.3)) and utilized by NNPP in an internal analysis, the maximum power limits for a waste package stored in proximity to a naval waste package were determined and specific thermal limits established. This calculation addresses issues raised by the NNPP in regards to thermal and misplacement issues and provides the probability of misplacement of a naval waste package that could violate thermal limits.

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2.1.2 EG-PRO-3DP-G04B-00046, Rev. 9. *Engineering Drawings*. Las Vegas, Nevada. Bechtel SAIC Company. ACC: ENG.20070724.0003. (CDIS 53304)

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2.1.4 LS-PRO-0201, Rev. 5. *Preclosure Safety Analyses Process*. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071010.0021. (CDIS 54505)

2.2 DESIGN INPUTS

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2.2.3 BSC 2006. *Calculation of the Naval Long and Short Waste Package Three-Dimensional Thermal Interface Temperatures.* 000-00C-WIS0-02700-000 REV 00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20061030.0001; ENG.20070611.0013. (DIRS 183333 V)

2.2.4 BSC 2007. *Basis of Design for the TAD Canister-Based Repository Design Concept.* 000-3DR-MGR0-00300-000-001. Las Vegas, Nevada: Bechtel SAIC Company. ACCs: ENG.20071002.0042; ENG.20071026.0033; ENG.20071108.0002; ENG.20071109.0001; ENG.20071120.0023; ENG.20071126.0049; ENG.20071214.0009; ENG.20071213.0005. (DIRS 182131 V)

2.2.5 BSC 2007. *Evaluation of Waste Stream Receipt Scenarios for Repository Loading.* 800-00C-WIS0-00500-000-00B. Las Vegas, Nevada: Bechtel SAIC Company. ENG.20071220.0004. (DC 55698)

2.2.6 BSC 2007. *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment*. 800-00C-WIS0-00600-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. (DIRS 184319 V)

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2.2.8 Hollnagel, E. 1998. *Cognitive Reliability and Error Analysis Method, CREAM.* 1st Edition. New York, New York: Elsevier. TIC: 258889. (DIRS 181532 V)

2.2.9 NRC (U.S. Nuclear Regulatory Commission) 2000. *Technical Basis and Implementation Guidelines for a Technique for Human Event Analysis (ATHEANA).* NUREG-1624, Rev. 1. Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 252116. (DIRS 157661 V)

2.2.10 Spurgin, A.J. 2005. *HRA Concepts and Applications Series of Workshops Given at Tsingua University, Beijing, China May 10th through 12th, 2005.* San Diego, CA: Anthony J. Spurgin. ACC: MOL.20071213.0108. (DIRS 184265 V)

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2.3 DESIGN CONSTRAINTS

2.3.1 10 CFR 63. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. (DIRS 180319 V)

2.4 DESIGN OUTPUT

2.4.1 None

3 ASSUMPTIONS

3.1 ASSUMPTIONS REQUIRING VERIFICATION

None used.

3.2 ASSUMPTIONS NOT REQUIRING VERIFICATION

3.2.1 Thermal Analysis Modeling

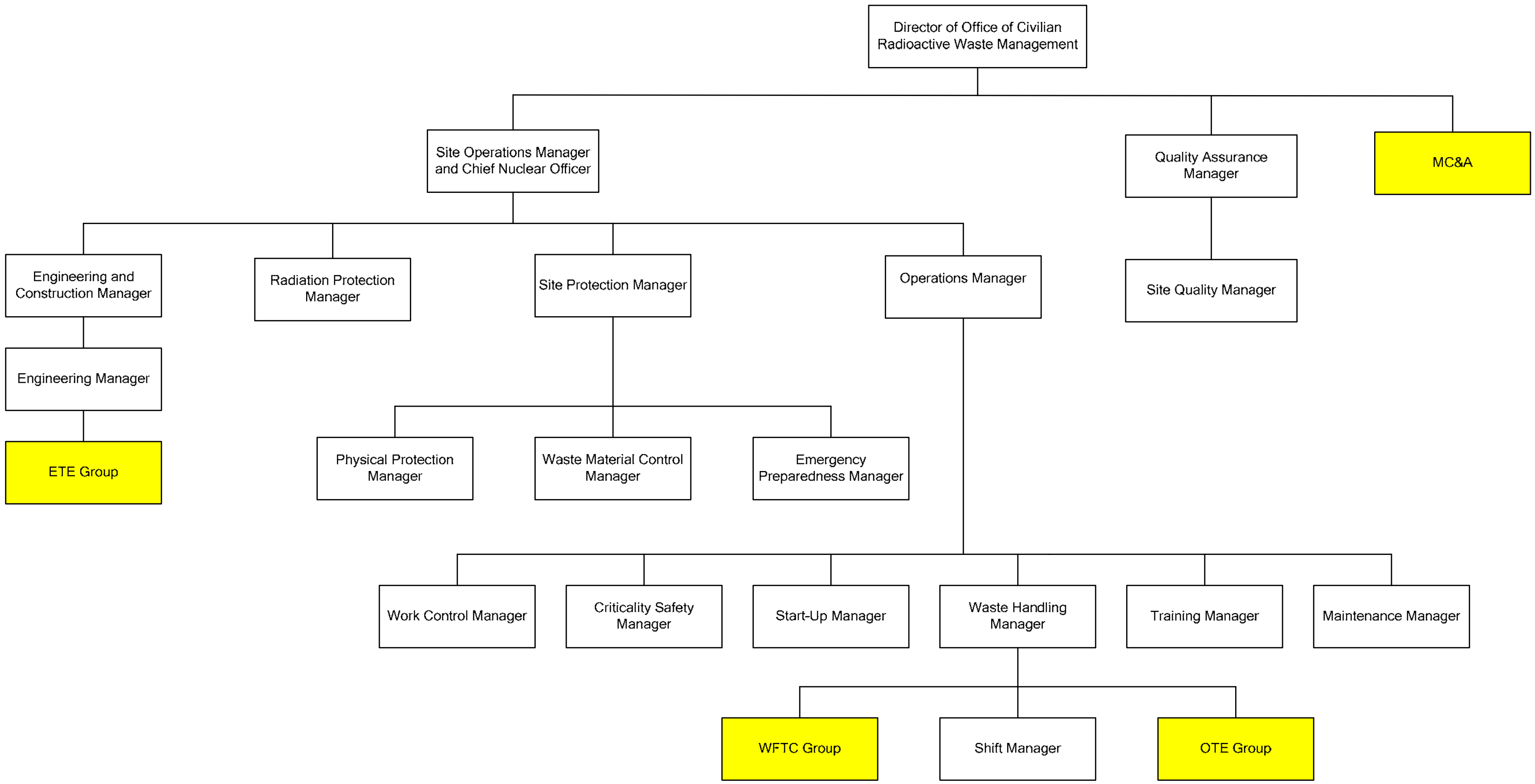
Assumption—The thermal calculation *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6), which forms much of the basis of this document, contains several assumptions related to thermal modeling.

Rationale—The rationale is provided in *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* ((Ref. 2.2.6), Section 3.1).

3.2.2 Restoration of Ventilation System

Assumption—It is assumed that ventilation can be restored within 30 days following a loss of power to the ventilation system.

Rationale—Despite the fact that the ventilation system uses commercially available equipment, its overall reliability is acceptable. The design features redundant fans, dual power supply lines, and mobile backup diesel generators; the capability to maintain ventilation in partially blocked drifts; natural ventilation sufficient for heat removal under the total loss of forced circulation; and the ability to replace fans, compensate for any loss of offsite power, loss of components or cable failure.



NOTE: ETE = engineering thermal evaluation; MC&A = material control and accounting; OTE = operations thermal evaluations; WFTC = waste form tracking and checking.

Source: Original

Figure 1. Functional Organizational Structure for GROA Operations

4 METHODOLOGY

4.1 QUALITY ASSURANCE

This calculation is prepared in accordance with EG-PRO-3DP-G04B-00037, *Calculations and Analyses* (Ref. 2.1.1), and LS-PRO-0201, *Preclosure Safety Analyses Process* (Ref. 2.1.4). The waste packages are classified as safety category items (important to safety and important to waste isolation) in the *Basis of Design for the TAD Canister-Based Repository Design Concept* (Ref. 2.2.4), Section 11.1.2. Therefore, the approved record version of this calculation is designated as "QA: QA."

In general, input designated "QA: QA" is used. However, some of the engineering drawings that are cited are designated "QA: N/A." Engineering drawings are prepared using the procedure EG-PRO-3DP-G04B-00046, *Engineering Drawings* (Ref. 2.1.2) which means, they are checked by an independent checker and reviewed for constructability and coordination before review and approval by the engineering group supervisor and the discipline Engineering Manager (*Engineering Drawings* (Ref. 2.1.2), Attachment 1). The check, review, and approval process provides assurance that these drawings accurately document the design and operational philosophy of the facility. For this reason, they are suitable for their intended use as sources of input to this analysis.

4.2 USE OF SOFTWARE

4.2.1 Level 2 Software

This section addresses software uses in this analysis classified as Level 2 software, as defined in *Software Management*, IT-PRO-0011 (Ref. 2.1.3). The software covered in this section were obtained from Software Configuration Management. They were used on a personal computer running either Windows XP Professional or Windows 2000. It is also listed in the current *Qualified and Controlled Software Report*.

The HRA uses the following software:

- The commercially available Visio Professional 2003 and Word 2003, which are components of part of the Microsoft Office 2003 suite of programs, were used in this analysis for the generation of graphics and text. The accuracy of the resulting graphics and text was verified by visual inspection. There were no inputs to this software. The output for Microsoft Word is the body of the report. The outputs for Visio are the block diagrams used in the figures.

- The commercially available Excel 2003 (a component of Microsoft Office 2003), Crystal Ball version 7.3.1 (an Excel-based risk-analysis tool) is used in this analysis to calculate probability distributions and to graphically display information. The inputs to the Crystal Ball code are from the HRA analysis (Figures 18 and 20) and the outputs from code are contained within a set of tables presenting the results of the Monte Carlo analysis in the body of the report (Tables 13 and 14). The outputs from Crystal Ball were checked both visually and confirmed by spot checks of the output values.

4.3 APPROACH TO CURRENT INVESTIGATION

The approach in the current analysis is centered on the following general activities:

- Thermal misload evaluations with respect to violation of preclosure and postclosure thermal limits, which considers a single misload in a seven-waste-package segment

- Development of reliability evaluations for the emplacement and thermal estimates of waste packages in accordance with the loading plans, which considers the human reliability associated with such procedurally controlled operations.

Once these issues are evaluated, event trees are constructed to determine the probability that a misplaced waste package can exceed a thermal limit, which are provided in Section 4.5. In this analysis, the incorrect evaluation of the thermal output of waste forms and the incorrect placement of waste packages by the actions of the operations and MC&A groups are evaluated.

A representative waste stream to show the flexibility of the repository to handle variability in waste receipt scenarios is presented. The estimated limiting waste stream and emplacement scenario reported in *Evaluation of Waste Stream Receipt Scenarios for Repository Loading* (Ref. 2.2.5) establishes an enveloping case for thermal misplacement of a waste package in the Subsurface Facility.

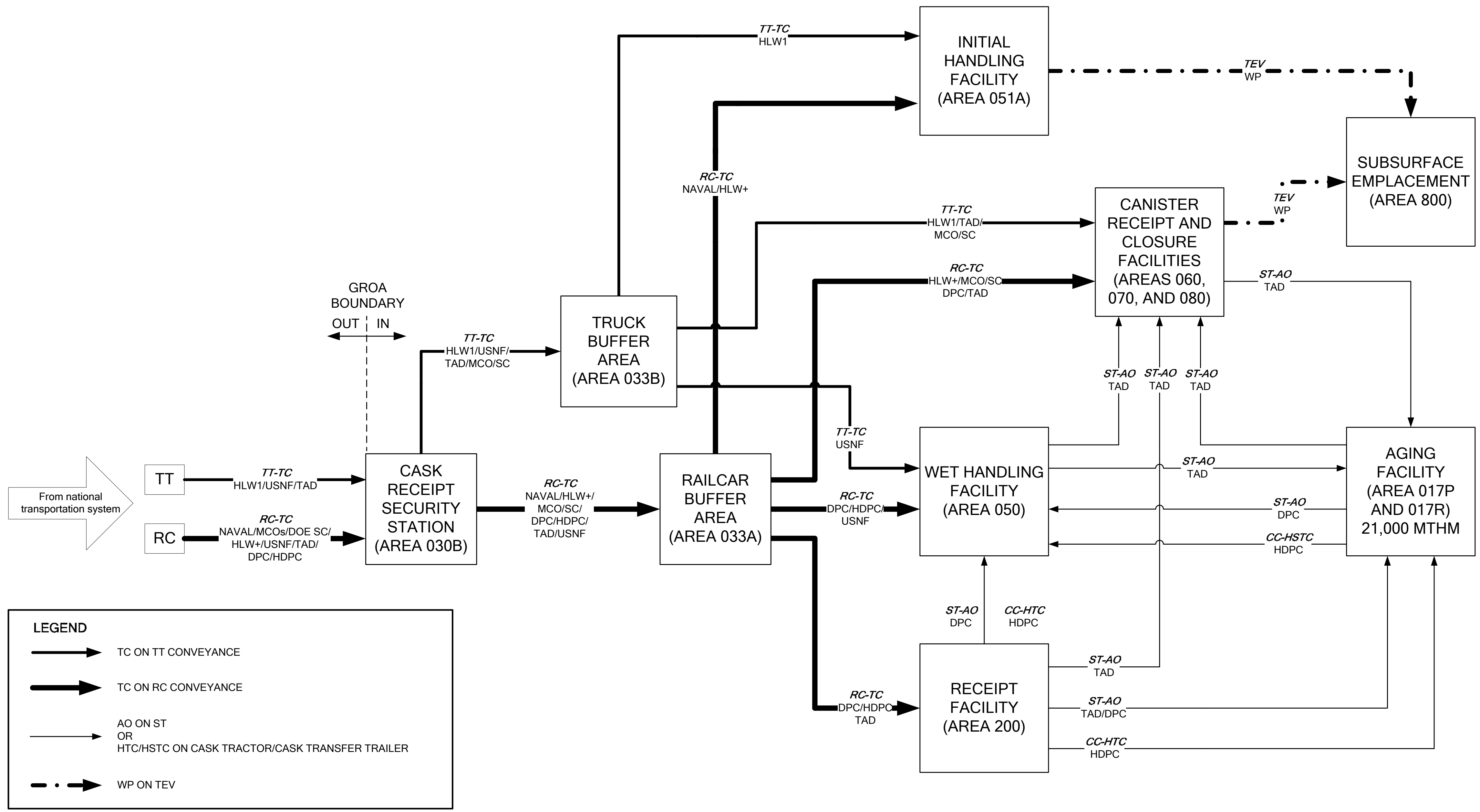
4.4 OVERVIEW OF SITE CHECKS AND BALANCES

Waste forms that are received at the GROA from the U.S. Navy, utilities, and the U.S. Department of Energy (DOE) are passed to selected facilities, depending on the waste forms involved and their handling requirements. Figure 2 depicts the various transportation pathways for each respective waste form after receipt from the national transportation system via railcar and truck trailer. The movement of each waste form is traced from initial receipt to repackaging at each respective facility to final emplacement in the repository.

Within the GROA, a variety of site operations occur, from the handling of waste packages to the maintenance of equipment. Figure 1 shows the site management organizational structure. With respect to this study, the operations associated with the tracking and logging of nuclear material, the calculation of the thermal output of waste forms, and the determination of the location for the placement of waste packages within drifts in the repository are of particular importance. There are four site management branches that deal with checks and balances:

- Waste form tracking and checking (WFTC)
- Material control and accounting (MC&A)
- Engineering thermal evaluation (ETE)
- Operations thermal evaluations (OTE).

Because of the importance of safety in these functions, steps have been taken to set up redundancy in the completion of each task, both within and between each organization. It is critical that the operations are carried out accurately to ensure the correct placement of waste packages with respect to each other within the repository (i.e., the probability of misplacement is acceptably low (1.0 E−4), as per 10 CFR Part 63.114 D (Ref. 2.3.1)).



NOTE: AO = aging overpack; CC = cask tractor with cask transfer trailer; DPC = dual-purpose canister; GROA = geologic repository operations area; HLW1 = high-level radioactive waste single canister; HLW+ = high-level radioactive waste multiple canisters (Type 5); HTC = a transportation cask that is never upended; HSTC = horizontal shielded transfer cask; MCO = multicanister overpack; NAVAL = naval spent nuclear fuel canister; RC = railcar; SC = Department of Energy standardized canister; ST = site transporter; TAD = transportation, aging, and disposal canister; TC = transportation cask (rail or truck type); TEV = transport and emplacement vehicle; TT = truck trailer; USNF = uncanistered spent nuclear fuel; WP = waste package.

Source: Original

Figure 2. Operations Waste Form Diagram

Figure 3 displays the operational flow of waste forms through the GROA with respect to the site management organization. The generalized steps performed by site management are as follows:

- Plan the arrival of the waste form (Waste Handling Manager plans arrival. Data from the waste form dispatcher (i.e., U.S. Navy, utilities, DOE) are forwarded six months prior to the planned arrival at the GROA).

- Check that the waste form arrived as planned (WFTC and MC&A groups).

- Calculate the thermal output of each package and then select the drift location (The ETE and OTE groups compare their calculations with the data supplied by the waste form dispatcher).

- Monitor and confirm the movement and repackaging of the waste forms (WFTC and MC&A groups).

- Monitor the movement of the waste form to the assigned drift and then check that the emplacement is correct (WFTC and MC&A groups).

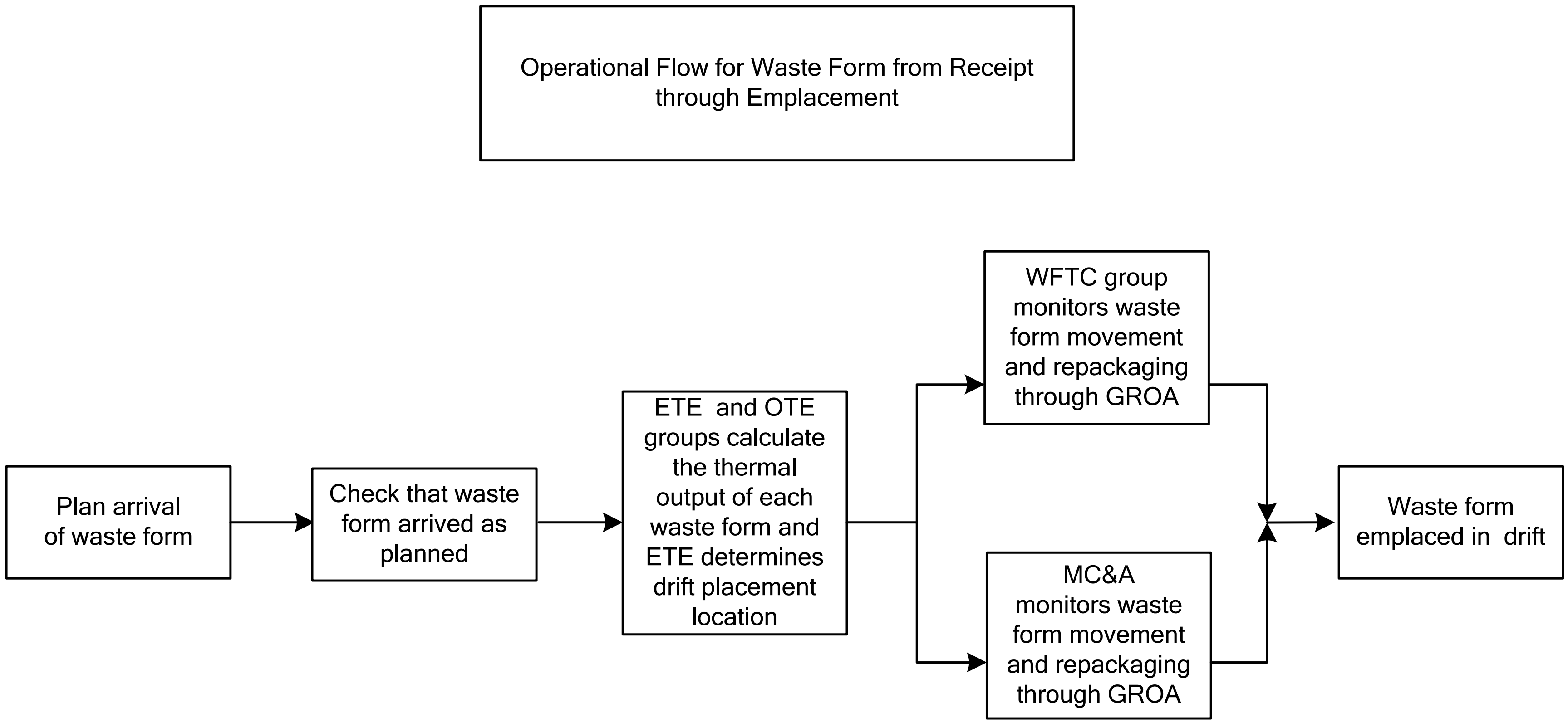
The details of activities of the WFTC, MC&A, ETE, and the OTE groups are covered in the following sections.

