BSC

Design Calculation or Analysis Cover Sheet

Complete only applicable items.

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2. Page: 1 of 64

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Subsurface Fire Exposure Calculation

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8. Notes/Comments
This document replaces the *Subsurface Fire Exposure Calculation,* 800-00C-PF00-00100-000-00A that was cancelled 10/18/2006. Significant design changes to the transportation system and the site plan have been implemented since the original issue of the document requiring major changes in the calculation.

Attachments	Total Number of Pages
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RECORD OF REVISIONS

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DISCLAIMER

The calculations contained in this document were developed by the Bechtel SAIC Company, LLC (BSC) and are intended solely for the use of BSC in its work for the Yucca Mountain Project.

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ACRONYMS AND ABBREVIATIONS

ACRONYMS

BSC	Bechtel SAIC Company, LLC
DBF	design basis fire
DOE	U.S. Department of Energy
GROA	geologic repository operations area
HRR	heat release rate
IEEE	Institute of Electrical and Electronics Engineers
IOM	interoffice memorandum
ITS	important to safety
ITWI	important to waste isolation
LHD	load-haul-dump
MRC	maintenance railcar
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
SFPE	Society of Fire Protection Engineers
SSC	structure, system or component
TEV	transport and emplacement vehicle
WP	waste package

ABBREVIATIONS

(with readily available conversions as appropriate)

C	Celsius
cfm	cubic feet per minute (1-cfm = $4.72 \cdot 10^{-4}$-m³/s)
ft	feet (1-ft = 0.3048-m)
gal	gallon (1-gal = 3.7853-l)
K	Kelvin
kg	kilogram (1-kg = 2.2046-lb)
kJ	kilojoule
kW	kilowatt

l	liter (1-l = 0.26418-gal)(1-l = 0.001-m^3)
lb	pound (1-lb = 0.45359-kg)
m	meter (1-m = 3.2808-ft)
min	minute
m^3/s	cubic meters per second (1- m^3/s = 2119-cfm)
MJ	megajoule
MW	megawatt
s	second

TERM DEFINITIONS

Burning rate or mass loss rate-The mass rate of solid or liquid fuel vaporized and burned. It is denoted as $\dot{m}''$ and expressed as mass flux or mass burning rate per unit area (kg/m²·s). (Reference 2.2.19, Section 3.1)

Emissivity-The fraction of radiative energy (0 to 1) emitted in relation to the maximum possible emission from a surface, given the symbol, ε. (A black body is considered a perfect radiator with an emissivity $\varepsilon = 1$). (Reference 2.2.19, Section 7.1)

Emissive power of flame-The turbulent mixing inside the fire plume causes the temperature within the flame to vary. Consequently, experimental data has been correlated to enable the calculation of the flame radiation/heat transfer to external targets in-terms-of an average emissive power of the flame. For that correlation, the flame is assumed a cylindrical, black body, homogeneous radiator with an average emissive power over the whole of the flame, which is significantly less than the emissive power that can be attained locally. Emissive power of the flame is a function of its diameter (kW/m²).

Flame height-The mean flame height, or flame height, marks the elevation in the flame where the combustion reactions are essentially complete and the inert fire plume can be considered to begin.

Flashover-The transition from the fire growth period to the fully developed stage in the enclosure fire development. The formal definition from the International Standards Organization (ISO) is: "the rapid transition to a state of total surface involvement in a fire of combustible material within an enclosure." In fire-safety engineering the word is used to indicate the demarcation point between two stages of a compartment fire, i.e., pre-flashover and post-flashover. Flashover is usually considered to occur when the upper gas layer temperature is in the range 500ºC to 600ºC. (Reference 2.2.19, Section 2.1)

Heat of combustion-A measure of how much energy is released when a unit mass of material combusts, typically given in kJ/kg. (Reference 2.2.19, Section 3.1)

Heat release rate-When an object burns it releases a certain amount of energy per unit time, usually given in kW (=kJ/s) and denoted $\dot{Q}$. (Reference 2.2.19, Section 3.1)

Hot gas layer-As smoke and hot gases are released from the fire they rise to the compartment ceiling in a buoyant plume and begin to form a layer. Then, as the fire produces additional smoke and hot gases they are entrained into the plume, causing the layer to increase in size and descend towards the compartment floor. The hot gas layer will transfer heat to targets within the layer.

Plume-When a mass of hot gases is surrounded by colder gases, the hotter and less dense mass will rise upward due to the density difference, or rather, due to buoyancy. This is what happens above a burning fuel source and the buoyant flow, including any flames, is referred to as a fire plume. (Reference 2.2.19, Section 4.1)

Target-The object of concern that is receiving the heat energy being transferred from the fire.

Ventilation-controlled fire-As the fire grows it may become ventilation-controlled when there is not enough oxygen available to combust most of the pyrolyzing fuel. The energy release rate of the fire is then determined by the amount of oxygen that enters the enclosure openings. (Reference 2.2.19, Section 2.1)

1. PURPOSE

1.1 OBJECTIVE

The objective of this calculation is to quantify the effects of fire in specific areas of the Geologic Repository Operations Area (GROA). The three fire exposure scenarios postulated in this calculation (Section 6) are:

- Surface Transit Fire Exposure (Section 6.1)
- Subsurface Repository Emplacement Area Fire Exposure (Section 6.2)
- Subsurface Repository Development (Construction) Area Fire Exposure (Section 6.3).

1.2 SCOPE

This document calculates fire parameters, such as, heat release rate (HRR), temperature increase, and fire duration for the postulated fire exposures. The calculation is limited to the targets shown in Table 1 for each of the postulated scenarios.

Table 1. Description of Fire Exposure Target

Fire Exposure Scenario	Target
Surface Fires	Exterior surface of Transport and Emplacement Vehicle (TEV) shielding (Waste Package (WP) located inside)
Subsurface Fire – Repository Emplacement Area	Exterior surface of TEV shielding (WP located inside); WP emplaced in an emplacement drift
Subsurface Fire – Development (Construction) Area	Ventilation/Isolation Barrier separating Development Area from Repository Operations Area

Results from this calculation are anticipated for use, as applicable, to support the Preclosure Safety Organization and the Engineering Fire Hazard Analyses.

1.3 LIMITATIONS

The inputs to and results from this calculation are based on levels of information that can be described as conceptual. The fires modeled may or may not occur as described herein depending on the manner of ignition, variations in combustible geometry, and ventilation conditions during the event and any attempts at hazard mitigation or fire fighting. Calculation results represent a potential fire outcome based on the simplified fire model used. The results of this calculation may be judged as defining a fire condition to the locations modeled by the prescribed input values and the capability of the model to analyze fire effects.

The level of completion of design is changing. This calculation documents the information available at the time of document preparation (Assumption 3.2.3). During detailed design when additional design information is available, this calculation may require updating.

Where drawing information is insufficient, additional typical details that would be anticipated are assumed as a given for the parameter of concern. This allows a calculation of fire effects to be determined where sufficient information is not available. Calculation revisions may be planned during the detail design phase if the significant deviation occurs between assumptions and finalized parameters.