4.4.1 Description of Operational Activities

Commercial spent nuclear fuel (CSNF) is received at the site by the operational group managed by the Operations Manager (Figure 1). Each facility has a Waste Handling Manager who oversees the day-to-day handling of waste at their assigned facility.

Six months prior to shipment of the waste, the owner determines the inventory of waste to be shipped. The inventory on each of the waste forms is included as part of the waste form record forwarded by each utility. Each shipment is checked by the operations group to ensure that the waste form expected during the planning stages corresponds with the waste form received at the GROA.

Each shipment includes a waste form record when it arrives at the GROA, and each contains a unique shipping identifier to track the movement of each waste form. The operations group establishes a series of facility area checkpoints to monitor the movement of waste forms through the GROA. This activity is managed by the Waste Handling Manager. Figure 2 shows the generalized flow path of waste forms through the GROA. The locations for waste checkpoints are generally between the staging areas, the Aging Facility, the nuclear facilities, or the Subsurface Facility. The waste form record is computer based and records the movement of each waste form into the next operational area. In addition, the waste form record is used to verify that the movement of the waste form was in fact the movement that was expected for the next operational area. This operational receipt and transfer of a waste form at the GROA is performed by trained and qualified individuals. The primary individual performing the hands-on control is the GROA Facilities Technician, who operates facility equipment to receive and repackage waste for emplacement.



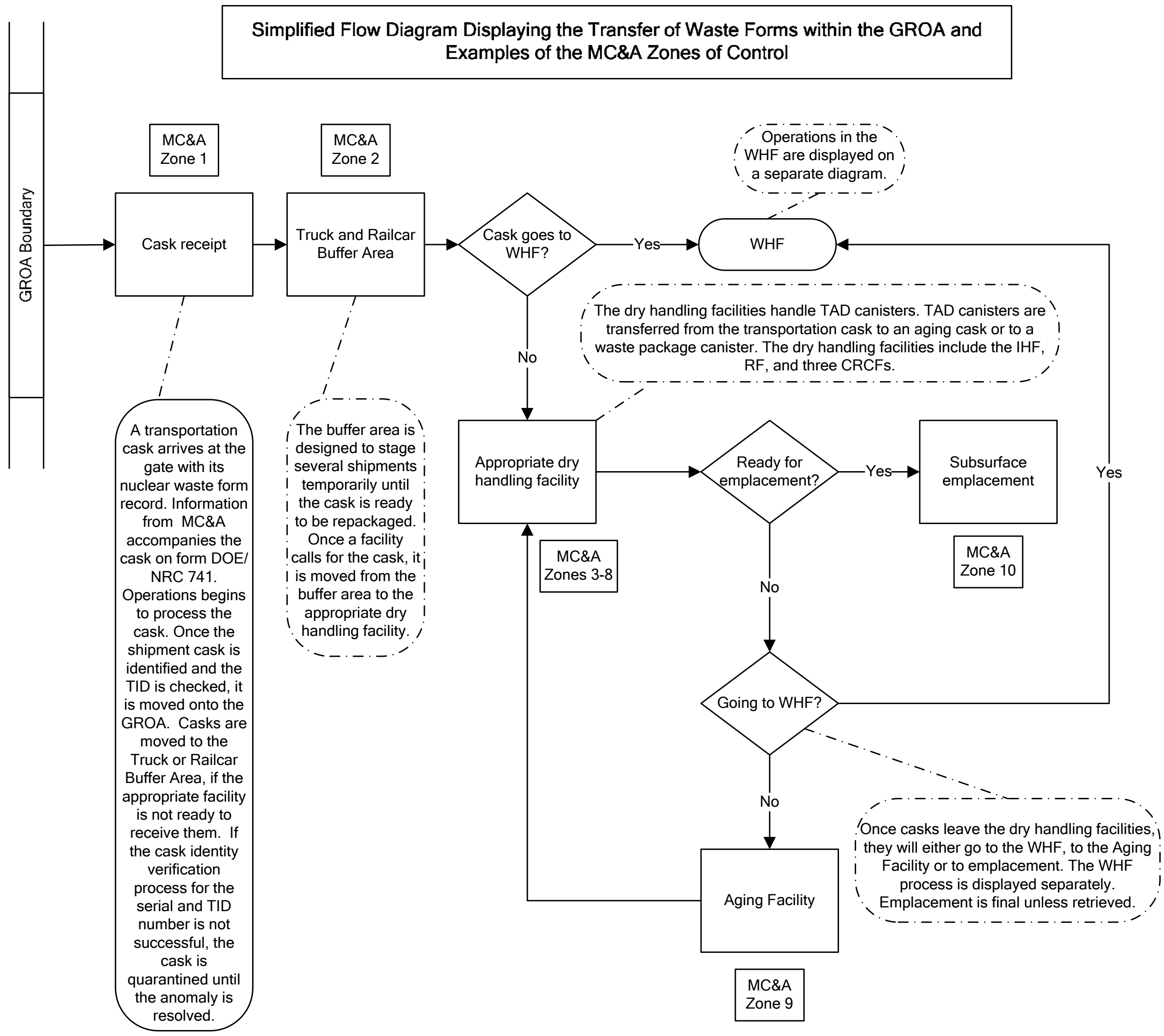
NOTE: ETE = engineering thermal evaluation; GROA = geologic repository operations area; MC&A = material control and accounting; OTE = operations thermal evaluations; SNF = spent nuclear fuel; WFTC = waste form tracking and checking.

Source: Original

Figure 3. Operational Flow for Waste Form from Receipt through Emplacement

The work plan for each day is established on an individual waste form basis. The movement of each waste form is checked against that work plan as well as the waste form record controls, in order to ensure that activities are proceeding as planned (Figure 3). The overall plan covering the checking of the thermal output of waste forms, the determination of their location within the drifts, and the process of checking their progress through the facilities on their way to emplacement in the Subsurface Facility is depicted in Figure 4. Figure 5 shows a block diagram approach to the checking of the transfer of waste forms between the operational areas of the facilities.

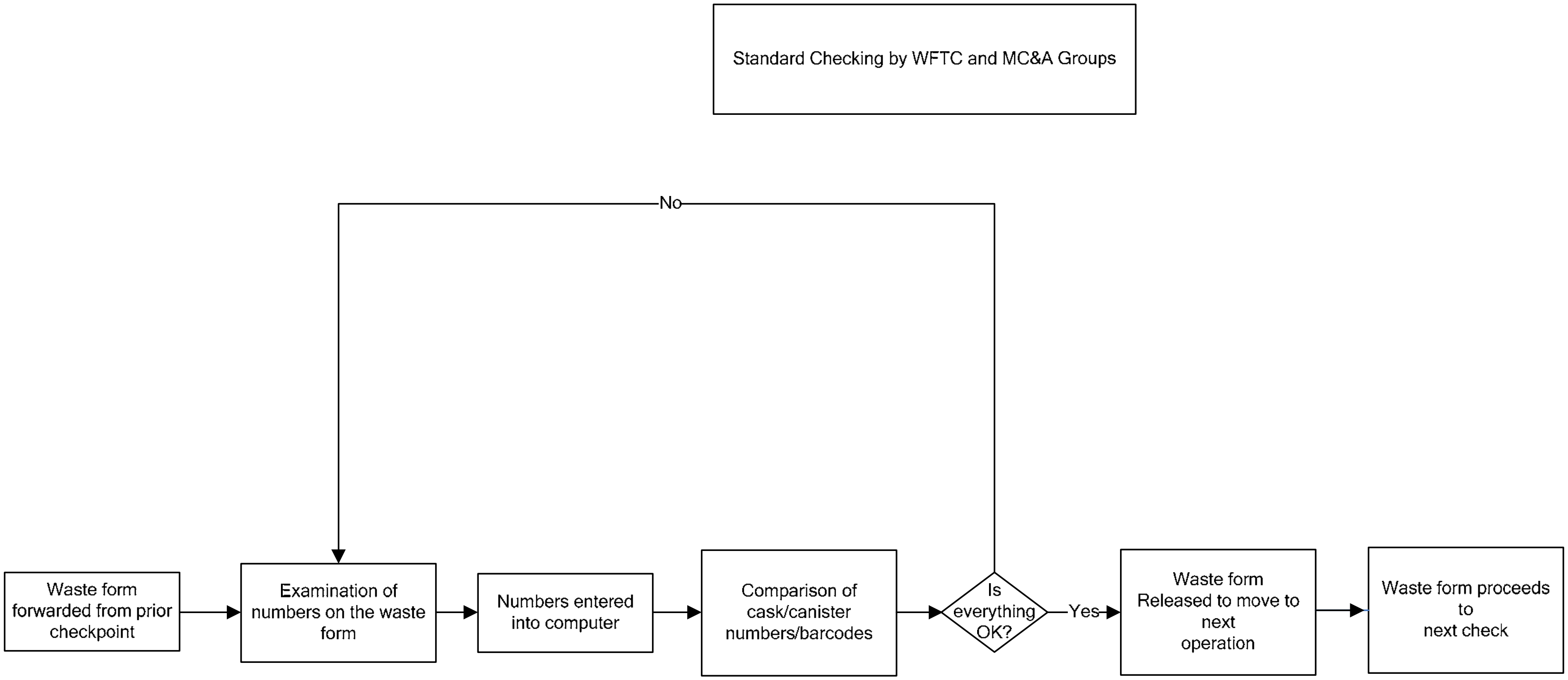
The Wet Handling Facility (WHF) offers a more complex canister, cask and individual CSNF assembly movement management scheme. Figure 6 displays the block flow diagram for the WHF operations. In the WHF, transportation casks are unloaded and CSNF assemblies are either placed directly into a TAD canister or into staging racks for later placement into a TAD canister. In this area, the waste is expected to be managed by physical locator means. That is, each CSNF assembly is sighted by an individual (using binoculars above the pool surface) and then tracked by manual means, with placards placed onto a physical representation of the staging racks or TAD canister. Each movement is videotaped and then reviewed by an independent individual prior to completing the movement report. Once the TAD canister is closed, then that information is entered into the waste form record system for movement to other areas in the GROA.



NOTE: CRCF = Canister Receipt and Closure Facility; GROA = geologic repository operations area; IHF = Initial Handling Facility; MC&A = material control and accounting; RF = Receipt Facility; TAD = transportation, aging, and disposal; TID = tamper-indicating device; WHF = Wet Handling Facility.

Source: Original

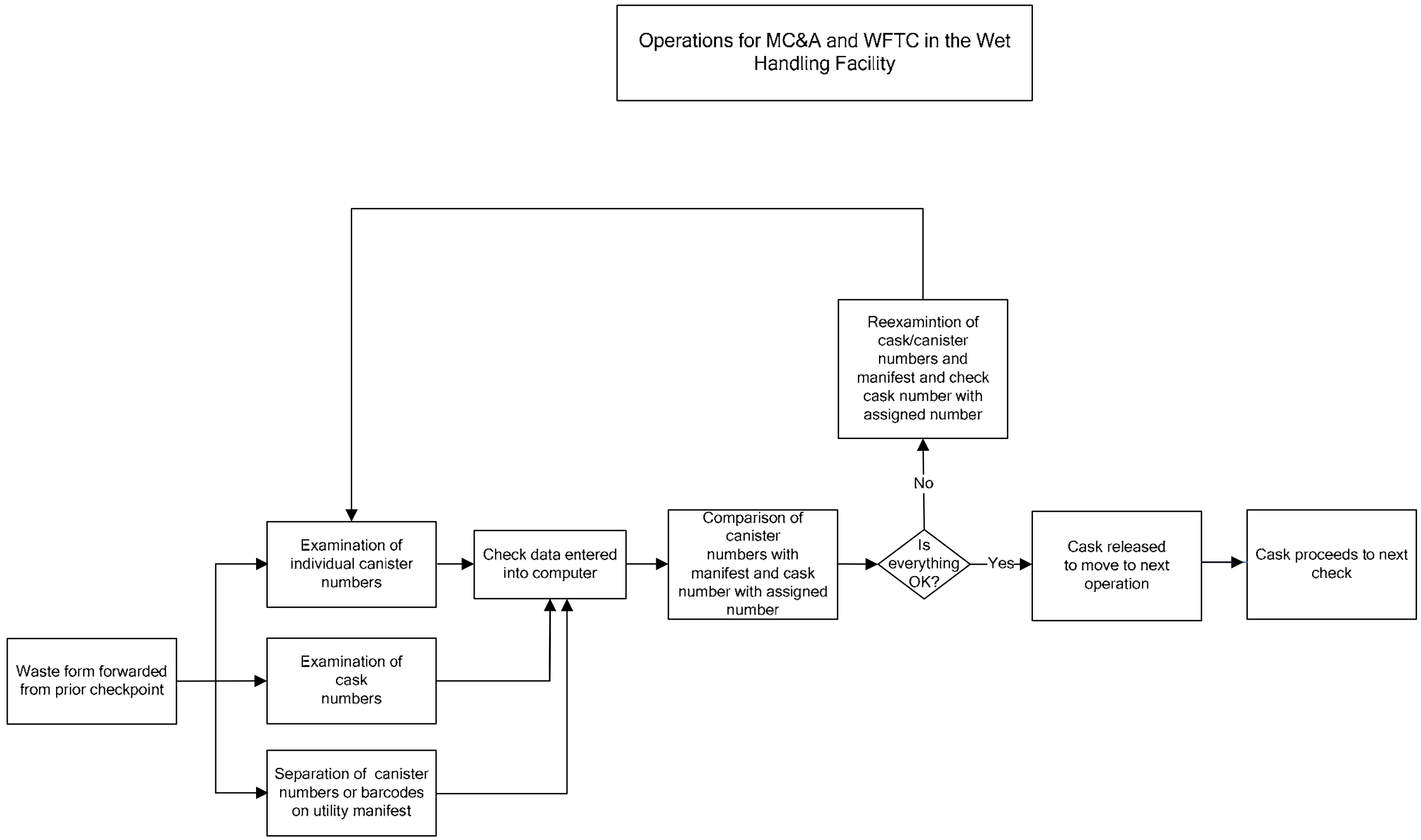
Figure 4. Simplified Flow Diagram Displaying the Transfer of Waste Forms within the GROA and Examples of the MC&A Zones of Control



NOTE: MC&A = material control and accounting; WFTC = waste form tracking and checking.

Source: Original

Figure 5. Standard Checking by WFTC and MC&A Groups



NOTE: MC&A = material control and accounting; WFTC = waste form tracking and checking.

Source: Original

Figure 6. Operations for MC&A and WFTC Groups in the Wet Handling Facility

4.4.2 Description of MC&A Activities

The MC&A group is responsible for monitoring waste forms through control areas as the waste form is received, processed, and transferred between facilities. The waste forms include naval SNF, DOE SNF and high-level radioactive waste in canisters, CSNF in TAD canisters, and CSNF assemblies in dual-purpose canisters and casks. A waste form arrives at the Cask Receipt Security Station and then passes to a buffer area until the waste form is ready for receipt at the appropriate facility.

On entry to the buffer area, the tamper-indicating device (TID) is examined. If the inspection detects any anomaly (e.g., the number on the cask doesn't match the shipping record, damage to the cask or TID), the discrepancy is reported to the waste form shipper, the U.S. Nuclear Regulatory Commission, and the DOE, and the waste form is quarantined until the anomaly is resolved. If the examination is successful, the waste form is accepted, the shipping facility is notified of its acceptance, and the receipt is entered into the Nuclear Materials Management and Safeguard System with the formats specified by the DOE and the U.S. Nuclear Regulatory Commission. The transaction requires a two-person sign-off to confirm that the correct procedures were implemented and that the identity of the waste form was authenticated. When the appropriate facility is ready to receive the waste form, it is forwarded with a two-signature sign-off process to confirm that the correct waste form is shipped.

The movement of waste forms follows the same procedure of controls and computer entry at each facility as in the buffer area. The waste form TID is examined upon arrival at the facility. If an anomaly is detected, the issue is investigated and promptly resolved. Once the identity is confirmed, the receipt is entered in the MC&A accounting system. It requires a two person signature sign-off for data entry or access to the computer database. Access to the MC&A office and computer system is limited to persons with access authorization and a need to know. All operations of the MC&A group are performed in a secure manner and the potential error rates, from similar operations at other facilities, show the approaches to be reliable. Thus, the ability of the GROA personnel to ensure that waste forms are correctly placed in the drift is enhanced.

Waste packages that are emplaced in a drift are recorded in the MC&A computer. Additionally, the drift door is locked and sealed with two independent TIDs affixed to the door and door frame. Entry into the MC&A computer system is performed after the standard two-person signature procedure is completed for each transfer.

4.4.3 Description of ETEs

Two independent groups perform thermal calculations to ensure that emplacement thermal limits are satisfied. The ETE group is responsible for ensuring that emplacement plans satisfy thermal limits, while the OTE group is responsible for ensuring that actual emplacement satisfies thermal limits. In each group a qualified engineer performs a quality assurance calculation in accordance with documented procedures, and then the calculation is checked by an independent qualified engineer and approved by the group manager. In performing the calculations, each individual will not access any prior calculation for the same waste form in order to ensure that the groups are as independent as possible.

The results of the two independent calculations are compared by the Subsurface Operations Manager before emplacement. If there are discrepancies, they are resolved before emplacement is permitted.

4.4.4 Description of Checking Process

The checking process description in this section covers the process of both the WFTC and the MC&A groups.

The steps in the checking process are depicted in Figure 5 and include the following:

1. The WFTC and MC&A groups separately examine the waste form to determine the cask or canister numbers. Each group consists of two checkers who work independently of one another. The data obtained from each checker are verified for concordance. If the results don't match, the data are referred to the respective group manager for resolution.

2 Once the two checker results match, then the data are entered into the respective and dedicated WFTC or MC&A computer. The data may be collected in numerical or barcode format.

3. The collected data are compared with the recorded data. If there is a difference in results, then the matter is referred to the Waste Handling Manager in the WFTC group or the Waste Material Control Manager in the MC&A group for resolution. This process may involve going back through the recorded data or referring back to the corresponding waste form record. If all is correct then the waste form is released to proceed to the next facility operation. Once the next operation has been carried out the checking process is repeated.

4. The data of the WFTC and the MC&A groups are compared at corresponding checkpoints for additional verification of data accuracy.

4.5 THERMAL DESIGN CRITERIA

4.5.1 Thermal Design Constraints

4.5.1.1 Thermal Limits at Receipt

The upper thermal limit on a loaded TAD canister is 22 kW; therefore, all TAD canisters received at the site are assumed to be at or below this value. TAD canisters with higher thermal limits are screened from consideration.

4.5.1.2 Emplacement Loading Temperature Constraints

The temperature limits for subsurface emplacement are explained in Section 7.1 of *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6) and are as follows:

- Postclosure
  - < 200°C on the drift wall
  - < 350°C fuel assembly cladding
  - < 96°C at the centerline of the pillar.
- Preclosure
  - < 200°C normal and off-normal (i.e., 30-day loss of ventilation) on the drift wall
  - < 350°C fuel assembly cladding normal
  - < 570°C fuel assembly cladding off-normal (i.e., 30-day loss of ventilation).
- Naval canisters
  - Temperature history bounded by existing analysis, reported in *Calculation of the Naval Long and Short Waste Package Three-Dimensional Thermal Interface Temperatures* (Ref. 2.2.3).

4.5.2 Emplacement Loading Rules

Emplacement rules to limit thermal power at emplacement and to ensure that preclosure temperature limits are satisfied follow:

- No waste package shall be emplaced that has a thermal power output greater than 18 kW at the time of emplacement.
- No seven-waste-package segment that does not contain a naval waste package shall exceed 2.0 kW/m at the time of emplacement.
- No seven-waste-package segment that contains a naval waste package shall exceed 1.45 kW/m at the time of emplacement. In addition, the two waste packages adjacent to the naval waste package in the seven-waste-package segment shall have a thermal output less than 11.8 kW at the time of emplacement.

4.5.3 Thermal Evaluations

Prior to emplacement, extensive thermal analyses are performed to ensure that the selected order of loading waste packages in emplacement drifts satisfies all thermal criteria. The WPLOAD computer program is used to select waste package loading sequences for waste arrival scenarios in compliance with temperature limits and emplacement loading rules. Decay heat for each TAD canister is calculated using utility records for burnup, enrichment, and time out of reactor. WPLOAD determines an emplacement sequence that processes the waste arrival stream considering facility throughput capability, minimization of aging pad requirements, and satisfaction of repository thermal criteria.

4.6 HUMAN RELIABILITY METHODOLOGY

The HRA is an analytical process used to estimate the probability of humans making errors in performing a given task. In this calculation, the objective of the HRA is to determine the probability of misplacement of a waste package. In this situation there are two sources of human errors:

- Incorrect information was developed for the thermal characteristics of the waste package (i.e., an error in the estimation of thermal output for a given TAD canister relative to the actual thermal output).

- The waste form was handled incorrectly or was incorrectly located in the emplacement drifts (i.e., physical error by the operator, including the nuclear MC&A activities group and the operational WFTC group).

The combined probability of these two errors determine an overall probability of misplacement of a waste package.

4.6.1 Human Reliability Approach

The approach to HRA is to follow a generalized step by step process, similar to those carried out in the Preclosure Safety Analysis (PCSA) reliability and event sequence categorization analyses. These steps are as follows:

- Define scope of analysis.
- Define base scenarios.
- Identify and define human failure events (HFE).
- Perform a screening analysis.
- Identify potential vulnerabilities.
- Search for scenarios of concern.
- Quantify HFEs.
- Incorporate HFEs into PCSA and interact with designers to reduce the risk factors.

Not all of the steps are required in the current analysis. In this study, the scope of the analysis is defined, the HFE are determined, a methodology is selected, and the HFE are quantified.

4.6.2 Human Reliability Events

There are two sets of human actions that can have a potential influence on the misplacement of a waste package. These actions are related to the incorrect calculation of the thermal output of canisters and the checking, logging, determination of location, and emplacement of canisters. Both processes have been designed to be as reliable as possible, but the requirements for emplacement of the canisters in the drifts are demanding.

4.6.3 Selection of a Human Reliability Method

The following HRA methods used in the PCSA are "preferred" only in that they are structured and reproducible; therefore, the resultant probabilities are easier to justify when compared to an expert elicitation approach:

- THERP from the *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report* (Ref. 2.2.11), Chapter 20, by Swain and Guttmann

- ATHEANA from the *Technical Basis and Implementation Guidelines for a Technique for Human Event Analysis (ATHEANA)* (Ref. 2.2.9), Chapter 10.

- NARA from *A User Manual for the Nuclear Action Reliability Assessment (NARA) Human Error Quantification Technique* (Ref. 2.2.7), p. 1-18.

- CREAM from the *Cognitive Reliability and Error Analysis Method, CREAM* (Ref. 2.2.8), Chapter 1.

- HEART from "*HEART - A Proposed Method for Assessing and Reducing Human Error*" (Ref. 2.2.12), p. 436-450.

The characteristics of each of these methods are not discussed in detail in this analysis. A more comprehensive review can be found in the main PCSA reliability and event sequence categorization analyses. The methodology used for this analysis, generally mirrors the methodology in the PCSA event sequence categorization analyses. Therefore, only a brief review of the previously mentioned methodologies is presented, along with the rationale for the selection of the chosen HRA model.

The actions taken by GROA personnel in performing the checking of the numbering of waste forms and the calculation of their thermal output involve a series of step-by-step operations. The operations performed by GROA personnel could fit very well into the THERP, NARA, or HEART HRA models. THERP, however, is based upon a task analysis approach and fits well in modeling the actions involved in the various tasks of checking the waste form numbers or the calculation of thermal outputs. In order to use THERP, it is necessary to compare each of the operational steps of the checking task with the nearest similar task description in the HEP tables in Chapter 20 of the *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report* (Ref. 2.2.11) and determine the suitability of each THERP task to the current analysis.

The calculation process follows the THERP methodology (*Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report* (Ref. 2.2.11), Chapter 20), with a few variations. For one, the database of THERP suffers from some limitations and does not cover all of the situations that may occur in this study. The second variation is concerned with dependency between two or more groups. The approach used in this analysis depends on the use of a dependency factor beta, which is used to weight the second partially dependent action following the failure of the first group. This subject is discussed in more detail in the report.

4.6.4 THERP HRA Model

Within the *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report* (Ref. 2.2.11), Chapter 20, THERP covers various rule-based types of operations and lists a number of the standard operations with estimates of the probability of failure with corresponding uncertainty measures. THERP can be used for tasks that can be characterized by a set of manual operations. A task analysis can be developed to cover all of the significant steps taken to accomplish the main task. There are 27 tables within Chapter 20 of the handbook that can be used to estimate various HEPs (Ref. 2.2.11). THERP lists the median values in the Chapter 20 tables, along with error factors; whereas, the main PCSA analyses use the mean. The following equation relates mean to median and the error factor.

$$m = M_D \times e^{\left(\left(\frac{\ln(EF)}{1.645}\right)^2 / 2\right)} \qquad \text{(Eq. 1)}$$

For each of the operations involved in both the thermal analysis and the monitoring/checking process, a task analyses is carried out, and the corresponding human reliability trees are developed. The task analysis is made up of several components or subtasks. A subtask and its corresponding description are selected and compared to the descriptions in the Chapter 20 tables of THERP. The most appropriate description is selected, which yields the HEP and uncertainty value for the subtask. This process is continued for each of the subtasks in the task analysis. This methodology is consistent with THERP (*Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report* (Ref. 2.2.11)). However, not all of the processes displayed in the THERP tables are used in this analysis. The tables in THERP cover both errors of commission (EOCs) and errors of omission (EOOs). EOCs are those actions taken by the operator that are performed incorrectly and lead to a change in configuration with the consequence of a degraded state, whereas EOOs are actions where operators fail to take an action required of the task. In this study, the potential for error is important, not whether it is an EOC or EOO. Traditionally, EOOs and EOCs are part of the HRA process and have a part in the analysis; however, in this analysis the details of the implementation of the various checking processes and calculation methods are not designed beyond the general schemes. Within this general outline of operations, both types of errors by the operator may result in the same effect. For example, the operator may enter the wrong number or he may fail to modify an earlier number, both resulting in an inaccurate entry. Therefore, for this analysis, there is no differentiation between EOO and EOC, since it is very difficult to conclude what the error type is likely to be.

The steps in the process of using THERP follow (*Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report* (Ref. 2.2.11)):

1. Review the details of the checking/calculation processes.

2. Develop a task analysis for each operation, and define each task so that the best corresponding task item from one of the THERP tables can be identified.

3. Construct an HRA event tree corresponding to each operational step in the checking or calculation process from the task analysis.

4. Use Chapter 20 of the *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report* (Ref. 2.2.11) to select the appropriate HEPs and error factors for each HFE.

5. Account for the possibility of recovery actions. Group decisions can lead to recovery actions and the restructuring of the HRA event tree.

6. Perform the HRA calculations, and obtain the individual HEP contribution for checker or calculator.

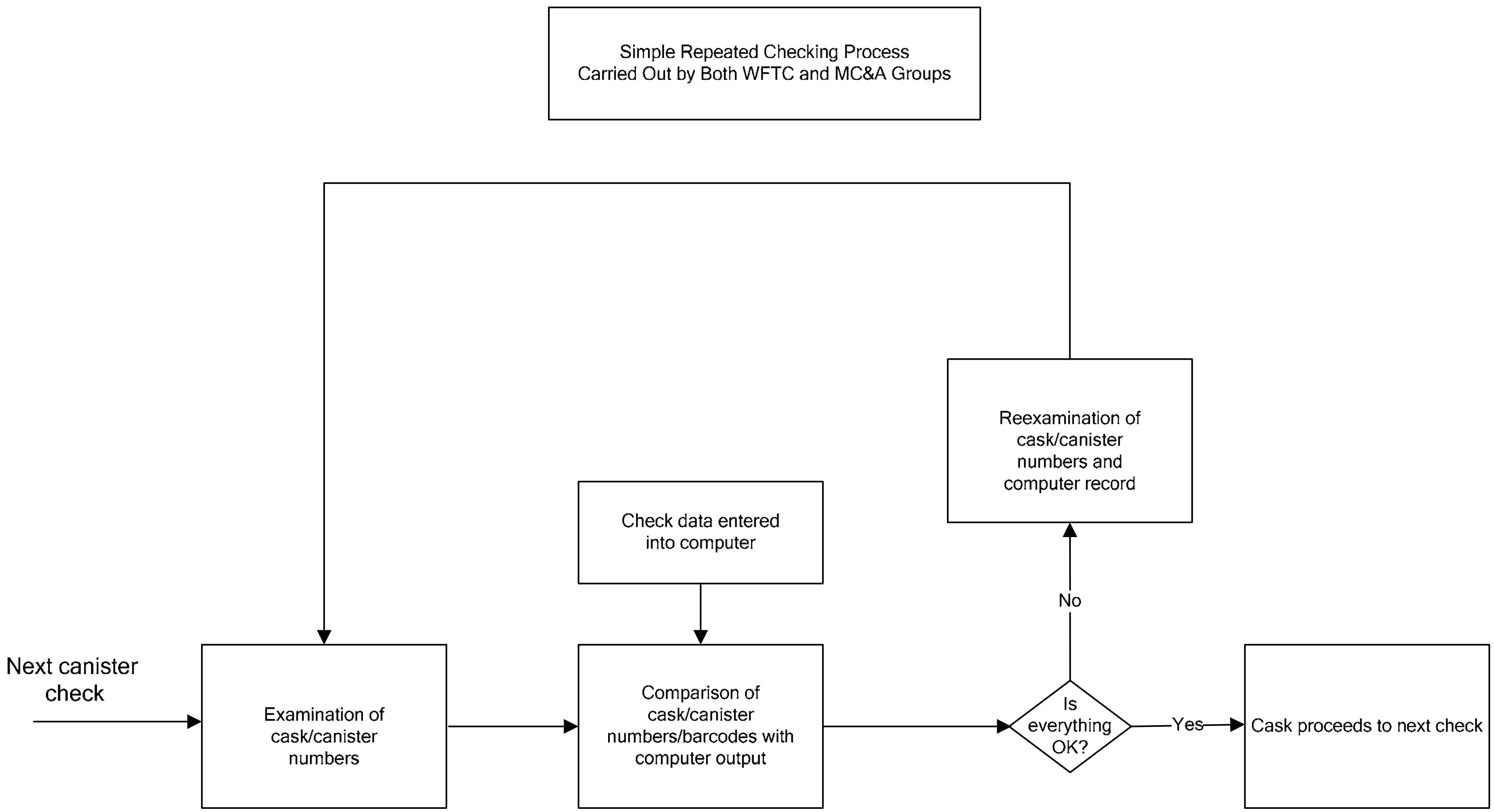
7. Use a dependency factor (β factor) for operations to account for the effects of redundancy. (This represents a departure from Swain, who has developed a set of dependency relationships covering dependency from zero to complete dependency between working groups (*Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report*, (Ref. 2.2.11), Chapter 20). The β factor approach has its basis in developments following from a review of various approaches used by PRA groups reflecting a need to better represent the influences that affect dependence effects).

8. Account for the number of opportunities for misplaced canisters and produce the overall HRA number for misplacement and thermal calculation errors.

9. Review numbers and correct values as necessary.

4.6.5 Illustration of the THERP Calculation Process

To illustrate how the THERP calculation process was applied in the current HRA analysis, a simplified version of the checking process is provided in this section, along with a step-by-step description of how the results were derived. Figure 7 shows the typical checking process that occurs during the movement of a waste form through a facility. The checking may be accomplished through the more automated scanning of a bumpy barcode, but it may also be carried out by the manual reading of the numbers on the waste forms. Both operations are carried out remotely because of the possibility of high radiation fields. Remote performance of these operations presents the opportunity for reading errors. For the purpose of this analysis, the data collection process is conservatively taken as a manual process.



NOTE: MC&A = material control and accounting; WFTC = waste form tracking and checking.

Source: Original

Figure 7. Simplified Repeated Checking Process Carried Out by Both WFTC and MC&A Groups

In practice, the checking operation is carried out by two independent teams and the results are cross-checked. Figure 8 shows the task analysis of the checking process. The task analysis process breaks the overall task of checking into a series of subtasks. The process is relatively simple; however, it is difficult to predict the HFEs because the process cannot be observed and the details of the operational activities are not clearly defined at this stage. Table 1 shows the task elements in more detail to enhance the ability of the analyst to understand the tasks and to better select the nearest THERP task description, corresponding HEPs, and error factors (*Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report* (Ref. 2.2.11), Chapter 20).

Table 1. Description of Subtasks for Waste Form Tracking Operations

Item	Description
Examine cask numbers	The waste form is in a staging area and the crew remotely views the cask and locates the cask numbers.
Read and document cask numbers	The crew uses the remote viewing camera to obtain a photograph of the numbers.
Enter numbers into computer	The crew reads the photograph and enters the numerical data into the computer.
Check numbers against computer record	The computer record contains the numerical data for the waste form at the prior control point. The crew compares the number from the prior checkpoint with the number they recorded.
Numbers are OK or crew reinvestigates numbers	The crew sees whether or not the numbers cross-check. If they do not then the crew investigates further to locate error.

NOTE: There are a number of different ways to carry out the checking process, which could enhance the reliability of the operation, such as the use of barcodes and remote wireless entry into the monitoring computers. However, the process used here was aimed at giving a realistic HEP.

Source: Original

Figure 9 depicts the HRA event tree derived from the task analysis. The convention is to draw a herringbone tree with the tasks indicated on the left side and the corresponding HEP values on the right side. For the task identified as "Enters numbers into computer" the corresponding THERP description is "Recording task: Number of digits to be recorded" (*Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report* (Ref. 2.2.11), Chapter 20). For this description, HEP = .001 (per symbol), and the error factor is 3. In this example the number of digits to be entered by the checker was selected to be 10 (this value is assumed since the system is not designed). Therefore the value of HEP is 0.01.

To calculate the HEP for the whole task, all of the HEPs on the branches of the event tree are added together, as follows:

$$HEP = (HEP_1 + HEP_2 + HEP_3 + HEP_4 + HEP_5) \qquad \text{(Eq. 2)}$$

Since the task is being carried out by two groups, the dependency between the two groups must be addressed. In addition, how the dependency factor (β) is estimated to account for the modification of the effective overall HEP for the operation of checking must be examined.

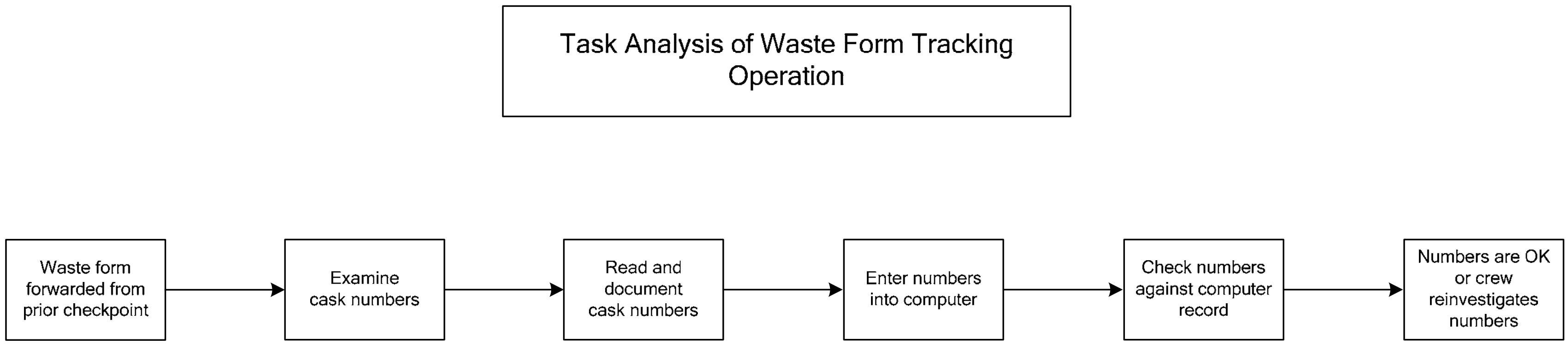
There are a number of different ways to account for dependency; one method is Swain's original method. However, this analysis used the method discussed in *HRA Concepts and Applications Series of Workshops Given at Tsinghai University, Beijing, China May 10th through 12th, 2005* (Ref. 2.2.10), Section 9.

The equation used to represent the effect of dependence follows:

$$HEP = HEP_a \times \beta \times HEP_b \quad \text{(Eq. 3)}$$

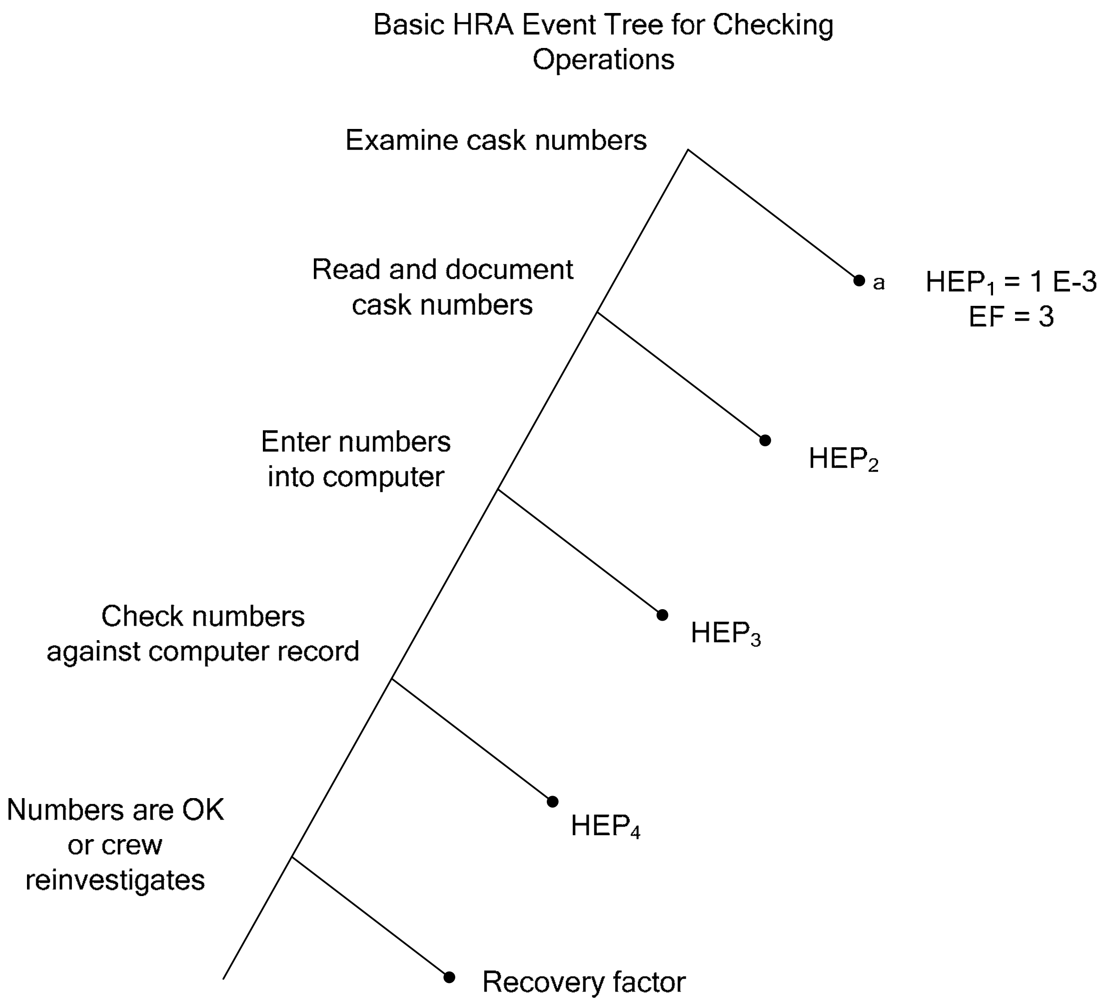
where $_a$ and $_b$ represent the two groups carrying out the checking.