The effects of an explosion adjacent to any inhabited GROA facility or public highway are not modeled herein. During repository operations explosives use and storage would be limited to construction activities at the south portal or north construction portal. Since the separation distance from these facilities to the GROA facility greatly exceeds the minimum of 610-m (2,000-ft), required by code (Reference 2.2.17, Table 3304.5.2(2)), modeling is not needed.

2. REFERENCES

2.1 PROCEDURES/DIRECTIVES

2.1.1 EG-PRO-3DP-G04B-00037, Rev. 8. *Calculations and Analyses*. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20070420.0002.

2.2 DESIGN INPUTS

This section identifies and documents technical product inputs and sources of input used in the development of this document.

2.2.1 10 CFR 71. 2006. Energy: Packaging and Transportation of Radioactive Material. Internet Accessible. [DIRS 176575]

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2.2.8 BSC 2007. *Technical Report on Nuclear Facility Fire Heat Release Rates*. 000-30R-FP00-00100-000-000. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20070329.0014.

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2.2.10 BSC 2007. *Turnout Design and Configuration.* 800-KMC-SSD0-00900-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20070625.0041.

2.2.11 Buchanan, A.H. 2002. *Structural Design for Fire Safety.* New York, New York: John Wiley & Sons. TIC: 256047. ISBN: 0-471-88060-X. [DIRS 168701]

2.2.12 Chagnon, C.W. 2004. "Naval SNF Waste Package Temperatures During a Fire." Interoffice memorandum from C.W. Chagnon (BSC) to D.C. Richardson, March 22, 2004, 0322040858. ACC: MOL.20040414.0090. [DIRS 168469]

2.2.13 Collins, H.E.; Levine, S.; Minners, W.; Moore, V.A.; Panciera, V.W.; and Seyfrit, K.V. 1976. *Recommendations Related to Browns Ferry Fire.* NUREG-0050. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20040511.0076. [DIRS 169008]

2.2.14 DOE G 440.1-5. 1995. *Implementation Guide for Use with DOE Orders 420.1 and 440.1 Fire Safety Program.* Washington, D.C.: U.S. Department of Energy. ACC: MOL.20050518.0094. [DIRS 144423]

2.2.15 Drysdale, D. 2003. *An Introduction to Fire Dynamics.* Second Edition. Chichester, West Sussex, England: John Wiley & Sons. TIC: 255852. ISBN: 0-471-97291-6. [DIRS 168771]

2.2.16 Heselden, A.J.M. 1976. "Studies of Fire and Smoke Behaviour Relevant to Tunnels." *Proceedings of the Second International Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels, held at Churchill College, Cambridge, England, 23rd – 25th March, 1976.* Pages J1-1 through J1-18. Cranfield, Bedford, England: BHRA Fluid Engineering. TIC: 250745. [DIRS 155953]

2.2.17 ICC (International Code Council) 2006. *2006 International Fire Code.* Country Club Hills, Illinois: International Code Council. TIC: 258068. ISBN: 1-58001-255-8. [DIRS 176293]

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2.2.19 Karlsson, B. and Quintiere, J.G. 2000. *Enclosure Fire Dynamics.* Environmental and Energy Engineering Series. Boca Raton, [Florida]: CRC Press. TIC: 250798. ISBN: 0-8493-1300-7. [DIRS 155952]

2.2.20 Moseley, N.C. 1975. Tennessee Valley Authority Browns Ferry Units 1 and 2, Fire of March 22, 1975. Letter from N.C. Moseley (NRC) to J.E. Watson (Tennessee Valley Authority), July 28, 1975, 50-259/75-1, 50-260/75-1, with enclosures. ACC: MOL.20040511.0079. [DIRS 169009]

2.2.21 NFPA 80A. 2006. *Recommended Practice for Protection of Buildings from Exterior Fire Exposures.* 2007 Edition. Quincy, Massachusetts: National Fire Protection Association. TIC: 258739. [DIRS 177989]

2.2.22 Nowlen, S.P.; Kazarians, M; and Wyant, F. 2001. *Risk Methods Insights Gained from Fire Incidents.* NUREG/CR-6738. Washington, DC: U. S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research. ACC: MOL.20040511.0073. [DIRS 167063]

2.2.23 Ohlemiller, T.J. and Cleary, T.G. 1998. *Aspects of the Motor Vehicle Fire Threat from Flammable Liquid Spills on a Road Surface*. NISTIR 6147. Gaithersburg, Maryland: U.S. Department of Commerce, National Institute of Standards and Technology. TIC: 250741. [DIRS 155967]

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2.3 DESIGN CONSTRAINTS

None.

2.4 DESIGN OUTPUTS

This calculation/analysis will be used as input for Preclosure Safety Organization and Engineering Organization calculations/analyses.

3. ASSUMPTIONS

3.1 ASSUMPTIONS REQUIRING VERIFICATION

These assumptions are being tracked in CalcTrac.

3.1.1 Surface Separation Distances

Assumption: The following separation distances are scaled from the partial site plan depicted here as Figure 1 and are assumed suitable for their intended use in this calculation.

3.1.1.1 TEV Rail Pathway to Site Buildings

- 34-m (112-ft) to Heavy Equipment Maintenance Facility Building Face (Area 220)
- 85-m (279-ft) to Wet Handling Facility Building Face (Area 050)
- 61-m (201-ft) to Diesel Generator Facility Building Face (Area 26D)
- 76-m (248-ft) to Canister Receipt and Closure Facility 1 Exit Vestibule (Area 060)
- 90-m (296-ft) to Low-Level Waste Facility Building Face (Area 160)