The beta factor depends on various contextual factors, which influence the dependence between operators. The influencing factors might be work load, time pressures, and which staff members are involved. The exact influences depend on the actual working conditions and the relationships between staff as far as communications are involved. As the influences change so does the dependence between the operators. In a given application a tree formulation is selected to reflect the changes in beta as the influences changed. However, in this case, it is difficult to make judgments as to the influences that affect dependence without resorting to a detailed evaluation of the various influences that affect checker performance. Therefore judgment was used to estimate β factors. The β factors selected were 3 and 5 and they account for crews with lesser and greater dependence, respectively. For example, the checking groups within the WFTC group are deemed to have a greater dependence, so a β factor of 5 is assigned. The MC&A group, by contrast, is highly security conscious relative to the operations group and, therefore, is assigned a β factor of 3. All analytic methods depend on an understanding of the working conditions between the groups. The values chosen here could be improved upon given a better understanding of the working relationships within the groups and the conditions under which the checking process is performed. The same rationale applies to the groups performing the calculations of the thermal output of the waste forms as well.



Source: Original

Figure 8. Task Analysis of Waste Form Tracking Operation



$$HEP = (HEP_1 + HEP_2 + HEP_3 + HEP_4)$$

NOTE: The *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report* by Swain and Guttmann (Ref. 2.2.11) was used to compare each task description with an equivalent HEP description. In this particular analysis, the Swain and Guttmann (THERP) method was used based on the fact that the methodology is applicable to this particular circumstance. The HEP values in Chapter 20 are used for the subtask quantification. This figure relates the subtasks to the HEP values and gives the locations of the HEP values within Chapter 20.
[a] (Ref. 2.2.11) Chapter 20, Table 10 (2)
EF = error factor; HEP = human error probability; HRA = human reliability analysis.

Source: Original

Figure 9. Basic HRA Event Tree for Checking Operations

5 LIST OF ATTACHMENTS

6 BODY OF CALCULATION

6.1 THERMAL ANALYSIS CALCULATIONS

Thermal responses to a single misplacement of a waste package in a seven-waste-package segment are described in *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6). *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6) uses several assumptions (Assumption 3.2.1). Three sets of limits are examined:

- Preclosure limits
- Postclosure limits
- Naval limits.

6.1.1 Seven-Waste-Package Segment 3D ANSYS Calculations

As described in *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6), a transient solution of the three-dimensional (3D), full-pillar, repository segment representation with multiple waste packages emplaced is obtained using time-dependent waste package heat loads. The effects of ventilation during the preclosure period are accounted for by the application of a ventilation efficiency (i.e., a reduction in heat generation) of 90%. During the postclosure period, ventilation is discontinued (i.e., the ventilation efficiency is removed). The transient solution also includes a 30-day total loss of ventilation during the preclosure period, which occurs at 30 days after emplacement (Assumption 3.2.2).

The multiple waste package representation includes a mixture of seven waste packages with an additional half a waste package at each end of the segment. The seven-waste-package segment is the estimated limiting seven-waste-package segment described in *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6). This calculation is used to determine the drift wall temperatures, which are provided as boundary conditions for the calculation of TAD canister and naval canister temperatures.

6.1.2 Geometry of Seven-Waste-Package Segment ANSYS Model

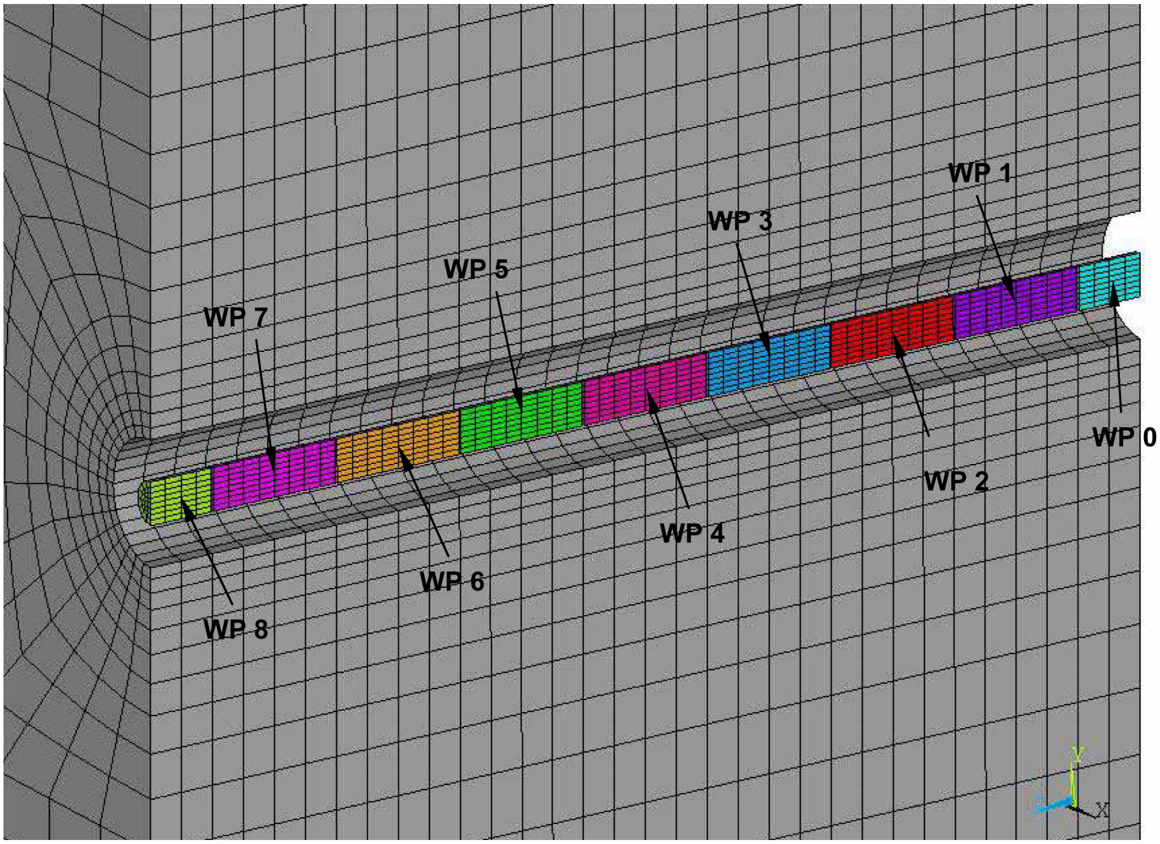
The 3D waste package emplacement repository is represented as a pillar of rock from the upper boundary of the ground surface at an elevation of 1,326 m (4,351 ft) and extends to the lower boundary, a depth of 1,085 m (3,560 ft).

The length of the pillar model is calculated based on a waste package spacing of 0.1 m and the individual waste package lengths to be emplaced in the repository. The width of the model is taken as the drift spacing of 81 m. The effect of water movement in the rock units is ignored; therefore, only conduction is considered in the rock.

The drift loading criteria for the estimated limiting seven-waste-package segment includes a maximum linear heat load at emplacement of 2.0 kW/m, a maximum waste package thermal power at emplacement of 18 kW, and a peak mid-pillar temperature of 96°C.

Since the temperature details internal to the waste package are not of interest in the 3D calculations, each waste package is treated as a solid homogeneous, heat-generating cylinder. The emplacement pallets, invert and drip shield are not represented in the drift; thus, radiation heat transfer between the waste packages and the rock is maximized.

The locations of the different waste packages are shown in Figure 10.



NOTE: WP = waste package

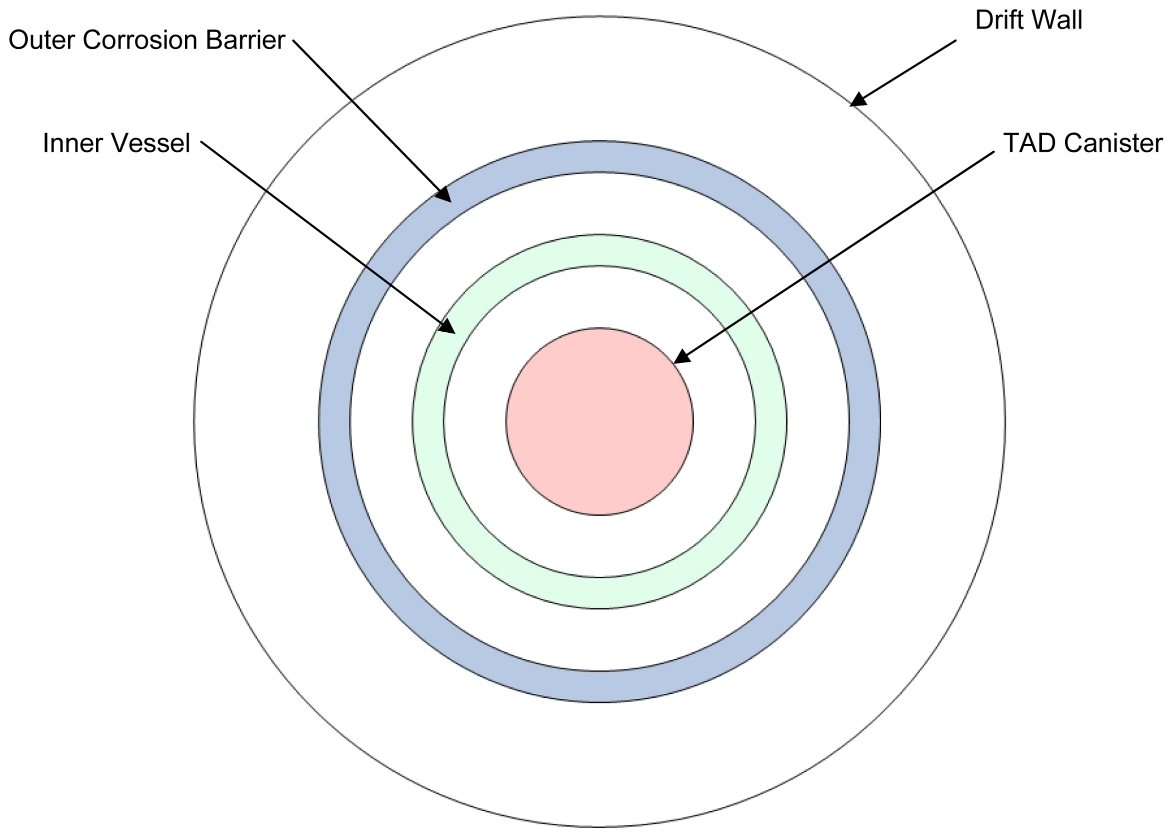
Source: *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6)

Figure 10. 3D ANSYS Representation

6.1.3 Geometry Used for TAD Waste Package Internal Temperature Calculations

In order to determine the peak cladding temperature inside the TAD waste package, an analytic approach using one-dimensional heat conduction and radiation exchange between infinite concentric cylinders is used. The geometry is shown in Figure 11.

In each case, the peak preclosure and postclosure drift wall temperature from the 3D pillar calculation was used as the boundary condition.



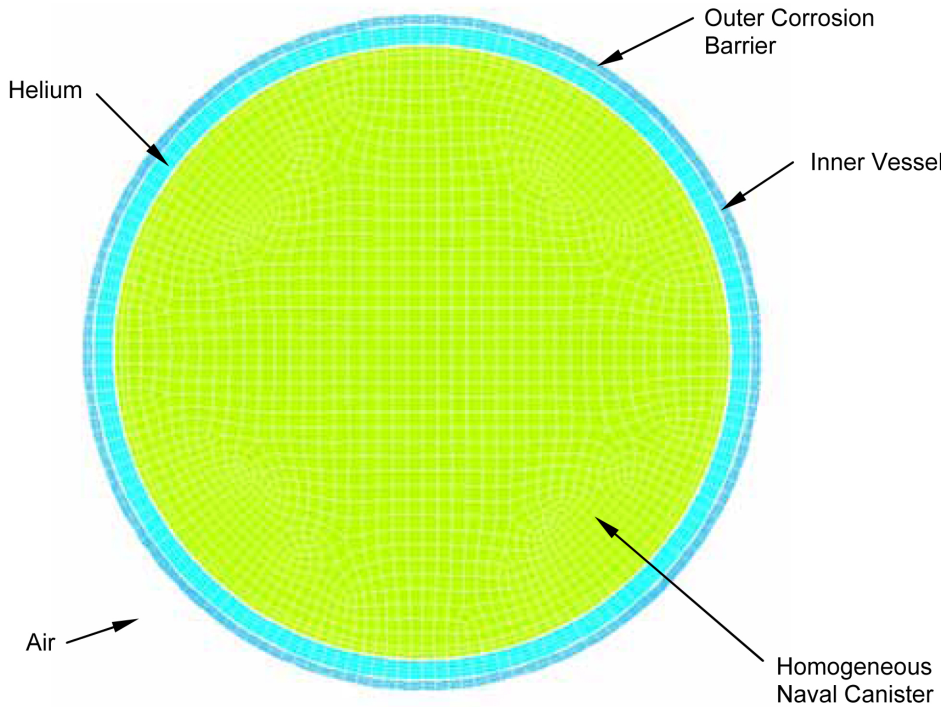
NOTE: TAD = transportation, aging, and disposal.

Source: *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6)

Figure 11. Simplified Geometry for Waste Package Internal Temperature Calculations

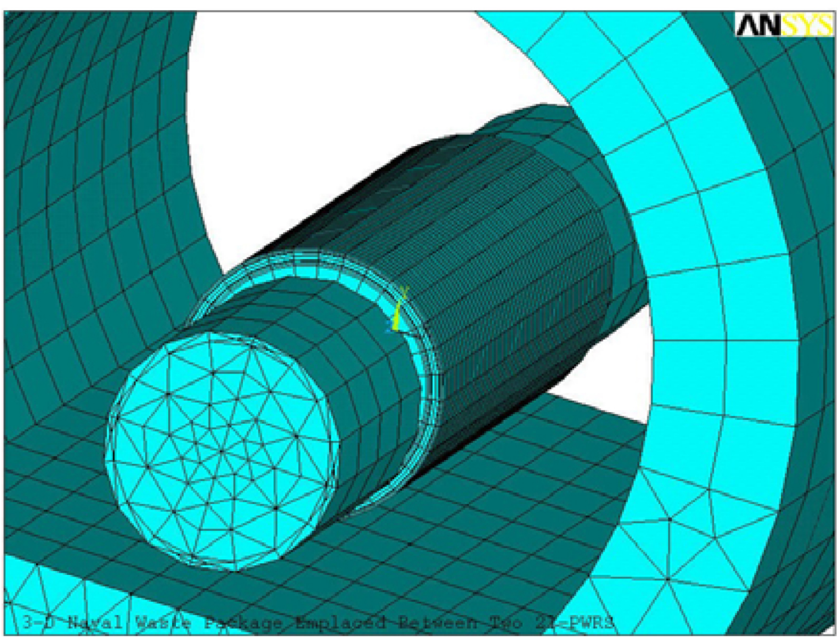
6.1.4 Geometry Used for Naval Canister Surface Temperature Calculations

The general approach for evaluating naval waste package thermal performance in the misload drift segment is to compare the naval canister surface temperature to the previous surface temperatures that were provided to the NNPP as a design basis. Some design parameters have changed. For the current cases, the drift wall temperatures used as boundary conditions are based on the slightly different rock properties, the higher ventilation efficiency (90% vs. 80%), and the longer ventilation duration (65 or 82 years of ventilation vs. 50 years). The changes could potentially lower the rock and waste package temperatures to provide enough margin for the misload cases to satisfy the thermal criteria. The geometry used is shown in Figures 12, 13, and 14.



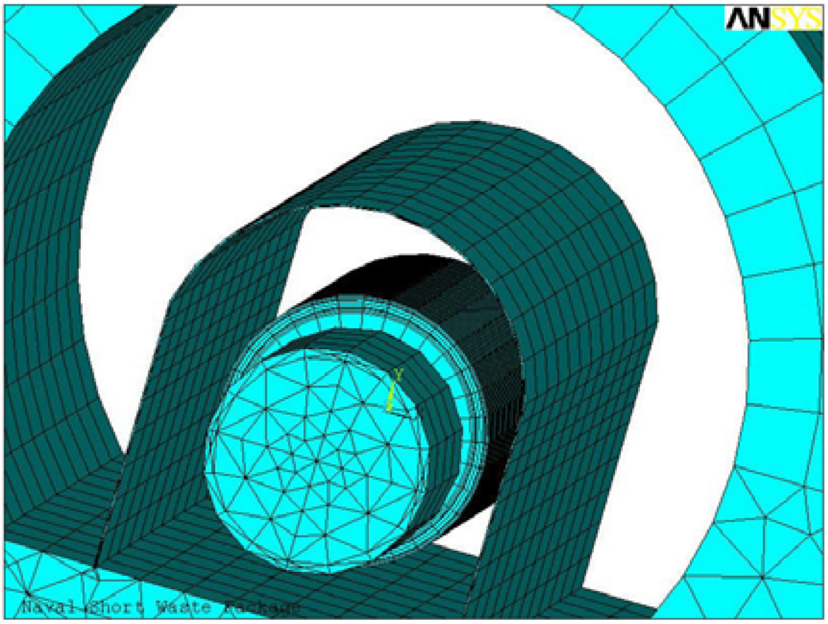
Source: *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6).

Figure 12. Cross Section of Naval Waste Package Representation



Source: *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6).

Figure 13. ANSYS Naval Waste Package Emplaced between Two TAD Waste Packages in Drift (Preclosure Representation)



Source: *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6).

Figure 14. ANSYS Naval Waste Package Emplaced between Two TAD Waste Packages in Drift (Postclosure Representation)

6.1.5 Thermal Calculation Cases for TAD Waste Package Temperatures in a Thermally Misloaded Drift Segment

Table 2 shows the initial waste package heat loads of the "as-loaded" seven-waste-package segment (shaded rows) used to calculate the linear heat load.

Table 2. Seven-Waste-Package Segment, "As-Loaded"

WP #	WP Type	Length (m)	Initial Heat (W)
0	44 BWR TAD	5.8501	7,768.7
1	21 PWR TAD	5.8501	17,809.3
2	44 BWR TAD	5.8501	5,412.0
3	44 BWR TAD	5.8501	7,751.0
4	21 PWR TAD	5.8501	14,822.7
5	44 BWR TAD	5.8501	5,357.4
6	44 BWR TAD	5.8501	18,326.0
7	44 BWR TAD	5.8501	13,347.8
8	21 PWR TAD	5.8501	17,098.8

NOTE: BWR = boiling water reactor; m = meters; PWR = pressurized water reactor; TAD = transportation, aging, and disposal; W = watts; WP = waste package.

Source: *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6).

The 3D ANSYS cases for the misloaded seven-waste-package segment are shown in Table 3.

Table 4 shows the initial waste package heat loads of the misloaded seven-waste-package segment (shaded rows) used in cases M1 and M2. To create the misloaded condition, the initial heat load of waste package 5 (the coolest waste package in the "as-loaded" segment) was scaled up to 22 kW with the thermal decay curve of waste package 5 normalized to the new initial value.

Table 5 shows the initial waste package heat loads of the misloaded seven-waste-package segment (shaded rows) used in cases M3 and M4. Cases M3 and M4 illustrate the case of a misload of a 22 kW waste package in an "as-loaded" drift with an initial linear heat load of 1.45 kW/m. Cases M3 and M4 are run to provide boundary conditions for the cases of a naval waste package in a thermally misloaded drift segment (Section 6.1.6), and, therefore, are not used to calculate TAD waste package temperatures. To create this misloaded condition, the initial heat loads of the "as-loaded" segment (as well as waste package 0 and waste package 8) were scaled by a factor of 0.7274 with the thermal decay curves normalized to the new initial values. The initial heat load of waste package 5 (the coolest waste package in the "as-loaded" segment) was then scaled up to 22 kW with the thermal decay curve of waste package 5 normalized to the new initial value.

Table 3. Seven-Waste-Package Segment 3D ANSYS Cases, Misloaded

Case	Linear Heat Load (kW/m)	Misloaded WP Max. Heat Load (kW)	Ventilation Efficiency (during loss of vent / during preclosure)	Ventilation Time (years)
M1	2.39	22	0% / 90%	77
M2	2.39	22	0% / 85%	65
M3	1.88	22	0% / 90%	82
M4	1.88	22	40% / 90%	65

NOTE: kW = kilowatt; kW/m = kilowatt per meter; WP = waste package.

Source: *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6)

Table 4. Seven-Waste-Package Segment, Misloaded (Cases M1 and M2)

WP #	WP Type	Initial Heat (W)
0	44 BWR TAD	7,768.7
1	21 PWR TAD	1,7809.3
2	44 BWR TAD	5,412.0
3	44 BWR TAD	7,751.0
4	21 PWR TAD	14,822.7
5	44 BWR TAD	22,000.0
6	44 BWR TAD	18,326.0
7	44 BWR TAD	13,347.8
8	21 PWR TAD	17,098.8

NOTE: BWR = boiling water reactor; PWR = pressurized water reactor; TAD = transportation, aging, and disposal, W= watts; WP = waste package.

Source: *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6)

Table 5. Seven-Waste-Package Segment, Misloaded (Cases M3 and M4)

WP #	WP Type	Initial Heat (W)
0	44 BWR TAD	5,651.0
1	21 PWR TAD	12,954.5
2	44 BWR TAD	3,936.7
3	44 BWR TAD	5,638.1
4	21 PWR TAD	10,782.0
5	44 BWR TAD	22,000.0
6	44 BWR TAD	13,330.3
7	44 BWR TAD	9,709.2
8	21 PWR TAD	12,437.7

NOTE: BWR = boiling water reactor; PWR = pressurized water reactor; TAD = transportation, aging, and disposal, W = watts; WP = waste package.

Source: *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6)

6.1.6 Thermal Calculation Cases for Naval Waste Package Temperatures in a Thermally Misloaded Drift Segment

There are two ways for a naval waste package to be placed in a drift segment with a linear heat load above 1.45 kW/m: (1) a hot TAD waste package (22 kW maximum) is misplaced in a segment that was intended to have a linear heat load of 1.45kW/m and maximum neighboring waste package heat load of 11.8 kW, and (2) a naval waste package is misplaced in a hot drift segment (2.0 kW/m maximum).

Table 6 lists the cases analyzed to capture these two scenarios. Cases M3-n-1, M3-n-2, M4-n-1, and M4-n-2 are used to analyze scenario (1) with different ventilation times and off-normal ventilation efficiencies. Cases A2-n-1, A2-n-2, A2-n-3, and A2-n-4 are used to evaluate scenario (2) with different naval waste package heat outputs.

Table 6. 3D Naval Waste Package Segment ANSYS Cases

Case	Linear Heat Load for Boundary Condition (kW/m)	Waste Package Initial Heat Output (kW) (TAD WP-Naval WP-TAD WP)	Ventilation Time (years)	Drift Wall Boundary Condition	Ventilation Efficiency Used in 7WP-Segment (loss of ventilation / preclosure)
M3-n-1	1.88	11.8 - 12.9 - 22	82	Case M3	0% – 90%
M3-n-2	1.88	11.8 - 11.8 - 22	82	Case M3	0% – 90%
M4-n-1	1.88	11.8 - 12.9 - 22	65	Case M4	40% – 90%
M4-n-2	1.88	11.8 - 11.8 - 22	65	Case M4	40% – 90%
A2-n-1	1.99	18 - 12.9 -18	82	Case A2	0% – 90%
A2-n-2	1.99	18 - 8.5 - 18	82	Case A2	0% – 90%
A2-n-3	1.99	18 - 8.5 - 22	82	Case A2	0% – 90%
A4-n-4	1.99	18 - 11.8 - 18	82	Case A2	0% – 90%

NOTE: 3D = three-dimensional; 7-WP = seven waste package; kW/m = kilowatt per meter; TAD = transportation, aging, and disposal, WP = waste package.

Source: *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6)

6.1.7 Thermal Results for TAD Waste Packages in a Misloaded Drift Segment

Table 7 lists the peak rock temperatures from the 3D ANSYS calculations of the misloaded segment. Table 8 lists the peak TAD waste package temperatures for a misloaded segment. Results show that temperatures are in compliance with the 200˚C postclosure drift wall limit and the 350˚C postclosure fuel cladding limit despite the thermal misloading.

Table 7. Peak Rock Temperatures from 3D ANSYS Calculations of Misloaded Segment

Case	Peak Preclosure Drift Wall Temperature (˚C)	Peak Postclosure Drift Wall Temperature (˚C)
M1	127.5	178.5
M2	128.6	195.3

NOTE: ˚C = degrees Celsius.

Source: *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6)

Table 8. Peak TAD Waste Package Temperatures for Misloaded Segment

Case	Preclosure WP Surface Temperature (˚C)	Postclosure WP Surface Temperature (˚C)	Preclosure TAD Cladding Temperature (˚C)	Postclosure TAD Cladding Temperature (˚C)
M1	170.8	182.9	351.2	210.8
M2	171.6	199.6	351.6	228.5

NOTE: ˚C = degrees Celsius; TAD = transportation, aging, and disposal; WP = waste package.

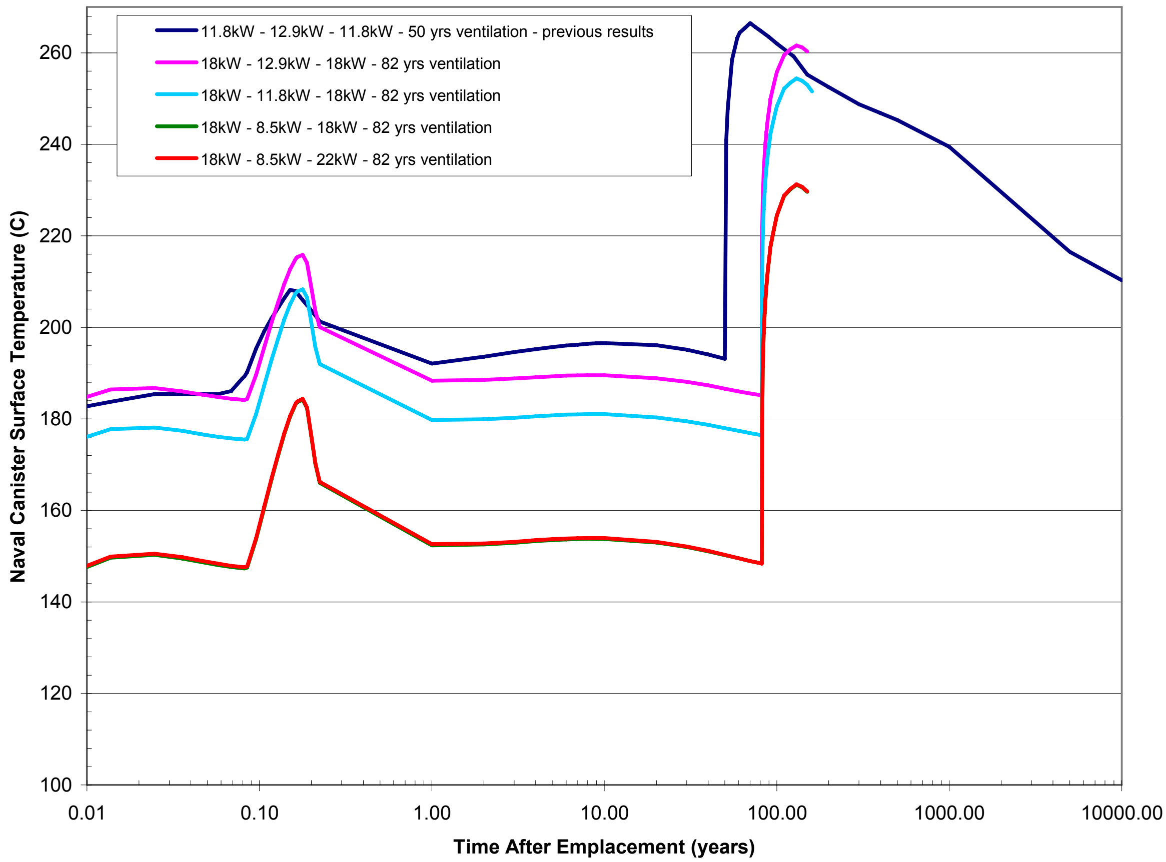
Source: *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6)

6.1.8 Thermal Results for a Naval Waste Package in a Misloaded Drift Segment

The criterion to evaluate the naval waste package thermal performance for misload scenarios is to compare the temperature history of the naval canister surface with previous temperature results from Case 1a of *Calculation of the Naval Long and Short Waste Package Three-Dimensional Thermal Interface Temperatures* (Ref. 2.2.3), which was provided to the NNPP as a design basis. It should be noted that this reference uses 12.9 kW for a naval waste package, even though the limit is 11.8 kW and the maximum expected naval package is 8.51 kW.

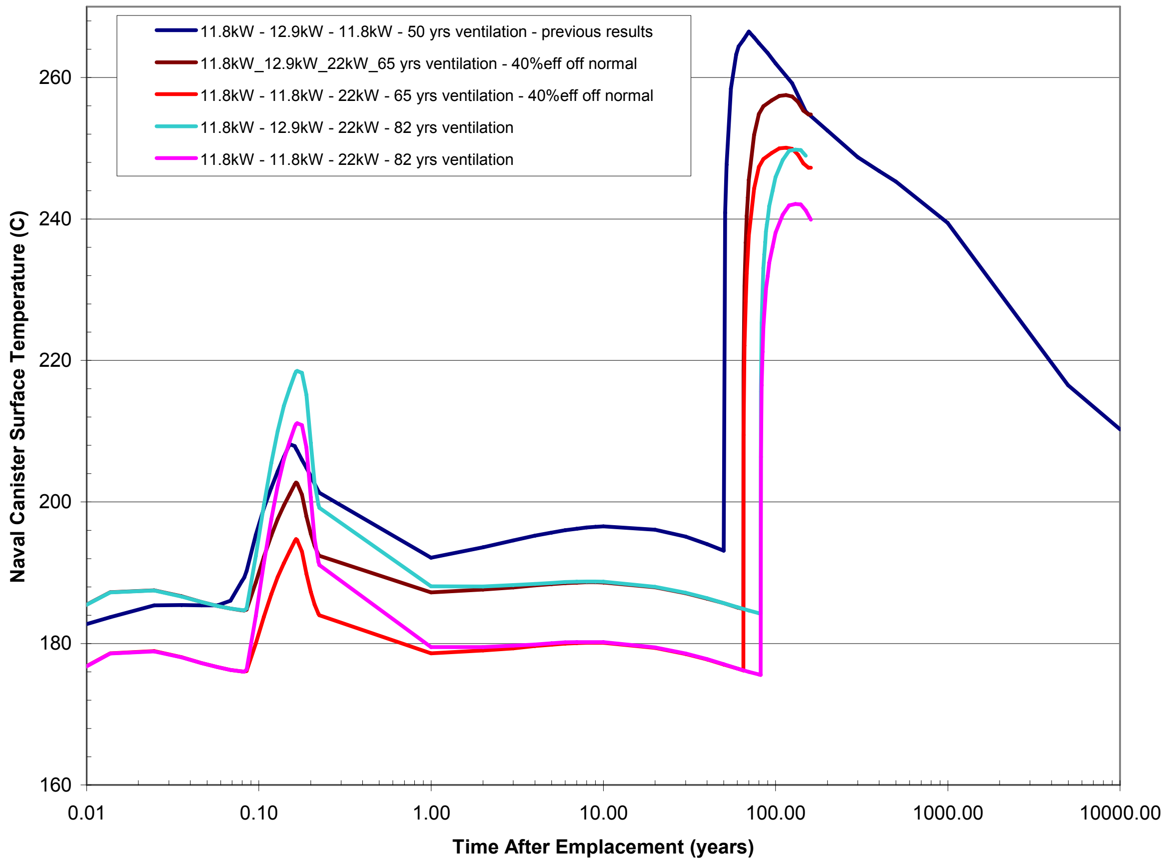
Figure 15 shows that if a 12.9 kW naval waste package were misplaced in a hot drift segment (2.0 kW/m), the naval canister surface temperatures during the preclosure off-normal event and postclosure period would be above the previous curve. However, if the naval waste package heat output is less than 8.5 kW, the canister surface temperature is significantly lower than the previous temperature results. If the naval waste package heat output is 11.8 kW, the canister surface temperature is the same or lower than the previous temperature results. The plot also indicates that the neighboring waste package heat output (e.g., one waste package heat changed from 18 kW to 22 kW) would not have significant impact on the naval canister temperature. It should be noted that all cases performed for this scenario are based on 82 years of ventilation, which assumes the naval waste stream arrival between calendar year 2017 and 2035.

Figure 16 shows that if a 22 kW TAD waste package were misplaced in a 1.45 kW/m naval drift segment, the naval canister surface temperatures would be below the previous curve except for the preclosure off-normal period. For the off-normal period, if no credit were taken for the natural ventilation effect, the canister temperature could be 3°C above the previous peak temperature about 25 days after the loss of ventilation for an 11.8 kW naval waste package; however, it would be below the previous temperature if the natural ventilation could remove 40% or more of the heat in the drift. The natural ventilation effect should have similar impact on the temperatures shown in Figure 15. The 65-year ventilation time is a conservative value used to simulate the naval canister arrival at calendar year 2052 (the last year of arrival for CSNF).



Source: *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6)

Figure 15. Naval Canister Surface Temperature Comparison – Misload in a Hot Drift Segment



Source: *Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6)

Figure 16. Naval Canister Surface Temperature Comparison – Misload in 1.45 kW/m Naval Drift Segment

6.1.9 Summary of Thermal Results

Table 9 shows the impact of a single misload of a 22 kW waste package in a nominal 2.0 kW/m drift segment on thermal conditions. Provided loss of ventilation does not exceed 30 days, there is no condition which causes a TAD waste package to fail thermal limits (Assumption 3.2.2). The only case that causes a naval waste package to exceed thermal limits is for a naval waste package above 8.5 kW (10% of the inventory) to be placed in the first 0.2% of the repository capacity or (120 m).

Table 9. Impact of Single Misplacement on Thermal Limits

Ventilation Operational	Commercial (TAD) Waste Package			Naval Waste Package	
	Power < 11.8 kW (33% of inventory)	11.8 < Power < 18 kW (23% of inventory)	18 < Power < 22 kW (44% of inventory)	Power less than or equal to 8.5 kW (90% of inventory)	Power above 8.5 kW (10% of inventory)
30 day loss of forced ventilation with natural ventilation (99.8% of repository)	Pass	Pass	Pass	Pass	Pass
30 day loss of forced ventilation without natural ventilation* (0.2% of repository)	Pass	Pass	Pass	Pass	Fail

NOTE: kW = kilowatt; TAD = transportation, aging, and disposal.
* Loss of forced circulation is assumed to be for no more than 30 days (Assumptions 3.2.2). This is considered to be a very conservative assumption given the capabilities to recover failed systems or components.

Source: Original.

These thermal results show that there are no TAD waste packages that suffer adverse thermal impacts if there is a single misplacement of a 22 kW package in a seven-waste-package segment. It would likely take two misloaded TAD waste packages in a seven-waste-package segment to cause a problem.

A 12.9 kW naval waste package slightly exceeds thermal limits if it is placed in the wrong drift (at 2.0 kW/m). However, if the naval waste package has thermal output less than or equal to 11.8 kW, no adverse impact is expected, since natural ventilation is expected for such cases.

If a 22 kW TAD waste package is placed in a naval segment (at 1.45 kW/m), the linear heat load increases to 1.89 kW/m. This increase causes an 11.8 kW naval waste canister to violate the currently analyzed NNPP thermal analyses by 3°C about 25 days after total loss of ventilation (i.e., no natural circulation) during the preclosure period. It should be noted that these results are dependent on the arrival schedules of naval canisters and on whether the estimated limiting waste stream is as analyzed. If, for example, the naval canister arrival schedule were lengthened, further analysis would be needed.

Potential Loss of Subsurface Isolation Barrier and Consequence Analysis (Ref. 2.2.2), Section 6.2.3, states natural ventilation will be established once the first 120 m of drift is filled. Approximately 20 waste packages could fit in the first 120 m of drift, so no more than 20 naval waste packages could possibly be affected by this scenario. If naval waste packages were ratioed with all the TAD waste packages, then there may only be one naval waste package in this 120 m section. This one naval waste package would have to be at or above 11.8 kW and the ventilation would have to be offline for about 25 days before the existing analysis for thermal history were violated (*Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6)). Natural ventilation provides additional margin for all other locations in the repository.

6.2 HUMAN RELIABILITY CALCULATIONS

6.2.1 Development of Probability of Misplacement

The thermal analysis indicates that a single misplacement, under worst case thermal initial conditions, can cause exceedance of naval thermal limits for only 10% of the naval inventory and only 0.2% of the drift length. Therefore, a human error that causes a single misplacement of a waste package with a frequency of less than 1.0 E-04/(0.1 × 0.002) = 0.5 over the preclosure period would cause this occurrence to be beyond Category 2. This analysis demonstrates that a single misplacement is by itself less than 0.5 over the preclosure period. This analysis demonstrates that a double misplacement is less than 1 E-04 over the preclosure period.

An event tree based upon human reliability considerations, (which includes waste form receipt, loading, and emplacement in the drift) has been prepared. Proposed operational approaches at the GROA are used to guide the event tree development. Included in this evaluation are the WFTC and MC&A control aspects, which account for movement of waste forms and the emplacement of waste packages. A logical argument for the HEP estimate is provided.

The calculation of thermal output from the TAD canisters is considered to account for any limiting issues as far as HEP estimates are concerned. The proposed processes and procedures associated with the calculation of thermal outputs of TAD canisters are documented, and the corresponding calculations of the probabilities are included.

In summary, the event trees consider the following:

- Proposed operational handling processes including MC&A and site operational considerations
- Proposed calculation methodology and controls for determining thermal output used in the emplacement calculations

- A summary of the previously mentioned processes to obtain the probability of a single waste package emplacement misplacement with respect to violation of thermal limits in the preclosure and postclosure time periods.

The results of these evaluations are presented in Section 6.2.2.