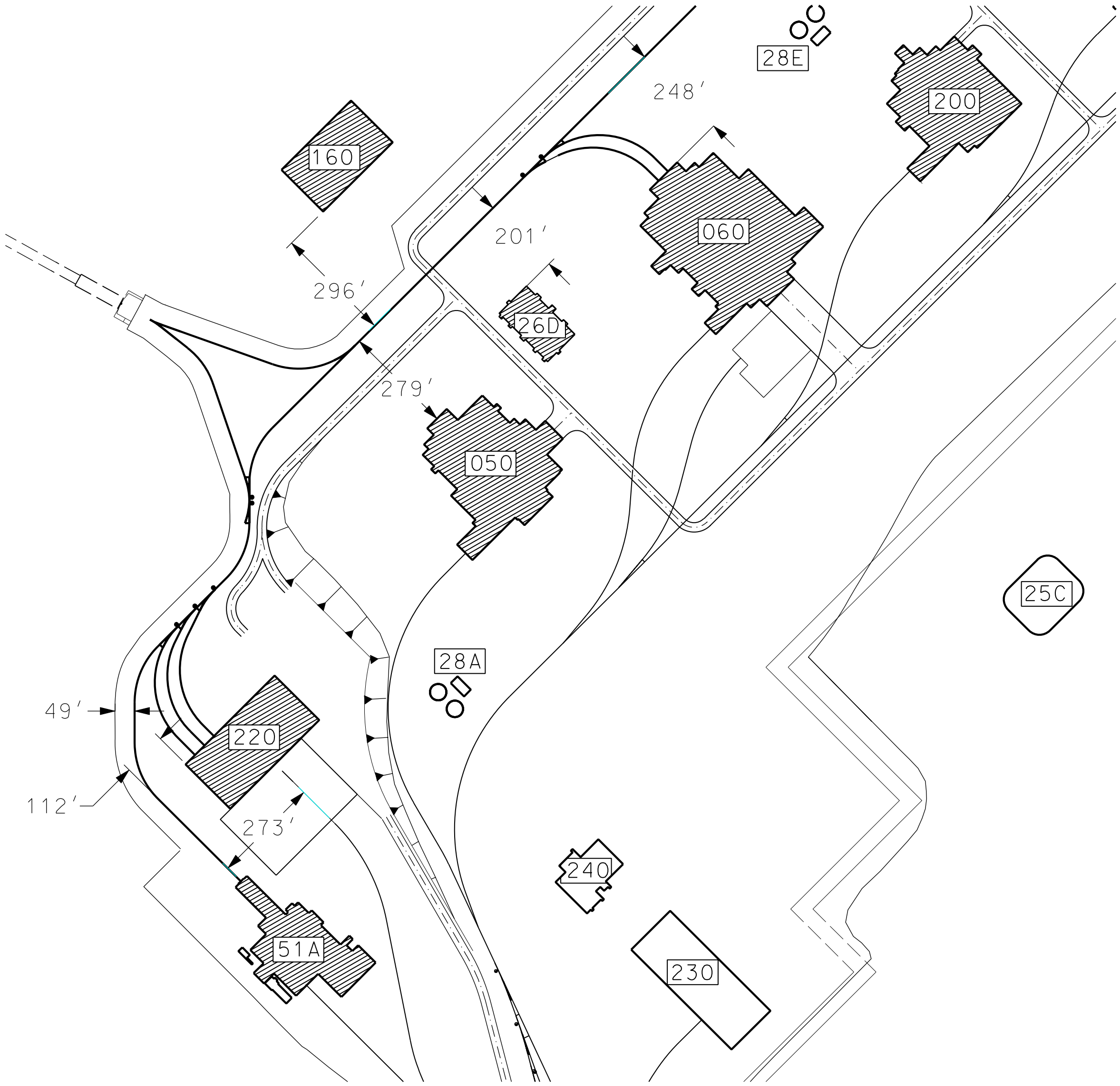
3.1.1.2 TEV Rail Pathway to Equipment

- 83-m (273-ft) center-to-center rail track spacing (the Site Locomotive with a full tank of diesel fuel is assumed to be on the adjacent track)

3.1.1.3 TEV Rail Pathway to Natural Vegetation

- 15-m (49-ft) at the nearest point

Rationale: These data represent available preliminary information and present reasonable estimates of the separation distances evaluated in this calculation.



LEGEND:

Area No.	Description
050	Wet Handling Facility (WHF)
060	Canister Receipt and Closure Facilty 1 (CRCF 1)
160	Low-Level Waste Facility (LLWF)
200	Receipt Facility (RF)
220	Heavy Equipment Maintenance Facility (HEMF)
230	Warehouse and Non-Nuclear Receipt Facility (WNNRF)
240	Central Control Center Facility (CCCF)
25C	Evaporation Pond
26D	Emergency Diesel Generator Facility (EDGF)
28A	Fire Water Facility
28E	Fire Water Facility
51A	Initial Handling Facility (IHF)

Source: Adapted from Reference 2.2.5

Figure 1. Partial Site Plan - Used to Scale Separation Distances

3.1.2 Main Drift Operating Envelope

Assumption: The location of the TEV and high-voltage cables relative to the TEV operating envelope is assumed to be in the general location shown in Figure 2 below.

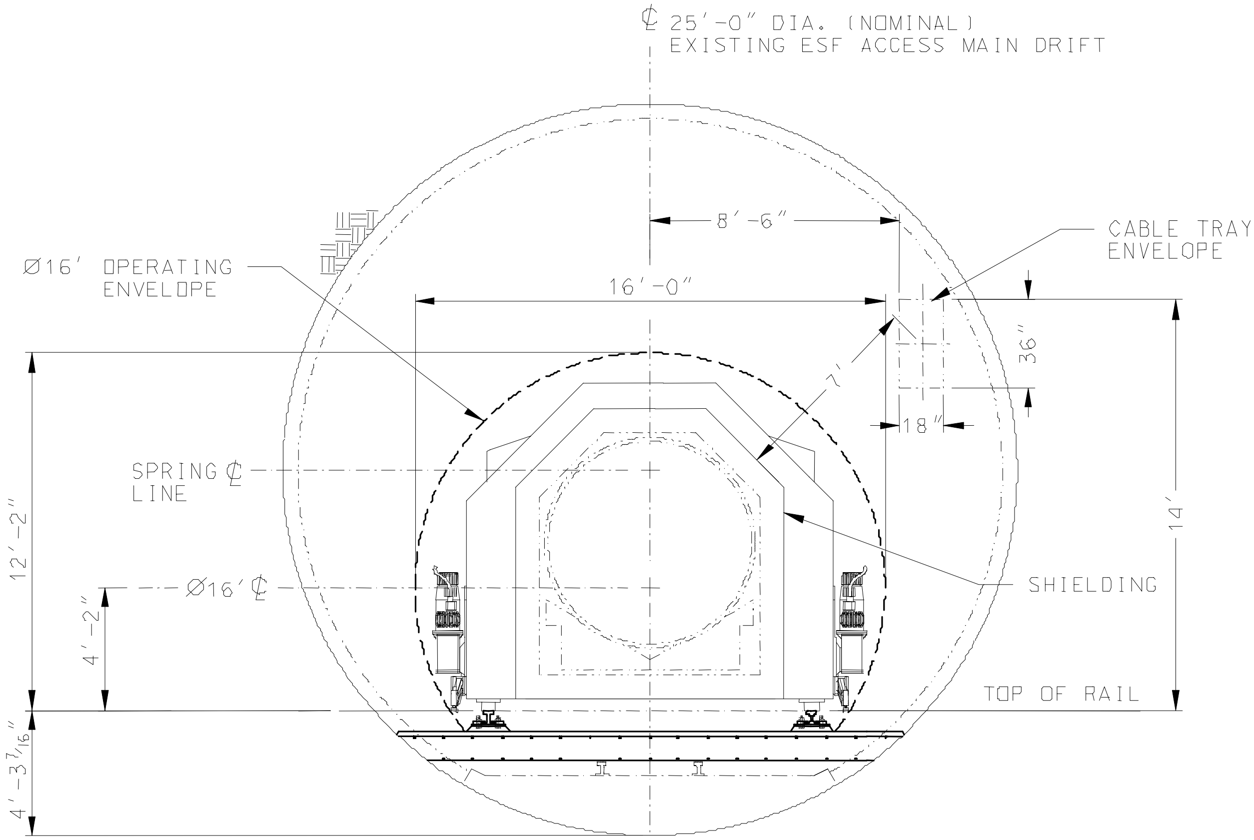
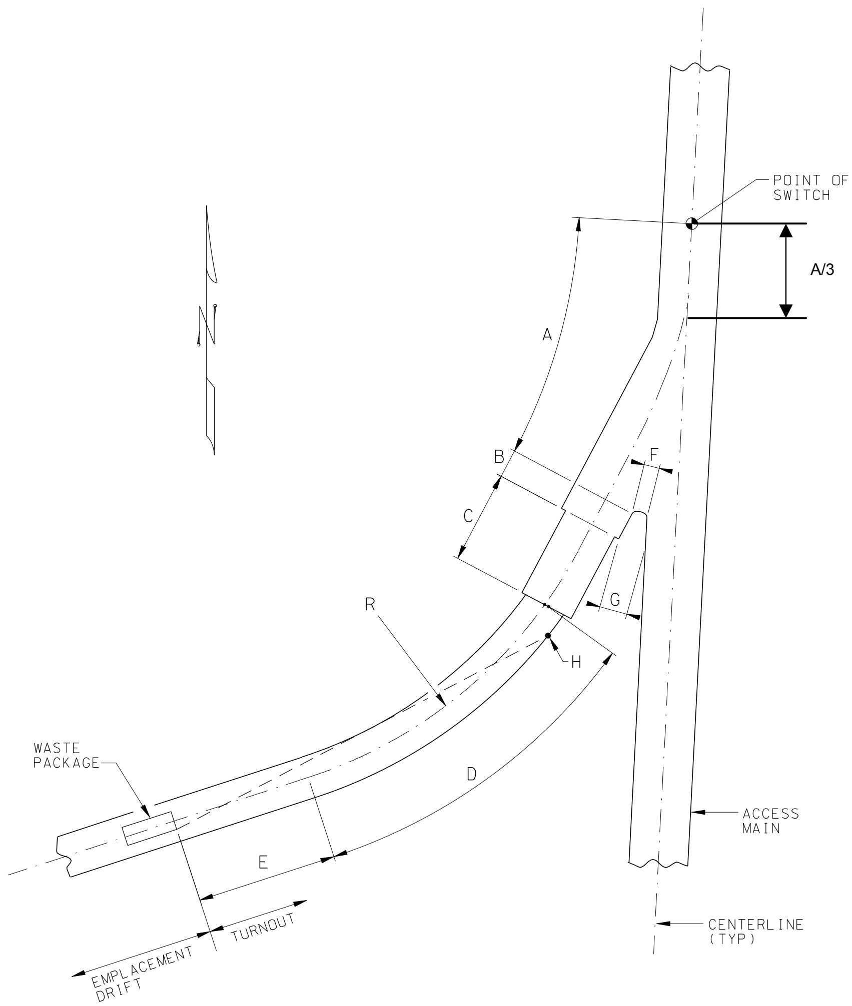


Figure 2. Access Main Operating Envelope

Rationale: The relative distance of the cables from the mobile equipment is not expected to be a significant factor in the exposure calculation. As the design progresses, this assumption will be re-evaluated and corrective action taken if determined necessary. A reasonable minimum separation distance of 2.1-m (7-ft) is used.

3.1.3 Emplacement Drift Turnout Configuration

Assumption: The Panel 3 emplacement drift turnout configuration shown here in Figure 3 is assumed to provide the worst-case (i.e. shortest) distance from the emplacement access door in the turnout to the closest WP. This distance is estimated from the figure below as E+D+C+½B = 71-m (232.5-ft) and is used in the fire exposure evaluation to an emplaced WP. The emplacement access door is located at the center of B. The centerline distance from a main drift to an emplacement access door is then ⅔A+½B = 27-m (88.8-ft).



Source: Adapted from Reference 2.2.10, Figure 1

Figure 3. Emplacement Drift Turnout Configuration

where:

Identifier	Description	Feet/Inches	Meters
A	Rail Turnout Segment	124'–1¾"	37.840
B	Turnout Bulkhead Segment	12'–0"	3.658
C	Launch Chamber	40'–0"	12.000
D	Turnout Curve	126'–6"	38.557
E	TEV Alignment Segment	60'–0"	18.288
F	Turnout Pillar	6'–6"	2.000
G	Launch Chamber Minimum Pillar Width	10'–0"	3.048
H	Radiation Sightline Intercept (minimum)	10'–0"	3.000
R	Centerline Radius	200'–0"	60.960

Source: Reference 2.2.10, Table 5

Rationale: The distance of 27-m (88.8-ft) calculated from Figure 3 is the shortest centerline distance from the centerline of a main drift to the face of an emplacement access door at a turnout. This information is based on review of available turnout details. The shortest distance provides the engineer with the worst-case dimension for flame radiation from a main drift fire to a WP.

3.1.4 MRC Configuration

Assumption: A typical MRC is assumed to have the configuration shown in Figure 4 and Figure 5.