6.2.2 Results of the Event Tree Development

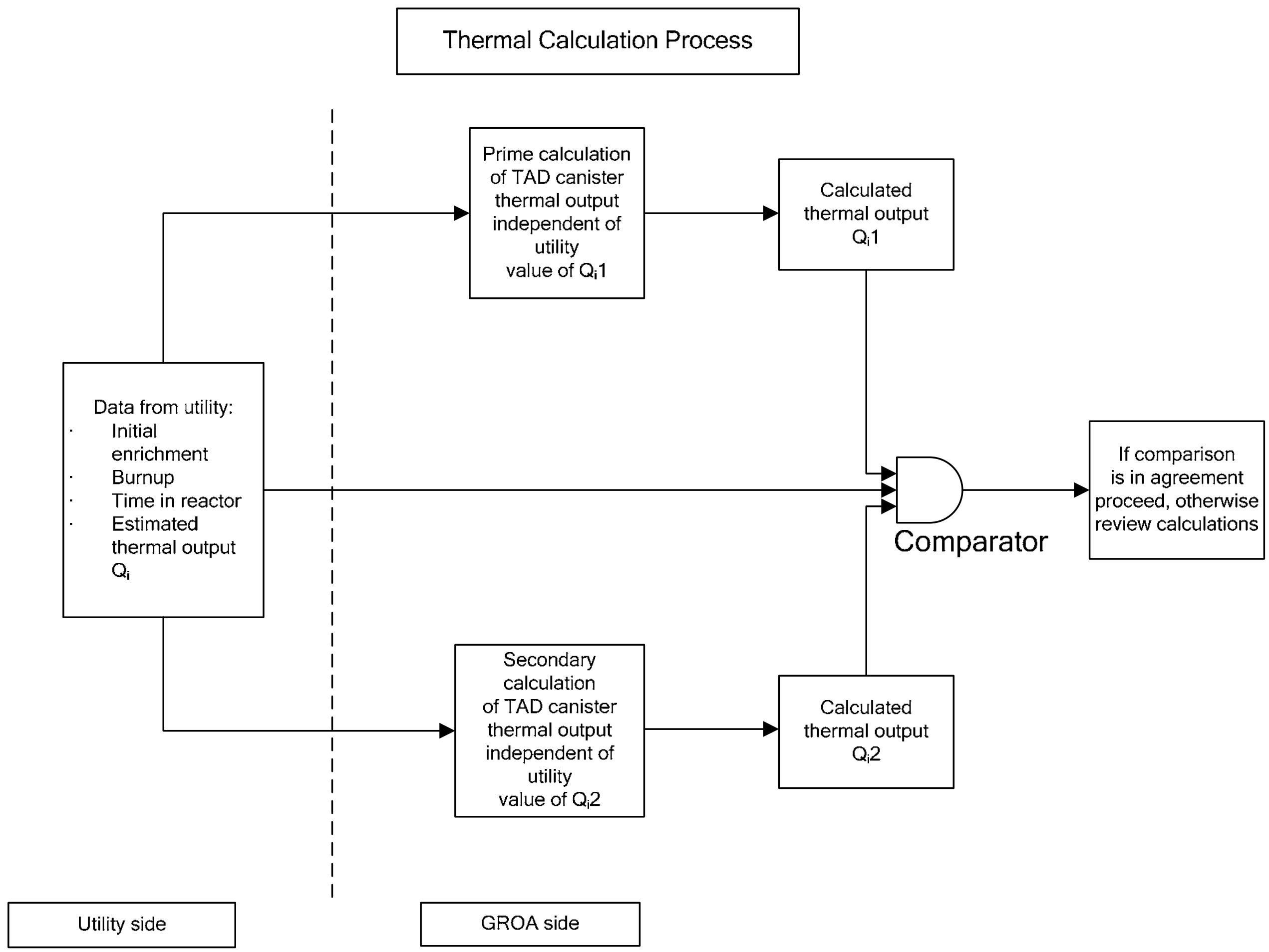
6.2.2.1 Thermal Calculation

6.2.2.1.1 Thermal Calculation Process Evaluations

In order to establish a loading plan that controls the movement of CSNF and high-level radioactive waste once it is received at the repository, it is necessary to determine the controlling characteristics and to establish inventory management directions. The controlling characteristic of most importance is thermal output. Based on thermal output, a TAD canister is either sent to the Aging Facility to decay or for future use in drift thermal blending, or sent directly to be placed in a waste package and emplaced.

The methodology for this loading plan calculation evaluates each waste type for its thermal characteristics and physical properties (e.g., length). The methodology also includes the emplacement loading constraints discussed in Section 4.5.1.2. These constraints include limits on commercial emplacement (i.e., <2.0 kW/m for a seven-waste-package segment and no greater than 18 kW thermal power output per waste package) and naval waste package emplacement (<1.45 kW/m for a seven-waste-package segment and no greater than 11.8 kW thermal power output per waste package adjacent to the naval package). The calculations described in the following sections include meeting each of these constraints as a loading plan is developed for use by the operations group to manage TAD canisters and to ultimately place waste packages in their appropriate locations.

Since this loading plan controls movement of the waste form following arrival at the repository, one of the fundamental errors that can occur in the emplacement of a waste package is to miscalculate its power output and allow the error to carry through the whole process, as described previously, undetected. Accordingly, it is necessary to impose strict controls on this calculation activity. First and foremost, to obtain reliability it must be ensured that the organization is focused on high quality performance. Aside from proper training and supervision, another means necessary to accomplish high-quality is by the separation of the operations and engineering groups in regards to the execution of the entire set of operations associated with emplacement. The proposed process for performance of the calculations is to use the waste form record information associated with each shipment (utility records) and have two separate individuals within ETE perform the calculations for the loading plan (which includes both the commercial and the naval segments). Independently of this process, two people within OTE perform the same calculations via a qualified computer program, and the results of both calculations are cross-checked for verification of accuracy. The input entered into the program is retrieved from the shipping form accompanying the waste form and consists of the following data: initial percentage enrichment, the fuel burnup, the time out of the reactor, and the estimate of thermal output (Qo). The thermal output is used by the GROA engineering staff (ETE and OTE) to develop the loading plan on a package-by-package basis. The loading plan is given to operations as a directive for loading the waste packaged in emplacement drifts in accordance with the established procedures. Figure 17 depicts the process of calculating and checking the validity of the thermal output of the waste forms.



NOTE: GROA = geologic repository operations area; TAD = transportation, aging, and disposal.

Source: Original

Figure 17. Thermal Calculation Process

The OTE and ETE groups carry out the thermal analysis based upon data covering fuel burnup, initial enrichment and length of time of removal from the reactor. A standard tested computer program is used to perform the calculation (Q Code WPLOAD). The human task is to obtain the fuel data and then correctly enter the data into the computer program. The crew of each quality control group checks the numbers associated with the analyzed fuel to determine if they are correct. The final calculated thermal output is checked with another engineer of the same group to ensure that the data and thermal output are correct. If the results show some differences then the total process is reviewed in order to locate the source of the error.

Each calculation performed by the engineer has been identified with a task analysis. In this case, the tasks involved include the following:

- Review cask numbers on the waste form record.
- Perform the analysis by entering key data into computer code to calculate the thermal output.
- Check the thermal output against the other group’s thermal calculation.

Table 10 provides details of the subtasks involved in the calculation of thermal output of waste packages and Table 11 outlines the steps necessary in the determination of waste package emplacement location in the drift.

Table 10. Calculation of Thermal Output of Waste Package

Item	Description
Review cask numbers and data on the manifest	The crew obtains the current shipping manifest that accompanies the waste form. The crew records the thermal power at time of shipment, initial enrichment, burnup, and time out of reactor.
Perform thermal analysis of the waste form	The crew enters the data into the thermal analysis computer and obtains the thermal power at the time of shipment and the decay heat curve for the waste package.
Compare the thermal output with prior estimates	The crew compares the calculated thermal power at the time of emplacement with the shipping records and compares the calculated decay heat curve with the decay heat curve provided by the ETE group. If there are differences, the crew stops work and brings the differences to the attention of the manager for resolution.

Source: Original

Table 11. Determination of Waste Package Emplacement Location in Drift

Item	Description
Select an available waste package	From the number of available waste packages select a candidate waste package
Determine the suitability of the waste package for emplacement	Enter the waste package thermal output into the computer and perform the calculation (Q code WPLOAD) to determine if the emplacement location for the waste package meets thermal criteria in the seven-waste-package drift segment
Send data to the emplacement group	If the waste package meets the criteria send the data to the emplacement operations group about the waste package number and the selected location in a specified drift

Source: Original

6.2.2.1.2 Calculation of HFEs for the Thermal Calculation Process

This task analysis has been quantified using the Swain THERP method (*Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report* (Ref. 2.2.11)). The individual HEPs are estimated in Figure 18. Each subtask of the task analysis is represented in the HRA tree. The process of calculating the thermal output of a waste form is carried out by two separate engineers (Figure 17). There are two engineers in both the ETE and OTE groups. The calculation starts with the data received from outside organizations. Once the thermal output for waste forms is established, the next step is to determine the location of the various forms in the Subsurface Facility drifts. The task analyses of both of these situations are carried out (Tables 10 and 11), and then the corresponding HRA event tree is drawn (Figure 18). In line with the HRA approach taken here, the HRA event tree is populated with data from the *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report* ((Ref. 2.2.11), Chapter 20, principally Tables 10 and 11). Both of these tables relate to reading, checking and recording. For the most part the human errors are likely to be EOCs but could be EOOs.

6.2.2.1.2.1 Single Engineer Calculation

The HRA event tree relates to the operation carried out by one engineer. The overall probability relating to both the calculation checking and the selection of an emplacement location is given by the following equation:

$$HEP = \text{Sum}(HEP_i)\ldots\ldots\ldots_i \text{ from 1 to 6}$$

$$HEP = 1.0E{-3} + 1.0E{-2} + 1.0E{-3} + 1.0E{-3} + 1.0\ E{-2} + 1.0\ E{-3} = 2.4\ E{-2} \quad \text{(Eq. 4)}$$

6.2.2.1.2.2 Two Engineer Calculation

The operation is carried out by two engineers. The combined HEP accounts for the dependency between the two engineers performing the calculation. If the two engineers act completely independently of one another, then the resulting HEP is:

$$HEP = HEP_a \times HEP_b = 5.8\ E{-4} \quad \text{(Eq. 5)}$$

However, in practice, the two engineers do not act independently and there is a degree of dependency between their actions, which is accounted for by the following relationship:

$$HEP = HEP_a \times \beta \times HEP_b$$

$$\text{If } \beta = 5, \text{ then } HEP = 2.9\ E{-3} \quad \text{(Eq. 6)}$$

The β factor is estimated by judgment and based on prior work (*HRA Concepts and Applications Series of Workshops Given at Tsinghai University, Beijing, China May 10th through 12th, 2005* (Ref. 2.2.10), Section 9). There are cognitive connections, computer interfaces, training, and working relationships between the operators, which are normally taken into consideration when estimating the beta factor. However, the exact causal factors are hard to evaluate at this time, since the exact working arrangements are not defined. The range of β values for this condition can be considered to compare with Swain's level of dependence in the zero to low range with the bias towards the low range (*Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report*, (Ref. 2.2.11), Chapter 20). The values of the β distribution go from 1.0 to 10 in the low dependency area.

6.2.2.1.2.3 Two Independent Groups Checking

The checking process is set up so that two independent groups perform the calculation and the results are compared to achieve a high degree of accuracy in the evaluation of the waste form thermal output.

A second checking group is expected to have the same HEP of the following:

$$HEP = 2.9\ E{-3} \quad \text{(Eq. 7)}$$

By combining the two groups, the overall probability is reduced. The effective overall probability is given by the following:

$$2.9\ E{-3} \times \beta \times 2.9\ E{-3} \quad \text{(Eq. 8)}$$

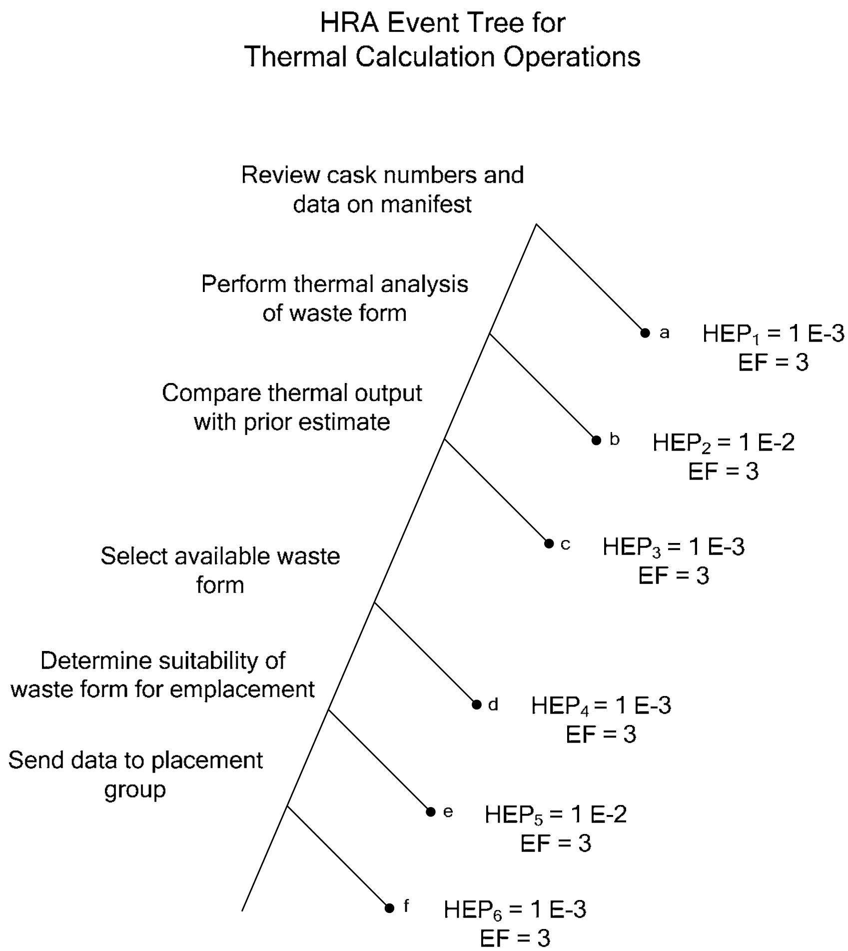
In this case, although the two groups are effectively separate entities, it is difficult to have groups that are entirely independent. A dependency factor of 3 is taken to account for this low degree of dependence between the two groups (Section 4.6.5). The resulting HEP follows:

$$HEP = 2.5\ E{-5} \quad \text{(Eq. 9)}$$

This calculation accounts for all of the steps in the calculation process with the exception of comparing the thermal output with the calculation carried out six months prior to shipping the waste form to the site. This calculation provides an additional check so that errors in the process can be caught and corrected. The net effect is to further reduce the overall HEP. A correction factor of 0.1 is estimated based upon expert judgment consistent with the scale approach documented in the PCSA HRA. This scale indicates that a factor of 0.1 is consistent with an "infrequently fails" situation (highly difficult or challenging; 1 in 10 would fail), which is considered appropriate for the analyzed case. Further, the selection of such a value has been used in earlier probabilistic risk assessment studies (*HRA Concepts and Applications Series of Workshops Given at Tsinghai University, Beijing, China May 10th through 12th, 2005* (Ref. 2.2.10)). Therefore, the HEP for the misload of a single waste package due to thermal output miscalculation follows:

$$HEP = 2.5\ E{-6} \qquad \text{(Eq. 10)}$$

It should be noted that a waste package received one day is unlikely to be emplaced in the Subsurface Facility shortly thereafter. There may be years between entry into the GROA and emplacement in a drift. The calculation of thermal output for a waste form and actual emplacement in the repository could occur during distinct and separate time periods. However, this analysis has focused on the total effect of misplacement due the combination of these events in order to derive an overall HEP value. The naval waste forms are the most likely to match the analytical process carried out in this analysis, since the naval waste forms are emplaced relatively soon after they arrive at the GROA.



$$HEP = (HEP_1 + HEP_2 + HEP_3 + HEP_4 + HEP_5 + HEP_6)$$

$$HEP = 2.4\ E\text{-}2$$

NOTE: The *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report* by Swain and Guttmann (Ref. 2.2.11) was used to compare each task description with an equivalent HEP description. In this particular analysis, the Swain and Guttmann (THERP) method was used based on the fact that their methodology is applicable to this particular circumstance. The HEP values in Chapter 20 were used for the subtask quantification. This figure relates the subtasks to the HEP values and gives the locations of the HEP values within Chapter 20.

[a] *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report.* (Ref. 2.2.11) Chapter 20, Table 10 (2)

[b] (Ref. 2.2.11) Chapter 20, Table 10 (9)

[c] (Ref. 2.2.11) Chapter 20, Table 10 (1)

[d] (Ref. 2.2.11) does not identify a similar item and the HEP value estimated at 1.0 E−3. EF = 3

[e].(Ref. 2.2.11) Chapter 20, Table 10 (9)

[f.] (Ref. 2.2.11) does not identify a similar item and the HEP value estimated at 1.0 E−3. EF = 3

EF = error factor; HEP = human error probability; HRA = human reliability analysis

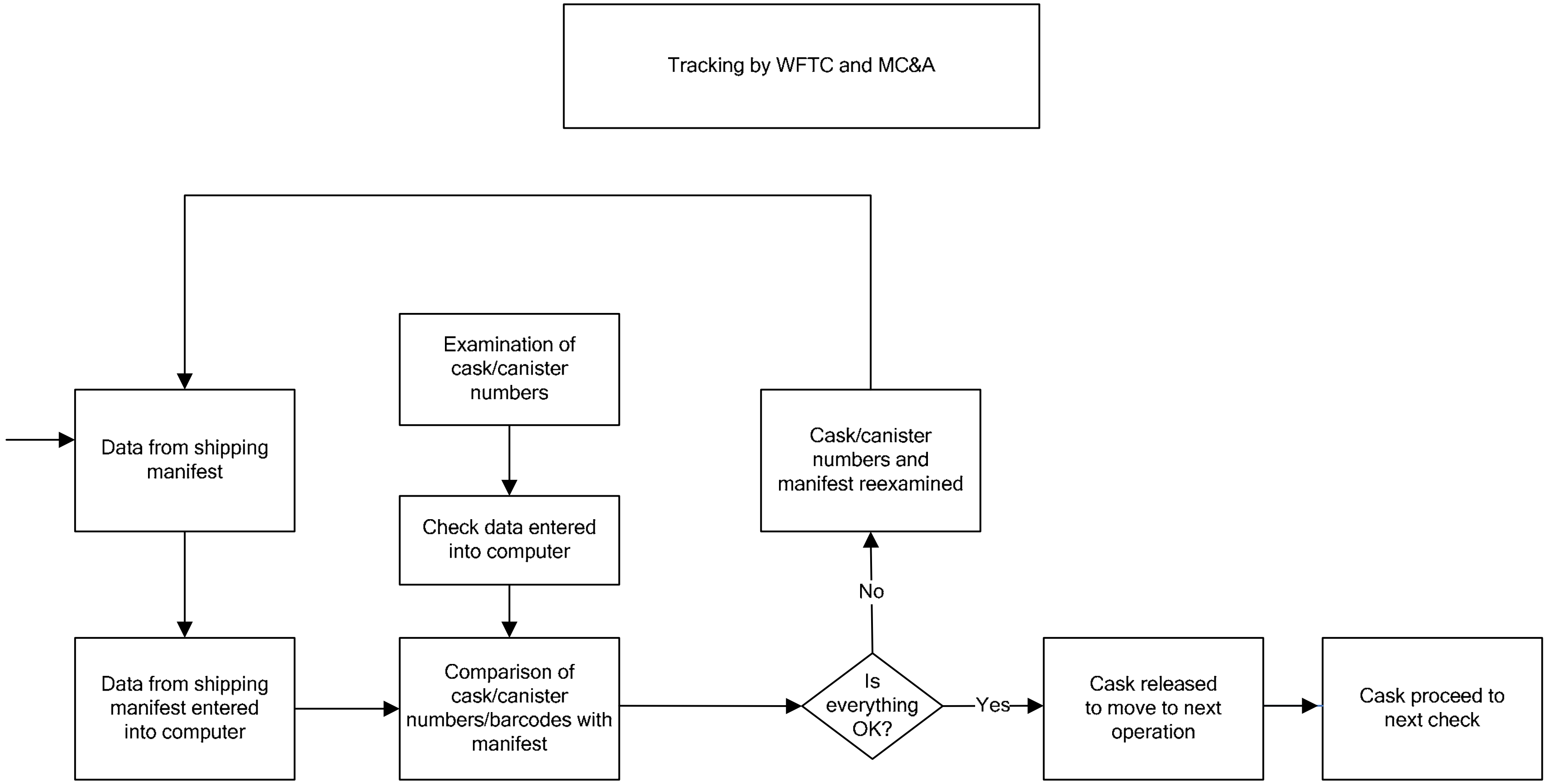
Source: Original

Figure 18. Basic HRA Event Tree for Thermal Calculation Operation

6.2.2.2 Checking Process Calculations

6.2.2.2.1 Checking Process Evaluations

The operations performed by the WFTC group and the MC&A personnel must include an initial inspection and an independent follow-up inspection to ensure quality. Each of these groups must be organized independently of one another in order to utilize the reliability estimates herein. Both WFTC and MC&A approach the receipt, handling, aging, and emplacement of waste in similar manners. In both groups, each organization sets up a control area for checking. For the WFTC group this area is generally a facility or staging area and for MC&A it is a defined set of material balance areas. A simplified flow of operational checkpoints and corresponding zones is displayed in Figure 4. Movement from one facility to another or from one material balance area to another requires two independent checks of each movement by each organization. This movement is reconciled with independent computer listings of the inventory. In the case of the WHF, tracking is accomplished at the assembly level, from one canister to another (Figure 6). Figure 19 shows the general approach to material flow and checking by the WFTC and MC&A groups.