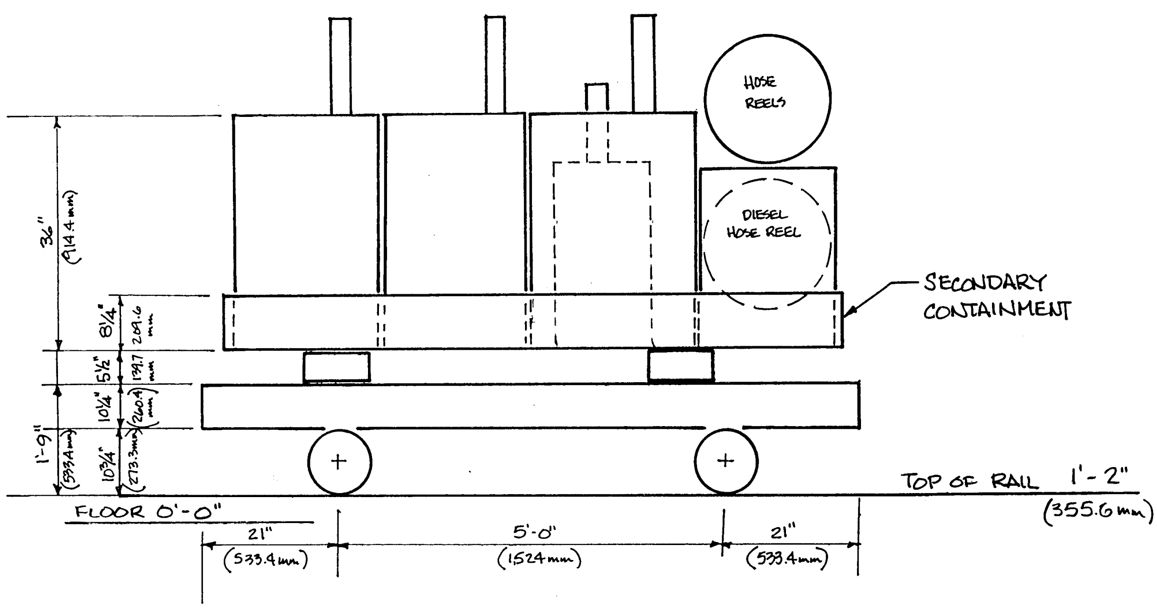


Figure 4. Typical Maintenance Railcar (MRC) - Elevation View

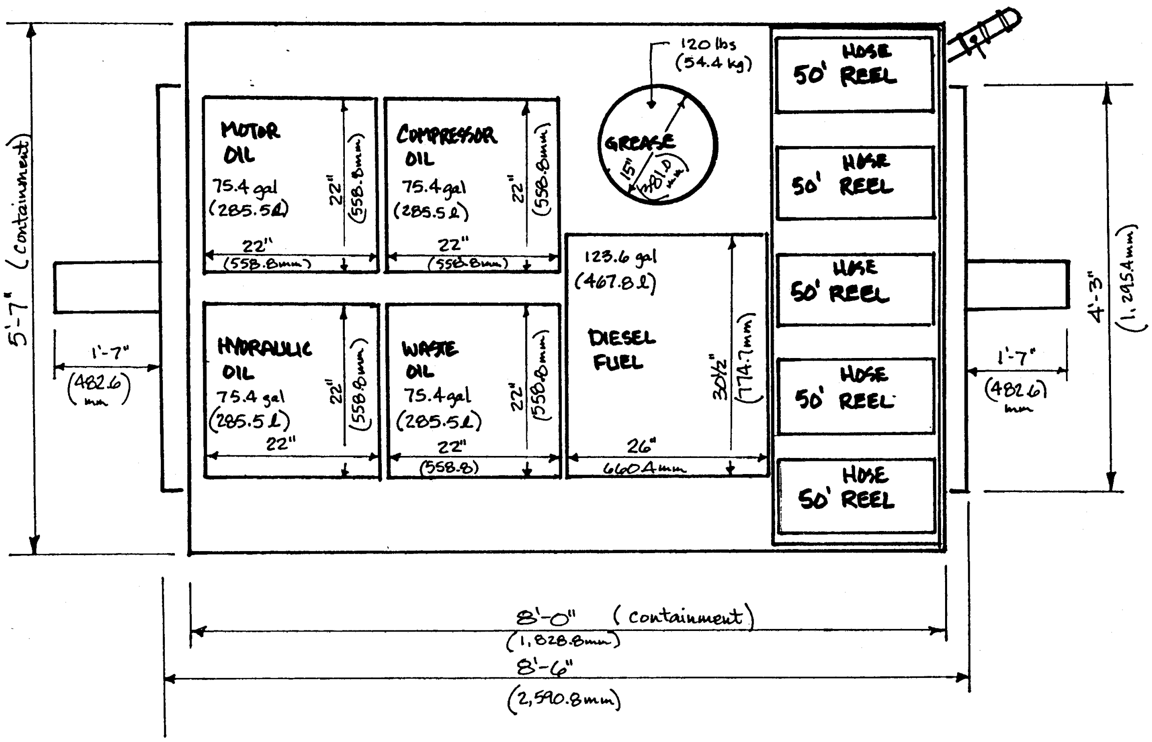
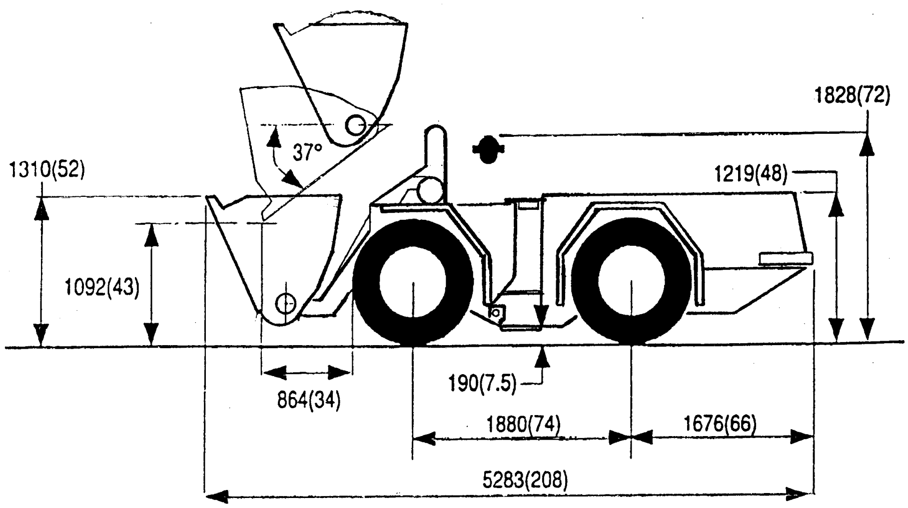


Figure 5. Typical Maintenance Railcar (MRC) - Plan View

Rationale: The vehicle configuration depicted in Figure 4 and Figure 5 is used to represent the vehicle (or vehicles) that will be specified at some future time for construction use. This configuration is considered representative of the vehicle likely to be used for construction vehicle support.

3.1.5 Development Area - Commonly Used Diesel-Powered Vehicle Fire Hazard

Assumption: A typical one cubic yard load-haul-dump (LHD) is assumed to have the configuration shown in Figure 6.



Tire Size: 9.00 R 20 (965mm (38 inches) OD)
Tire Weight: 49 kg (108 lb)
Foam Weight: 107 kg (236 lb)
Total Tire/Foam Wt.: = 156 kg (344 lb)
Fuel Tank: 83 l (22 gal)
Hydraulic Tank: 83 l (22 gal)
Transmission: 57 l (15 gal)

Figure 6. Typical One Cubic Yard Load-Haul-Dump Vehicle

Rationale: The vehicle configuration depicted in Figure 6 is used to represent the vehicle (or vehicles) that will be specified at some future time for construction use. This configuration is considered representative of the vehicle likely to be used for construction.

3.1.6 Development (Construction) Railroad Tie Dimensions and Spacing

Assumption: Temporary construction railroad ties are assumed to be of non-combustible material (steel or concrete), approximately 8-in wide, 6-in deep, 5-ft long, and spaced at 2′-6″ on-center.

Rationale: The tie size and spacing is typical for temporary construction uses, and was previously used in construction of the existing 5.0-m (16-5) diameter drift. Neither steel nor concrete ties will increase the combustible fuel available for burning.

3.1.7 Cable Tray Loading

Assumption: A single vertical column of three 18-in-wide cable trays (1-power, 1-control, and 1-instrument) is assumed for calculation of electrical cable loading in the access main. The trays are assumed to be sufficiently close (over and below) that it is likely that vertical tray-to-tray flame spread occurs prior to any significant horizontal flame spread.

Rationale: This arrangement is typical for cable tray installation and it provides a conservative estimate of cable exposures in an access drift.

3.2 ASSUMPTIONS NOT REQUIRING VERIFICATION

3.2.1 Fire-Fighting

Assumption: No active or manual fire protection system suppression is postulated to occur. A fire is modeled as a free burning fire affected only by the heat release rate of the fuel and available ventilation to support combustion.

Rationale: This permits analysis of the fire without taking credit for any mitigation. This represents the worst-case bounding effect of a fire to a specified target.

3.2.2 Subsurface Design Basis Fire

Assumption: The design basis fire (DBF) in the subsurface repository assumes and evaluates the consequences of the worst-case fire that can be postulated for specified hazard within a fire area. The fire is assumed to burn at a steady-state HRR from a period immediately after ignition until fire decay.

Rationale: The assumption models a fire at its peak HRR as a steady-state condition during its burning period. This is consistent with the handling of a worst-case fire for a given fire area (Reference 2.2.14, Sections 4.6 and 4.7).

3.2.3 Reference Drawings

Assumption: The reference drawings used as the basis for this document are adequate/suitable to describe the facility functional areas.

Rationale: The drawings comprise the best available information when this calculation was prepared. In addition, QA: N/A drawings are considered suitable for use in this calculation because information from non-safety category systems is needed to evaluate fire exposure. As information that is more detailed is developed, this document will be revised. Revisions are planned during the detail design phases.

3.2.4 Surface Locomotive Fuel Spill

Assumption: An accident involving a surface diesel fuel powered locomotive is assumed to create a fuel spill onto the ground that catches fire. It is assumed that a fuel leak is the likely result rather than a catastrophic failure of the fuel tank.

Rationale: Locomotive fuel tanks may contain hundreds of gallons of fuel. In the event of an accident involving the locomotive fuel tank, it is reasonable to postulate that a portion of the tank's capacity will spill out of the tank onto the ground. The spill quantity may be quantified in future analyses.

3.2.5 MRC Effective Fuel Tank Capacities

Assumption: The effective capacity of each storage tank onboard the MRC is assumed as 95-percent of the calculated capacity.

Rationale: The reduction to 95-percent provides an adequate allowance for filling shutoff, expansion and overfilling.

3.2.6 MRC Volume Supporting Burning

Assumption: The complete volume of the MRC secondary containment is assumed available to contain burning fuel. The secondary containment is not postulated to leak during the fire event.

Rationale: The volume is readily identifiable without having to postulate unsteady-state leak condition and model spill size on drift floor. Ignoring exact failure mode of tanks and/or the secondary containment, which is difficult to determine, is not expected to materially change the calculation results.

3.2.7 MRC Fire Event Location

Assumption: The MRC fire event location is assumed as able to occur anywhere in the development (construction) operations.

Rationale: The postulated fire size is independent of MRC location.

3.2.8 MRC Fire Suppression Failure

Assumption: The MRC's onboard, automatic fire suppression system is assumed to fail. Manual fire extinguishing equipment, i.e. portable fire extinguishers and small fire hoses are assumed unavailable or use is not possible.

Rationale: By assuming these systems fail, or are unavailable, the worst-case fire can be calculated. This represents a single event failure concurrent with the fire.

3.2.9 MRC Available Fuel and Tank Failure

Assumption: The assumed initial fire event, a fire in the MRC, first consumes the available diesel fuel. The other fuel tanks on the MRC fail in a successive manner. At no time does the failure of any tank or tanks result in overflow of the MRC secondary containment. The contents of the secondary containment are consumed at a rate that prevents overflow.

Rationale: Catastrophic simultaneous tanks failures are unlikely and the assumption of successive failure provides a reasonable method for assessing this fire event. The actual failure mechanisms of the individual tanks are not addressed and are beyond this analysis.

3.2.10 MRC Locomotive Fuel Contribution

Assumption: It is assumed that the fuel (diesel) onboard the locomotive (loci) will not contribute to the fire HRR.

Rationale: The loci located in the analysis control volume has such a large mass, distance from the MRC, and the fuel tank is sufficiently shielded, that the fuel onboard will not contribute to the fire HRR.

3.2.11 Development Area Initiating Fire Event

Assumption: The fire event is assumed to be initiated from an electrostatic discharge onboard a maintenance railcar (MRC) during fuel or lubricant transfer operations.

Rationale: This bounds the initiating event for the identified fire hazard in terms of HRR (kW).

3.2.12 Development Area - Alterative Vehicle Fire Event

Assumption: An assumed pool fire at a typical LHD, fueled by a small puncture (5-mm diameter) to the diesel fuel tank, consumes all available diesel fuel, causes catastrophic failure of the hydraulic oil tank and hydraulic transmission containment, and subsequently involves all four of the vehicle's tires.

Rationale: The flame from the pool fire occurring under the fuel tank/engine compartment will impinge on the underside of the LHD and spread laterally to involve the adjacent tires.

3.2.13 Failure of Hydraulic Systems

Assumption: The assumed alternative fire event caused by a leaking diesel tank causes subsequent catastrophic failure of the hydraulic oil systems, dumping the oil on the floor of the drift, forming a pool of approximately 10-mm thickness.

Rationale: Catastrophic failure of hydraulic systems due to exposure to the initial diesel pool fire is more likely than another slow leak. The leaking oil forming a pool that spreads out to a depth of 10-mm is reasonable for determining the consequence of this flammable event.

3.2.14 Pool Location and Size

Assumption: For the assumed alternative fire event, the worst-case fuel spill occurs over the temporary construction ties. In such an event, the fuel would pool between the ties. The worst-case pool would be one that forms where the voids under the ties and along the sides of the ties are filled with muck.

Rationale: The assumption bounds the worst-case fire event by confining the pool size to that stated, forming a deep pool with a relatively small surface area, thus extending the total burning time. A shallow pool would have a larger surface area that would be consumed by the fire in a shorter duration.

3.2.15 Regulatory Fire

Assumption: All WPs are assumed to have been analyzed for outer barrier peak temperature during a fire and found bounded by the 10 CFR 71 regulatory fire exposure of 800ºC (1,073-K) for 30 minutes (Reference 2.2.1, Part 73(c)(4)).

Rationale: An Interoffice Memorandum (IOM) (Reference 2.2.12) is used to bound the WP temperatures during a fire event. This IOM is suitable for use in this calculation because the IOM is not expected to be superseded by any future analyses.

4. METHODOLOGY

4.1 QUALITY ASSURANCE

This calculation was prepared in accordance with EG-PRO-3DP-G04B-00037, *Calculations and Analyses* (Reference 2.1.1). The fire protection systems, other than certain specific components in Nuclear Facilities, are classified as non-ITS in the *Basis of Design for the TAD Canister-Based Repository Design Concept* (Reference 2.2.4, Section 18.1.2). However, fire exposure results are used to evaluate the WP which is classified as important to safety (ITS) and important to waste isolation (ITWI) (Reference 2.2.4, Sections 11.1.2 and 12.1.2); the TEV is also classified as ITS (Reference 2.2.4, Sections 14.1.2). Therefore, the approved version is designated as QA: QA.