Source: Original

Figure 19. Tracking by WFTC and MC&A

In terms of the checking process, the evaluation of the MC&A and WFTC control processes and the estimation of HEP values are very similar processes to that process mentioned in Section 6.2.2.1. However, the tasks are not identical since one subgroup comes from the WFTC group, and the other subgroup comes from the MC&A organization. A task analysis of the checking process has been set and quantified. In this case, the tasks involved include the following:

- The crew examines cask numbers.
- The crew reads and documents cask numbers.
- The crew enters numbers into the computer.
- The crew checks the numbers against the computer record.

A task analysis was performed on the checking tasks performed by both the WFTC and the MC&A subgroups as an initial step in the quantification process. The task analysis led to the descriptions of each of the subtasks (Table 12) and to the construction of a HRA event tree (Figure 9).

Table 12. Checking of Waste Numbers at a Check Point

Item	Description
Examine the cask numbers	The waste form is in a staging area and the crew remotely views the cask and locates the cask numbers.
Read and document the cask numbers	The crew uses the remote viewing camera to obtain a photograph of the numbers.
Enter the numbers into the computer	The crew reads the photograph and enters the numerical data into the computer
Check the numbers against the computer record	The computer record contains the numerical data for the waste form at the prior control point. The crew compares the number from the prior checkpoint with the number they recorded.
The numbers are OK or the crew reinvestigates the numbers	The crew sees whether or not the numbers cross check. If they do not then the crew investigates further to locate the error.

NOTE: There are a number of different ways to carryout the checking process, which could enhance the reliability of the operation, such as the use of barcodes and remote wireless entry into the monitoring computers. However, the process used here was aimed at giving a realistic HEP.

Source: Original

6.2.2.2.2 Calculation of HFE's for the Checking Process

The process of tracking the waste forms through the GROA is carried out by two groups: the WFTC and the MC&A groups. Each of the groups follows the waste forms as they pass through the GROA from entry to emplacement in a drift. To ensure reliability in the operations, two people are associated with each move of a waste form. The process followed by these groups is outlined in the task analysis (Table 12). The HRA process used was covered in Section 4.6.5 with a representative example to illustrate the process.

6.2.2.2.2.1 Single-Person Checking Operation

The single-person checking operation applies to a single-person checker in either of the WFTC or MC&A groups. The HRA event tree for a single-person checking operation is given in Figure 20. Within a single-person checking operation, there is an element of self-checking, which could lead to a recovery or reduction in the error probability; however, people are not very good at checking themselves, so it is assumed (conservatively) that there is no personal recovery.

For a single-person checking operation, the overall probability is given by the following equation:

$$HEP = \text{Sum}\,(HEP_i) \quad i = 1 \text{ to } 4$$

$$HEP = 1.0\text{ E}{-3} + 3.0\text{ E}{-3} + 1.0\text{ E}{-2} + 1.0\text{ E}{-3} = 1.5\text{ E}{-2} \qquad \text{(Eq. 11)}$$

6.2.2.2.2.2 Two-Group Checking Operation

In each of WFTC and MC&A groups, there are two crew members checking the numbers associated with the waste forms.

In the WFTC group, the crew members are supposed to be independent, but since they have a close working relationship there is a degree of dependency between them. Because of the steps taken to set up the checking process, it is expected that the dependence between the checking groups will be low. In the case where the two groups are organizationally separate, the dependence between the groups is likely to be lower still. The range of β values for this condition can be considered to compare with Swain's level of dependence in the zero to low range with the bias towards the low range (*Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report*, (Ref. 2.2.11), Chapter 20). The values of the β distribution go from 1.0 to 10 in the low dependency area. The HEP for the two separate WFTC checking groups is given by the following equation:

$$HEP = HEP_a \times \beta \times HEP_b$$

$$\text{If } \beta = 5, \text{ then } HEP = 1.125\text{ E}{-3} \qquad \text{(Eq. 12)}$$

The MC&A group operates in a similar fashion to the WFTC group, and their comparable HEP is taken to be the same. Because the operations group and the MC&A groups are separate and because the MC&A group is highly security conscious, the dependency between the two groups should be very small. The β factor is taken to be 3 (Section 4.6.5). The overall HEP is then given by the following equation:

$$HEP = 1.125\text{ E}{-3} \times 3 \times 1.125\text{ E}{-3} = 3.8\text{ E}{-6} \qquad \text{(Eq. 13)}$$

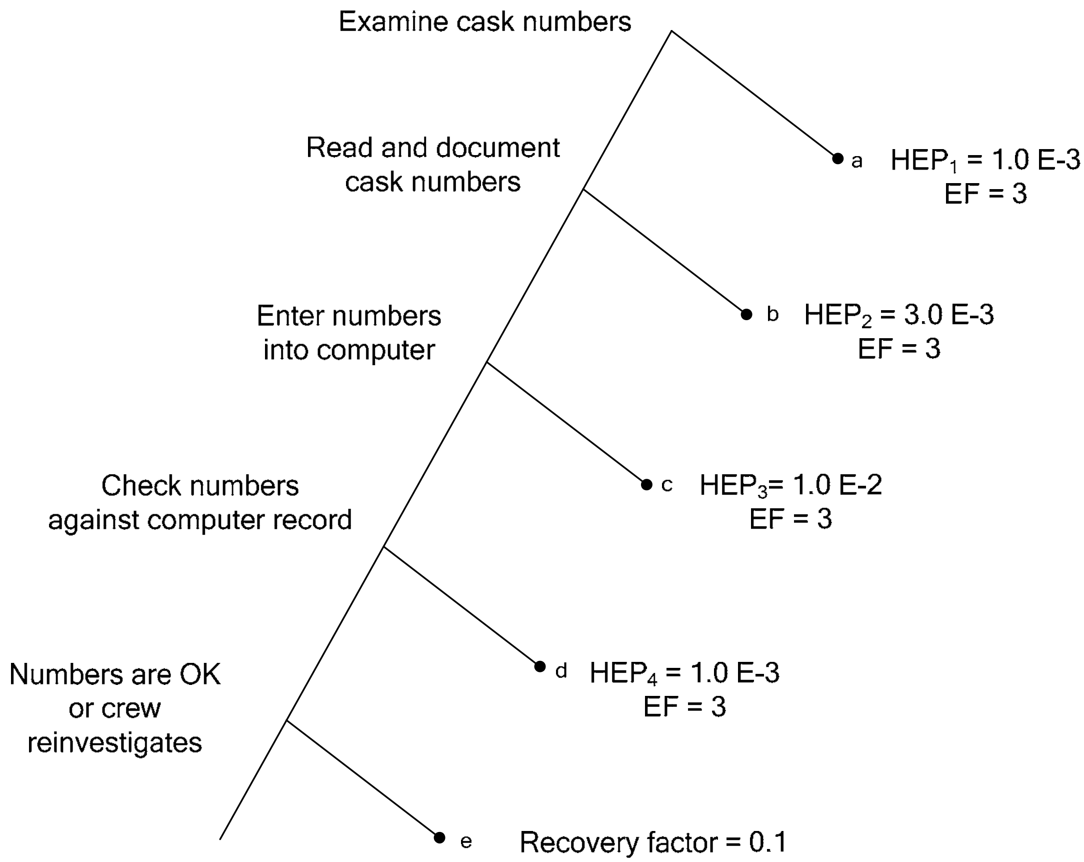
It is assumed that there is no recovery factor for either the WFTC or the MC&A groups until they compare their respective data. If an error is discovered in the process of cross-checking between the groups, the process of transferring the waste forms ceases, and the waste forms are isolated until the problem is resolved. Consistent with the estimation of the correction factor of 0.1 previously discussed, a recovery factor is estimated based upon expert judgment consistent with the scale approach documented in the PCSA HRA. This scale indicates a factor of 0.1 as being consistent with an "infrequently fails" situation (highly difficult or challenging; 1 in 10 would fail), which is considered appropriate for the analyzed case.

The overall HEP for misplacing waste forms is presented in the following equation:

$$HEP = 3.8\ E{-6} \times 0.1 = 3.8\ E{-7} \quad \text{(Eq. 14)}$$

Therefore, the HEP for the misplacement of a single waste package due to the checking process is 3.8 E-7.

Basic HRA Event Tree for Checking Operations



$$HEP = (HEP_1 + HEP_2 + HEP_3 + HEP_4)$$

$$HEP = 1.5\ E\text{-}2$$

NOTE: The *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report* by Swain and Guttmann (Ref. 2.2.11) was used to compare each task description with an equivalent HEP description. In this particular analysis, the Swain and Guttmann (THERP) method was used, based on the fact that the methodology is applicable to this particular circumstance. The HEP values in Chapter 20 are used for the subtask quantification. This figure relates the subtasks to the HEP values and gives the locations of the HEP values within Chapter 20.

[a] (Ref. 2.2.11) Chapter 20, Table 10 (2).

[b] (Ref. 2.2.11) does not identify a similar item and the HEP value estimated at 3.0 E−3. EF = 3.

[c] (Ref. 2.2.11) Chapter 20, Table 10 (9).

[d] (Ref. 2.2.11) Chapter 20, Table 11 (1).

[e] A recovery factor of 0.1 takes into account that there are two groups checking the data.

Source: Original

Figure 20. Basic HRA Event Tree for Checking Operations

6.2.2.3 HEP Uncertainty Evaluation using Monte Carlo Simulation

The prior human reliability calculations (Sections 6.2.2.1.2 and 6.2.2.2.2) were based upon the Swain THERP methodology with the exception of the use of a decision tree approach generating a weighting factor (beta) to account for dependency between human activities. It has been decided to convert the median values estimated by using THERP into mean values more typically used in PRA studies. The multiplication of the HEPs and the incorporation of β into the calculation are accomplished by the use of the Monte Carlo approach. The actions of both checking and thermal teams have been accounted for. The program used for this purpose was Crystal Ball; results from a typical example of the application of Crystal Ball are provided in Attachment A. It was decided at the same time to incorporate a normal distribution for β into the process (Attachment B). The distribution selected was one that encompassed both previously selected β values 3 and 5. The ranges for the normal β distribution selected were 1.0 at 0.1% of the range and 10 at 95% of the range. The mean value for this distribution is 6.9, which is clearly greater than both of previous values of 3 and 5 and thus more conservative than either. This distribution is used in Equations 6 and 13.

Earlier it was pointed out the range for low dependency was about 1 to 10 and this is the range selected for the normal distribution. Also, it was decided to stay with a mean value of 6.9 for all circumstances even though it is believed that some operations are less dependent, but there is sufficient uncertainty within the processes to accept this higher value. Once the final checking and calculation processes have been designed and tested it should be possible to refine the calculations.

While the HEP and β values shown in the previous section were cited as point estimates, they are actually better characterized as distributions to reflect the inherent uncertainty in the estimates. For this reason, an analysis was performed on the human reliability calculations using Crystal Ball software to run Monte Carlo simulations so that the uncertainty could be more thoroughly evaluated. Thus, all HEP values were expressed as lognormal distributions, using the values presented in equations 4 and 13 as medians. The corresponding error factors are given in Figures 18 and 20. From the median and error factors, the sigma and the mean can be calculated using equations 15 and 16 as follows:

$$\sigma = \frac{\ln(EF)}{1.645} \qquad \text{(Eq. 15)}$$

$$mean = median \times e^{\left(\frac{\sigma^2}{2}\right)} \qquad \text{(Eq. 16)}$$

The mean and median were utilized as input to Crystal Ball to define each HEP distribution. The sum of the medians is an output from the application of Swain's HRA tree, but is also an output of the Crystal Ball data. The sum of the means is also an output from the software. The output from the above equations provides the mean and median, but not sigma or the error factor. These values were calculated using equations 17 and 18 as follows:

$$\sigma = \sqrt{2 \times \ln\left(\frac{mean}{median}\right)} \quad \text{(Eq. 17)}$$

$$EF = e^{(1.645 \times \sigma)} \quad \text{(Eq. 18)}$$

Crystal Ball was utilized to square the results from equations 4 and 13 and multiply by β. Because the resultant distribution was lognormal, Equations 17 and 18 were utilized to calculate sigma and the error factor. Beta value distributions cover ranges similar to the values of 3 and 5 selected in the prior calculations. Using a single distribution for the beta factors covers the uncertainty in estimating the reliability of the checking and thermal analysis crews performing their respective tasks.

Finally, the resultant distribution is again multiplied by itself and beta (Equations 8 and 13). Results obtained from Crystal Ball output for each step of the calculation are included in Tables 13 and 14.

Table 13. HFE Calculation Results with Uncertainty for Thermal Miscalculation

	Equation Number	Mean	Median	Error Factor	Sigma	Standard Deviation
Sum (HEP_i)	4	3.0 E-02	2.4 E-02	2.1	0.4	N/A
β	N/A	6.9	6.9	N/A	N/A	4.1
HEP_a × β × HEP_b	6	6.2 E-03	5.1E-03	2.9	0..7	N/A
HEP × β × HEP	8	2.6 E-04	1.7E-04	4.9	1.0	N/A
HEP × β × HEP x 0.1	Including recovery factor	2.6 E-05	1.7E-05	4.9	1.0	N/A

NOTE: The precision of the above results reflect the application of Monte Carlo methods and are not an analytic solution.
HEP = human error probability; N/A = not applicable.

Source: Original.

Table 14. HFE Calculation Results with Uncertainty for Checking

	Equation Number	Mean	Median	Error Factor	Sigma	Standard Deviation
Sum (HEP_i)	11	1.9 E-02	1.5 E-03	2.3	0.5	N/A
β	N/A	6.9	6.9	N/A	N/A	4.1
HEP_a × β × HEP_b	12	2.4 E-03	1.8 E-03	3.5	0.8	N/A
HEP × β × HEP	13	4.0 E-05	2.2 E-05	6.3	1.1	N/A
HEP × β × HEP x 0.1	Including recovery factor	4.0 E-06	2.2 E-06	6.3	1.1	N/A

NOTE: The precision of the above results reflect the application of Monte Carlo methods and are not an analytic solution.
HEP = human error probability; N/A = not applicable.

Source: Original.

6.2.2.4 Overall Probability of Misplacement of a Waste Package

The probability associated with the misplacement of a waste package is composed of two components. One is the placement of a waste package in the wrong location, which could be in the wrong drift or in the wrong position within a drift. The other problem arises with putting a waste package in the right location according to its estimated thermal output when the calculated thermal output is incorrect. Even though this waste package may have been placed in the correct assigned location, it is considered a misplacement since it is not in a thermally suitable location in the drift. The overall probability is given by the sum of these two probabilities.

The probability associated with placing a waste package in the wrong location is 4.0 E−6 per demand. The probability of placing a waste package in the right location, but with the wrong thermal load is 2.6 E−5 per demand. The combined probability of placing a waste package in the wrong location with the wrong thermal load is:

$$4.0\ \text{E}{-6} + 2.6\ \text{E}{-5} = 3.0\ \text{E}{-5} \quad \text{(Eq. 19)}$$

The probability of misplacing two waste packages in the same seven-waste-package segment is very low. Once the misplacement of one waste package occurs, a second misplacement would have to occur in one of the six waste package segments on either side of the misplaced waste package (12 locations). The resulting probability of this occurring can be represented as the first misplacement probability multiplied by the second misplacement probability multiplied by the number of possible locations for the second misplacement. This overall probability is given by:

$$\text{HEP} = 3.0\ \text{E}{-5} \times 3.0\ \text{E}{-5} \times 12 \times 400 = 4.3\ \text{E}{-6} \text{ over the preclosure period} \quad \text{(Eq. 20)}$$

Equation 20 indicates a very low HEP number; however, in risk assessment studies the use of a lower limit is often invoked. In the present calculation a lower limit value was not used since the calculated value was close to the lower limit.

7 RESULTS AND CONCLUSIONS

7.1 THERMAL RESULTS

The effect of off-normal (loss of ventilation) events on naval canister temperatures has been evaluated using a highly conservative approach including a full 30 day loss of HVAC in the surface facilities and another full 30 day loss of ventilation (*Calculation of the Naval Long and Short Waste Package Three-Dimensional Thermal Interface Temperatures* (Ref. 2.2.3)). Calculation of canister temperatures for thermally misloaded drift segments (*Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6)) up to 2.0 kW/m are bounded by the analyzed basis. The analyzed basis includes only 50 years of ventilation which is the minimal ventilation time required. The misload calculations include 65 and 85 years of ventilation which correspond to the minimum ventilation times for TAD waste packages and naval waste packages, respectively, using the limiting waste stream receipt scenario (*Thermal Calculation for Off-Normal Scenarios* (Ref. 2.2.1)). The peak canister temperature for an 8.5 kW naval waste package, erroneously placed in a 2.0 kW/m drift segment between an 18 kW and a 22 kW waste package, at the end of a 30 day complete loss of ventilation is bounded by the normal operating temperatures for the analyzed basis (Figure 15 and Assumption 3.2.2). The peak canister temperature for an 11.8 kW naval waste package in a 1.45 kW/m drift segment between an 11.8 kW and an erroneously placed 22 kW waste package, at the end of 30 days with only natural ventilation is also bounded by the normal operating temperatures for the analyzed basis (Figure 16 and Assumption 3.2.2).

The following thermal results relate to the impact of a single misplacement event on the thermal limits (Section 6.1.9):

1. A single misplacement does not cause a TAD waste package to violate thermal limits so long as ventilation is restored within 30 days (Assumption 3.2.2). This is true with or without natural ventilation (Section 6.1.9).

2. A single misplacement does not cause an 8.5 kW naval waste package to violate thermal limits so long as ventilation is restored within 30 days (Assumption 3.2.2). This is true with or without natural ventilation (Figure 15).

3. An 11.8 kW naval package does not violate thermal limits so long as there is not a misplaced, high power (>11.8 kW) adjacent package (within 6 packages on either side) (Figure 16).

4. A single misplacement may cause an 11.8 kW naval waste package to violate thermal limits if there is no natural ventilation (Figure 16).

5. Natural ventilation is expected once the first 120 m of the first drift are loaded. Hence, a thermal violation will occur only if a naval package greater than 8.5 kW is placed in the first 120 m of the first drift, misplacement of a high power (>11.8 kW) waste package occurs, and there is a loss of forced ventilation (Section 6.1.9).

7.2 MISPLACEMENT RESULTS FOR A SINGLE WASTE PACKAGE

This calculation has evaluated the probability that a misplacement of a waste package might cause a violation of thermal limits. The probabilities related to misplacement are summarized below.

1. Based on the proposed organization division of responsibilities for calculation and development of waste package emplacement loading plans, the probability for misplacement of a waste package due to an error in thermal calculations is 2.6 E−5 (Section 6.2.2.3).

2. The probability of a single misplacement due to an error in operational handling of any waste package is 4.0 E−6 (Section 6.2.2.3).

3. The total combined probability per demand of placing a waste package in the wrong location is 2.6 E−5 + 4.0 E−6 = 3.0 E−5 (Section 6.2.2.4).