4.2 USE OF SOFTWARE

The calculation process is performed manually and equations used are documented in Section 6 of this document for checking by manual calculation. No software routines or models were developed or used.

4.3 CALCULATION APPROACH

The general approach to calculation of the postulated non-exterior fire events is to use a technique called a zone model. A zone model essentially assumes a compartment may be idealized for analysis by the use of two different regions. The first region consists of a hot upper layer that is filled with hot combustion gases. The second region lies immediately below the hot upper layer and is essentially filled with cool air. Each region or layer is considered idealized with uniform temperatures and gas concentrations. A plane dividing the two zones is an interface layer that may move vertically during a fire.

The zone model concept simplifies a room thermal environment into two temperatures and an interface height rather than a three-dimensional temperature field. Zone models predict approximate results as a result of these simplifications. These approximate results can yield significant insights into many fire problems.

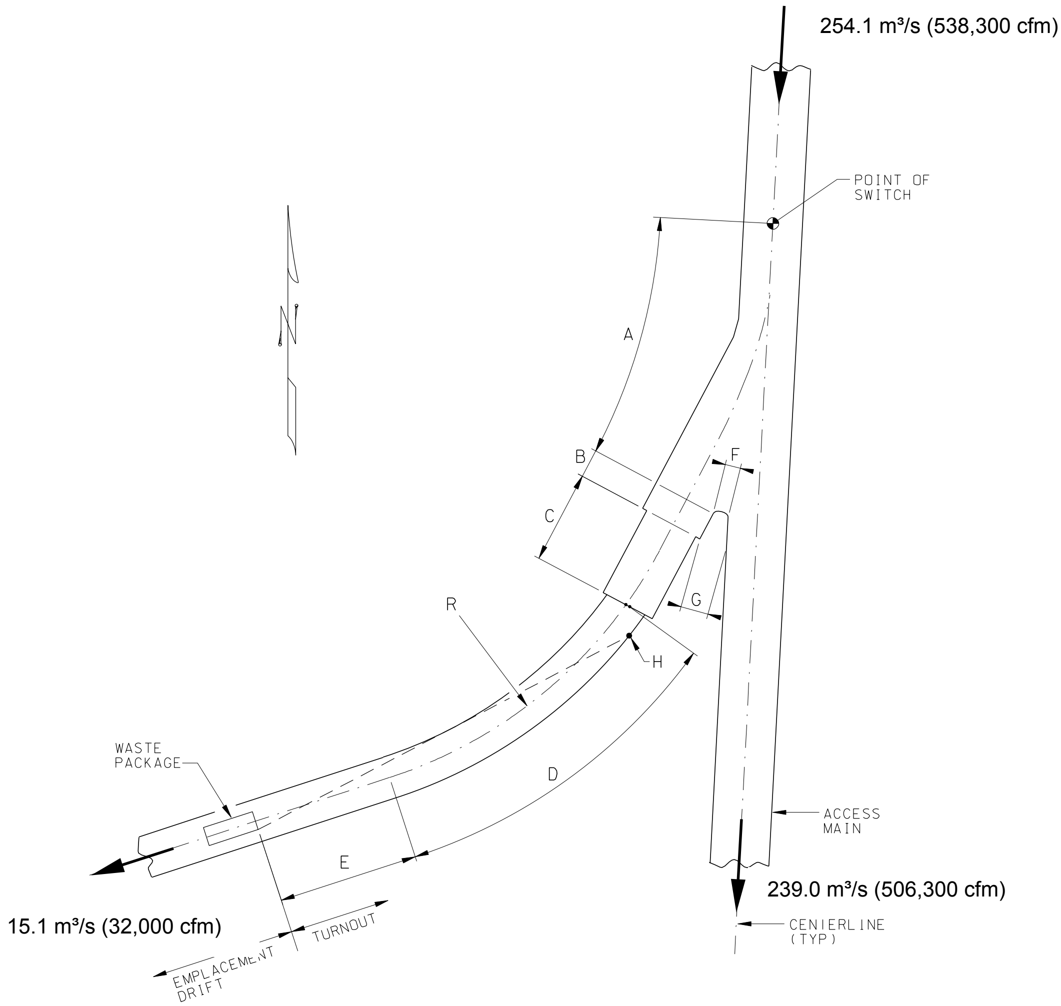
A fire is modeled as a worst-case free-burning fire, affected only by the heat release rate of the fuel and available ventilation to support combustion (Assumptions 3.2.1 and 3.2.2). The effects of surface and subsurface fires are evaluated to specified targets from a postulated fire source of a stated size. These fire effects are quantified to determine the effect of an unmitigated fire on a specified target.

4.4 INPUTS

This section identifies and documents all technical product inputs and sources of input that are used in the development of this document.

4.4.1 Drift Airflow

Maximum airflow for the selected access main and emplacement drift configuration (Assumption 3.1.3) is as shown in Figure 7. Drift Airflow Quantities.



Airflow Source: Reference 2.2.7, Attachment C, Branch 417 & 419

Figure 7. Drift Airflow Quantities

4.4.2 Ambient Air Temperature

The weighted average dry-bulb temperature of ambient air (taken from United States Geological Survey monitoring station 28-93 with highest listed average temperature) entering the subsurface is:

23.82ºC (74.88ºF) (Reference 2.2.6, Table 12)

4.4.3 Access Main Perimeter

The perimeter of access main is:

23.94-m (78.54-ft) (Reference 2.2.7, Table 4)

4.4.4 Cable Tray Heat Release Rate

370-kW/m² (Peak) (Reference 2.2.25, Table 9.4)

4.4.5 Effective Heat of Combustion for PE/PVC Cable

ΔH_c = 24,000-kJ/kg (using PE/PVC cable from Reference 2.2.18, Table 8-1)

4.4.6 Stephan-Boltzmann Constant

σ = Stephan-Boltzmann constant = $5.67 \cdot 10^{-11}$ kW/m²·K^4 (Reference 2.2.19, p. 143)

4.4.7 Radiative Exposure View Factors

View factors used in Equation 4.5-3:

$F_{12} = 1$ (Reference 2.2.19, eq.7.51b)

$F_{13} = 0$ (Since the lower gas layer has no view of the upper surface of the TEV, this factor equals zero)

4.4.8 Effective Emission Coefficient (Smoke Layer)

K = 1.8-m^{-1} (for polypropylene-representative of cable jacketing and insulation materials) (Reference 2.2.15, Table 2.10)

4.4.9 Specific Heat of Gas (Smoke Layer)

c_p = 1.0-kJ/kg·K (Reference 2.2.24, Table B-2)

4.4.10 Density of Concrete

ρ = 2,100-kg/m³ (Reference 2.2.24, Table B-7)

4.4.11 Thermal Conductivity of Concrete

$k = 1.4 \cdot 10^{-3}$-kW/m·K (Reference 2.2.24, Table B-7)