7.3 CONCLUSIONS

The only event that may cause a violation of thermal limits is the loading of a naval waste package greater than 8.5 kW into one of the storage locations in the first 120 m of the first emplacement drift and there is a single misplacement event as described in Section 6.1.9. This may create a thermal limit violation because there is not enough heat to drive natural ventilation until the first drift is loaded beyond 120 meters. Combining the insights from the thermal analysis with the human reliability analysis, a probability of a single misplacement causing exceedance of thermal limits may be calculated as follows. The probability of a single naval waste package (>8.5 kW) misplacement in the first 120 m was determined to be the HEP per waste package placement multiplied by a fraction of naval waste packages that exceed 8.5 kW multiplied by the fraction of total drifts multiplied by the total number of waste packages(y) to be placed multiplied by the total naval waste packages/total number of waste packages(y) to be placed, as follows in Equation 21:

$$3.0 \text{ E-5} \times 0.1 \times 0.002 \times y \times 400/y = 2.4 \text{ E-6 over the preclosure period} \qquad \text{(Eq. 21)}$$

Therefore, the probability of a single misplacement causing exceedance of naval waste package thermal limits is beyond Category 2. It was previously shown in Section 6.2.2.4 that the probability of misplacing two naval waste packages is also beyond Category 2.

ATTACHMENT A
RESULTS FROM CRYSTAL BALL MONTE CARLO SIMULATION CODE

The complete output from Crystal Ball is provided to give the reader an insight into the capability of the code. The output shows the number of Monte Carlo trials run per solution. The code is capable of increasing the number of trials if needed. In this case the interest is in the relationship between median and mean and depicting the characteristics of the lognormal distribution; both curves and data sets are given. Also analyzed are cases where medians are multiplied, with or without the use of a dependence factor β (also with a Gaussian probability distribution).

Crystal Ball Report - Full

Simulation started on 1/21/2008 at 9:45:17
Simulation stopped on 1/21/2008 at 9:45:33

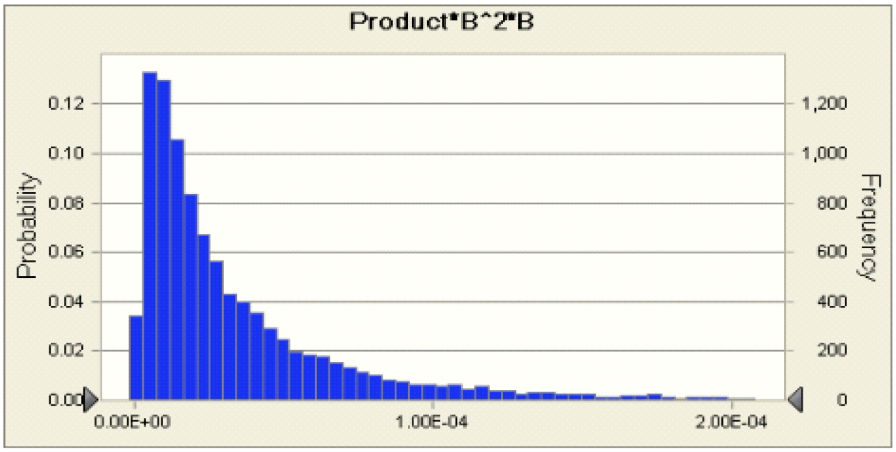
Run preferences:	
Number of trials run	10,000
Monte Carlo	
Random seed	
Run statistics:	
Total running time (sec)	15.86
Trials/second (average)	631
Random numbers per sec	6,307
Crystal Ball data:	
Assumptions	10
Correlations	0
Correlated groups	0
Decision variables	0
Forecasts	3

Forecasts

Forecast: Product*B^2*B

Summary:

Entire range is from -6.14E-06 to 1.32E-03
Base case is 4.03E-05
After 10,000 trials, the std. error of the mean is 6.13E-07



Statistics:	Forecast values
Trials	10,000
Mean	4.00E-05
Median	2.15E-05
Mode	---
Standard Deviation	6.13E-05
Variance	3.76E-09
Skewness	6.45
Kurtosis	80.26
Coeff. of Variability	1.53
Minimum	-6.14E-06
Maximum	1.32E-03
Range Width	1.33E-03
Mean Std. Error	6.13E-07

Forecast: Product*B^2*B (cont'd)

Percentiles:	Forecast values
0%	-6.14E-06
10%	5.11E-06
20%	8.32E-06
30%	1.17E-05
40%	1.60E-05
50%	2.15E-05
60%	2.85E-05
70%	3.93E-05
80%	5.57E-05
90%	8.98E-05
100%	1.32E-03
90%	6.87E-04
100%	1.49E-02

ATTACHMENT B
BETA FACTOR DISTRIBUTION

Median	0.1% Value	95 % Value
6.88	1	10

Mean	Median	SD
6.88	6.87	1.92

Crystal Ball Report - Full

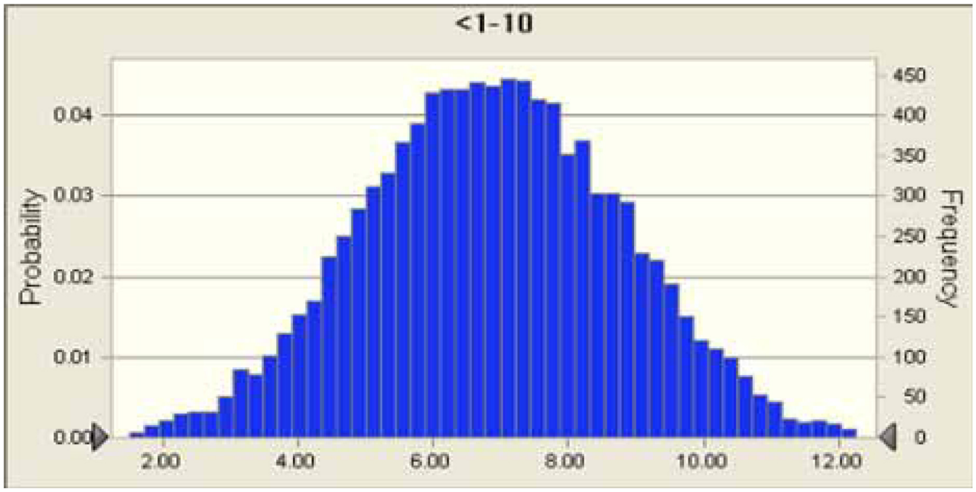
Simulation started on 1/21/2008 at 12:09:35
Simulation stopped on 1/21/2008 at 12:09:44

Run preferences:	
Number of trials run	10,000
Monte Carlo	
Random seed	
Run statistics:	
Total running time (sec)	9.10
Trials/second (average)	1,099
Random numbers per sec	5,495
Crystal Ball data:	
Assumptions	5
Correlations	0
Correlated groups	0
Decision variables	0
Forecasts	5

Forecast: <1-10

Summary:

Entire range is from 0.05 to 15.18
Base case is 6.69
After 10,000 trials, the std. error of the mean is 0.02



Statistics:		Forecast values
	Trials	10,000
	Mean	6.88
	Median	6.87
	Mode	---
	Standard Deviation	1.92
	Variance	3.68
	Skewness	0.0420
	Kurtosis	2.93
	Coeff. of Variability	0.2787
	Minimum	0.05
	Maximum	15.18
	Range Width	15.12
	Mean Std. Error	0.02

Forecast: <1-10 (cont'd)

Percentiles:		Forecast values
	0%	0.05
	10%	4.44
	20%	5.24
	30%	5.85
	40%	6.37
	50%	6.87
	60%	7.36
	70%	7.89
	80%	8.53
	90%	9.36
	100%	15.18

BSC	**Calculation/Analysis Change Notice** *Complete only applicable items.*	1. QA: QA 2. Page 1 of 6

3. Document Identifier:	4. Rev.:	5. CACN:
000-PSA-MGR0-02500-000	00A	001

6. Title:
Waste Package Misplacement Probability

7. Reason for Change:

Increase resolution of equations and analysis to obtain total probability of misplacements that violate canister thermal limits.

8. Supersedes Change Notice: ☐ Yes If, Yes, CACN No.: ______ ☒ No

9. Change Impact:

Inputs Changed:	☐ Yes	☒ No	Results Impacted:	☒ Yes	☐ No
Assumptions Changed:	☐ Yes	☒ No	Design Impacted:	☐ Yes	☒ No

10. Description of Change:

Delete the last paragraph in Section 6.2.2.4 and replace all of Section 7 as indicated in the attached text.

11. REVIEWS AND APPROVAL

Printed Name	Signature	Date
11a. Originator: Michael Frank	[signature]	4/04/08
11b. Checker: Pierre Macheret	P. Macheret	04/04/08
11c. EGS: Abdelhalim Alsaed	[signature]	4/4/08
11d. DEM: Thomas Dunn	Thomas Dunn	4/4/08
11e. Design Authority: Barbara Rusinko	[signature]	4/4/08

Delete the last paragraph in Section 6.2.2.4, Page 66, as follows:

~~The probability of misplacing two waste packages in the same seven-waste-package segment is very low. Once the misplacement of one waste package occurs, a second misplacement would have to occur in one of the six waste package segments on either side of the misplaced waste package (12 locations). The resulting probability of this occurring can be represented as the first misplacement probability multiplied by the second misplacement probability multiplied by the number of possible locations for the second misplacement. This overall probability is given by:~~

~~HEP = 3.0 E–5 × 3.0 E–5 ×12 × 400 = 4.3 E–6 over the preclosure period (Eq. 20)~~

~~Equation 20 indicates a very low HEP number; however, in risk assessment studies the use of a lower limit is often invoked. In the present calculation a lower limit value was not used since the calculated value was close to the lower limit.~~

Replace all of Section 7, pp. 67 and 68, with the following text:

7 RESULTS AND CONCLUSIONS

7.1 THERMAL RESULTS

The effect of off-normal (loss of ventilation) events on naval canister temperatures has been evaluated using a highly conservative approach including a full 30 day loss of HVAC in the surface facilities and another full 30 day loss of ventilation (*Calculation of the Naval Long and Short Waste Package Three-Dimensional Thermal Interface Temperatures* (Ref. 2.2.3)). Calculations of canister temperatures for thermally misloaded drift segments (*Temperatures in an "As-Loaded" and Thermally-Misloaded Drift Segment* (Ref. 2.2.6)) up to 2.0 kW/m are bounded by the analyzed basis. The analyzed basis includes only 50 years of ventilation which is the minimal ventilation time required. The misload calculations include 65 and 85 years of ventilation that correspond to the minimum ventilation times for TAD waste packages and naval waste packages, respectively, using the limiting waste stream receipt scenario (*Thermal Calculation for Off-Normal Scenarios* (Ref. 2.2.1)). The peak canister temperature for an 8.5 kW naval waste package, erroneously placed in a 2.0 kW/m drift segment between an 18 kW and a 22 kW waste package, at the end of a 30 day complete loss of ventilation is bounded by the normal operating temperatures for the analyzed basis (Figure 15 and Assumption 3.2.2). The peak canister temperature for an 11.8 kW naval waste package in a 1.45 kW/m drift segment between an 11.8 kW and an erroneously placed 22 kW waste package, at the end of 30 days with only natural ventilation is also bounded by the normal operating temperatures for the analyzed basis (Figure 16 and Assumption 3.2.2).

The following thermal results relate to the impact of a single misplacement event on the thermal limits (Section 6.1.9):

1. A single misplacement does not cause a TAD waste package to violate thermal limits so long as ventilation is restored within 30 days (Assumption 3.2.2). This is true with or without natural ventilation (Section 6.1.9).

2. A single misplacement does not cause an 8.5 kW naval waste package to violate thermal limits so long as ventilation is restored within 30 days (Assumption 3.2.2). This is true with or without natural ventilation (Figure 15).

3. An 11.8 kW naval waste package does not violate thermal limits so long as there is not a misplaced, high power (>11.8 kW) adjacent waste package (within 6 packages on either side) (Figure 16).

4. A single misplacement may cause an 11.8 kW naval waste package to violate thermal limits if there is no natural ventilation (Figure 16).

5. Natural ventilation is expected once the first 120 m of the first drift are loaded. Hence, a thermal violation will occur only if a naval waste package greater than 8.5 kW is placed in the first 120 m of the first drift with a commercial waste package of high power (>11.8 kW), and there is a loss of forced ventilation (Section 6.1.9).

The above five conclusions are derived from bounding initial conditions. The probabilistic analysis below does not include the likelihood of these initial conditions actually occurring.

7.2 MISPLACEMENT RESULTS FOR A SINGLE WASTE PACKAGE

This calculation has evaluated the probability that a misplacement of a waste package might cause a violation of thermal limits. The probabilities related to misplacement are summarized below.

1. Based on the proposed organization division of responsibilities for calculation and development of waste package emplacement loading plans, the probability for misplacement of a waste package due to an error in thermal calculations is 2.6 E−5 (Section 6.2.2.3).

2. The probability of a single misplacement due to an error in operational handling of any waste package is 4.0 E−6 (Section 6.2.2.3).

3. The total combined probability per demand of placing a waste package in the wrong location is 2.6 E−5 + 4.0 E−6 = 3.0 E−5 (Section 6.2.2.4).

7.3 CONCLUSIONS

The only event that may cause a violation of thermal limits is the loading of a naval waste package greater than 8.5 kW into a segment in the first 120 m of the first emplacement drift, using initial conditions of 1.45 kW/m with a segment that includes a commercial waste package at greater than 11.8 kW (Section 6.1.9). This event may create a thermal limit violation because there is not enough heat to drive natural ventilation until the first drift is loaded beyond 120 m. Note that commercial waste packages are used for all non-naval waste packages because they represent the majority of waste packages and the distribution of thermal output used in Section 6.1.9 yields generally higher thermal output than co-disposal waste packages that contain high level waste, multicanister overpack, and/or DOE standard canisters. Combining the insights from the thermal analysis with the human reliability analysis, a probability of a single misplacement causing exceedance of thermal limits may be calculated as follows. If at least a 1.45 kW/m linear power density is taken as a probability of one, then the above initial conditions lead to only one situation to analyze. The situation is that of emplacing a greater than 11.8 kW commercial waste package with a naval SNF canister greater than 8.5 kW within 13 waste packages (e.g., the misplaced naval waste package or hot commercial waste package with the surrounding 6 on either side containing the other one). Using a random placement policy, there are 20 possible positions of a naval waste package (or a hot commercial waste package) in the first 120 m. The probability of this situation may be calculated as the product of the following factors (Equations 20 and 21):

$$p(\text{NSNF} > 8.5 \text{ and CSNF} > 11.8 \text{ kW and linear power} > 1.45 \text{ kW/m}) = \text{HEP} \times D \times p(\text{CSNF} > 11.8 \text{ kW}) \times p(\text{NSNF}) \times p(\text{NSNF} > 8.5 \text{ kW/NSNF}) \qquad \text{(Eq. 20)}$$

- HEP = the HEP per waste package placement = 3E-05. The HEP expresses the probability of misplacement of a waste package independent of causing a violation of thermal limits.

- D = the number of misplacement opportunities for a naval waste package misplacement in a 7 segment group = 12

- p(CSNF > 11.8 kW) = the conditional probability > 11.8 kW commercial waste package exists in the segment = 0.67 (This is the fraction of commercial waste packages greater than 11.8 kW.)

- p(NSNF) = the conditional probability that a naval waste package is placed in this segment = 0.04 × 20 = 0.8 (This is the fraction of 400 naval waste packages over the total population of approximately 10,000 waste packages times the number of opportunities for a naval waste package to be placed in the first 120 m.)

- p(NSNF>8.5kW/NSNF) = the conditional probability that the naval waste package is greater than 8.5 kW = 0.1 (This is the fraction of naval waste packages over 8.5 kW.)

Then,

$$p(\text{NSNF} > 8.5 \text{ and CSNF} > 11.8\text{kW and linear power} > 1.45 \text{ kW/m}) = 3\text{E-}05 \times 12 \times 0.67 \times 0.8 \times 0.1 = 2\text{E-}05 \qquad \text{(Eq. 21)}$$

Suppose that it is known with certainty that a naval waste package will be placed in that segment. Then the factor of 0.8 is removed and the probability is 2.5E-05. Note that the analysis is independent of the order. In other words, Equations 20 and 21 apply to either a naval waste package greater than 8.5 kW or a commercial waste package greater than 11.8 kW being emplaced first. Therefore, the probability of a configuration causing exceedance of naval waste package thermal limits is beyond Category 2.

The analysis for two misplacements can be done simply and conservatively by calculating the probability of two placements involving at least one hot commercial waster package in the same seven package segment, anywhere in the drifts, regardless of the heat output of the naval waste package.

There are three situations to include: 1) one naval waste package and one hot commercial waste package are placed; 2) two naval waste packages are placed with a hot commercial waste package correctly placed; and 3) two hot commercial waste packages are misplaced with a naval waste package correctly in place. Once the misplacement of one waste package occurs, a second misplacement would have to occur in one of the six waste package segments on either side of the misplaced waste package (12 locations).

Situation 1

The probability of misplacement of one hot commercial waste package and one naval waste package is sought (Equations 22 through 25). The results are order independent. As above and as demonstrated below, it does not matter which is misplaced first. Once a misplacement occurs, the combination of opportunities for the second misplacement is n!/[r!(n-r)!]. In this situation, n = 12 and r = 1, because 1 has already been misplaced. Therefore, D_2 in Equations 22 and 24 = 12.

$$P(\text{Double misplacement} - 1a) = HEP \times D_C \times p(CSNF > 11.8\ kW) \times HEP \times D_2 \times p(NSNF1) \quad (\text{Eq. } 22)$$

$$P(\text{Double misplacement} - 1a) = (3\ E\text{-}05)^2 \times 10000 \times 0.96 \times 0.67 \times 12 \times 0.04 = 3E\text{-}06 \quad (\text{Eq. } 23)$$

$$P(\text{Double misplacement} - 1b) = HEP \times D_N \times HEP \times D_2 \times p(CSNF > 11.8\ kW) \times p(CSNF1) \quad (\text{Eq. } 24)$$

$$P(\text{Double misplacement} - 1b) = (3\ E\text{-}05)^2 \times 10000 \times 0.04 \times 12 \times 0.67 \times 0.96 = 3E\text{-}06 \quad (\text{Eq. } 25)$$

where,

D_C = number of commercial waste package = 10000 × 0.96

D_N = number of naval waste package = 10000 × 0.04

P(NSNF1) = probability that misplaced waste package is a naval SNF = 0.04

P(CSNF1) = probability that misplaced waste package is a commercial SNF = 0.96

Situation 2

A hot commercial SNF waste package is correctly placed and the probability of misplacing two naval waste packages in the surrounding 12 is sought (Equations 26 and 27). In this case, there are n!/[r!(n-r)!] combinations because n = 12 and r = 2. Therefore, D_2 in Equation 26 = 66.

$$P(\text{Double misplacement} - 2) = HEP \times HEP \times D_2 \times p(NSNF1)^2 \times D_c \times p(CSNF > 11.8\text{ kW}) \quad \text{(Eq. 26)}$$

$$P(\text{Double misplacement} - 2) = (3E\text{-}05)^2 \times 66 \times (0.04)^2 \times 9600 \times 0.67 = 6E\text{-}07 \quad \text{(Eq. 27)}$$

Situation 3

A naval waste package is correctly placed and the probability of placing two hot commercial waste packages in the surrounding 12 is sought (Equations 28 and 29). In this case, there are n!/[r!(n-r)!] combinations because n = 12 and r = 2. Therefore, D_2 in Equation 28 = 66.

$$P(\text{Double misplacement} - 2) = HEP \times HEP \times D_2 \times p(CSNF > 11.8\text{ kW})^2 \times p(CSNF1)^2 \times D_N \quad \text{(Eq. 28)}$$

$$P(\text{Double misplacement} - 2) = (3E\text{-}05)^2 \times 66 \times 0.67^2 \times (0.96)^2 \times 400 = 1E\text{-}05 \quad \text{(Eq. 29)}$$

The total probability of double misplacement is conservatively taken to be the sum of Equations 23, 25, 27, and 29, which is 2E-05 over the preclosure period. The conservatism stems from the interpretation that Situations 1a and 1b are mutually exclusive. In such a case, summing the two probabilities is appropriate. However, an alternative interpretation holds that Situation 1 will occur with 96% of the misplacements and Situation 2 will occur with 4% of the misplacements. The latter interpretation produces a lower total probability of double misplacements. Double misplacements are, therefore, beyond Category 2 and the sum of single and double misplacements are beyond Category 2.