4.4.12 Specific Heat of Concrete

$c = 0.88$-kJ/kg·K (Reference 2.2.24, Table B-7)

4.4.13 Convective Heat Transfer Coefficient for Steel

$h_c = 25$-W/m²·K (Recommended value from Reference 2.2.11, p.179. This would represent a reasonably conservative value for steel)

4.4.14 Emissivity of Emitting Surface

$\varepsilon = 0.9$ (typical value for hot surface) (Using average value for emissivity from Reference 2.2.11, p. 52. This represents emissivity for hot surface smoke particles or luminous flames)

4.4.15 External Heat Flux (Carcass)

$\dot{q}''_e = 56$-kW/m² (Reference 2.2.2, Page 231)

4.4.16 Surface Re-radiation Heat Flux

Using the value for Styrene-Butadiene:

$\dot{q}''_{rr} = 10$-kW/m² (Reference 2.2.24, p.3–68, Table 3-4.4)

4.4.17 Heat of Gasification at Ambient Temperature

Using the value for Styrene-Butadiene:

$\Delta H_g = 2.7$-kJ/g (Reference 2.2.24, p.3–68, Table 3-4.4)

4.4.18 Foam Burning Rate

Using the value for rigid polyurethane foam:

$\dot{m}'' = 0.025$-kg/m² s (Reference 2.2.19, Table 3.2)

4.5 EQUATIONS USED IN SUBSURFACE REPOSITORY EXPOSURE CALCULATIONS

4.5.1 Heat Release Rate for Horizontal Cable Tray

$$\dot{Q}_{\max} = N_{tray} A_{tray} \dot{Q}'' \quad \text{(Reference 2.2.25, Eq. 9.5.2)} \qquad \textbf{Equation 4.5-1}$$

where:

$\dot{Q}_{\max}$ = cable tray HRR (kW)

N_{tray} = number of trays

A_{tray} = tray horizontal area loaded with cables (m²)

$\dot{Q}''$ = peak HRR per unit area of burned cables (kW/m²)

4.5.2 Solid Combustible Burn Time

$$t_{solid} = \frac{m_{fuel} \Delta H_c}{\dot{Q}'' A_{fuel}} \quad \text{(Reference 2.2.18, Eq. 8-1)} \qquad \textbf{Equation 4.5-2}$$

where:

t_{solid} = burning duration (s)

m_{fuel} = mass of solid fuel (kg)

ΔH_c = effective heat of combustion (kJ/kg)

$\dot{Q}''$ = HRR per unit floor area (kW/m²) (Peak)

A_{fuel} = exposed fuel surface area (m²)

4.5.3 Radiative Exposure from Cable Tray to Target

$$\dot{q}_r'' = \varepsilon_{g,u} \sigma T_{g,u}^4 + F_{12}(1-\varepsilon_{g,u})\sigma T_{w,u}^4 + F_{13}(1-\varepsilon_{g,u})\sigma T_a^4 - \sigma T_s^4$$

(Reference 2.2.19, Eq.7.51a) **Equation 4.5-3**

where:

$\dot{q}_r''$ = net radiative flux of the hot gas (kW/m²)

ε_g = emissivity of the hot gas

T_g = temperature of the gas (K)

T_w - temperature of the wall (K)

T_a = ambient temperature (K)

T_s = temperature of the solid (K)

σ = Stephan-Boltzmann constant

F_{12} = view factor

F_{13} = view factor

4.5.4 Emissivity of Upper Smoke Layer

$$\varepsilon = 1 - e^{-KL}$$ (Reference 2.2.15, Eq.2.83) **Equation 4.5-4**

where:
K = effective emission coefficient (m^{-1})
L = path length (m) - (mean beam length/flame thickness)
$\varepsilon = \varepsilon_g$ (for consistency in equations)

4.5.5 Upper Smoke Layer Temperature

$$\frac{\Delta T_g}{T_\infty} = 0.63\left(\frac{\dot{Q}}{\dot{m}c_p T_\infty}\right)^{0.72}\left(\frac{h_k A_T}{\dot{m}c_p}\right)^{-0.36}$$

(Reference 2.2.24, p. 3-140, Eq. 16) **Equation 4.5-5**

where:
ΔT_g = upper gas temperature rise above ambient (K)
T_∞ = ambient air temperature (K)
$\dot{Q}$ = HRR of the fire (kW)
$\dot{m}$ = compartment mass ventilation rate (kg/s)
c_p = specific heat of gas (kJ/kg·K)
h_k = effective heat transfer coefficient (kW/m·K)
A_T = total area of the compartment-enclosing surfaces (m²)
and

$$h_k = \left(\frac{k\rho c}{t}\right)^{1/2} \quad \text{for } t \le t_p$$

(Reference 2.2.24, p. 3-139, Eq. 15) **Equation 4.5-6**

where:
k = thermal conductivity of compartment surface (kW/m·K)
ρ = density of the compartment surface (kg/m³)
c = specific heat of the compartment surface material (kJ/kg·K)
t = exposure time (s)

4.5.6 Convective Flux at Target

$$\dot{q}'' = h_c(T_f - T_s)$$ (Reference 2.2.11, Eq.8.5, ignoring the right-hand term of the source equation since we are specifically looking at convection only) **Equation 4.5-7**

where:
$\dot{q}''$ = heat transfer at surface (W/m²)
h_c = convective heat transfer coefficient (W/m²·K)
T_f = temperature in fire environment (K)
Let $T_f = T_g$

T_s = temperature of the steel (K)

4.5.7 Emissive Power of the Regulatory-Defined Fire

$$\dot{q}'' = \varphi \varepsilon \sigma T_e^4$$ (Reference 2.2.11, Eq. 3.18) **Equation 4.5-8**

where:

$\dot{q}''$ = radiant heat flux at a point on receiving surface (kW/m²)

φ = configuration factor

= 1.0 (worst-case factor)

ε = emissivity of emitting surface

T_e = absolute temperature of the emitting surface (K)

4.5.8 Mass Loss Rate

$$\dot{m}'' = \dot{m}''_\infty \left(1 - e^{-k\beta D}\right)$$ (Reference 2.2.24, Page 3-3, Eq. 1) **Equation 4.5-9**

where:

$\dot{m}''$ = burning rate (kg/m² s)

$\dot{m}''_\infty$ = mass loss rate per unit area for very large pool diameters (kg/m²·s)

k = extinction-absorption coefficient (m^{-1})

β = mean-beam-length corrector (-)

D = diameter of the pool (m)

4.5.9 Pool Fire Burning Time

$$t_b = \frac{V\rho}{\dot{m}''A}$$ (Reference 2.2.8, Eq. 3) **Equation 4.5-10**

where:

t_b = burning duration of pool fire (sec)

V = volume of liquid (m³)

ρ = liquid fuel density (kg/m³)

$\dot{m}''$ = mass burning rate of fuel (kg/m² s)

A = area of pool (m²)

4.5.10 Pool Fire Heat Release Rate

$$\dot{Q} = \Delta h_c \, \dot{m}'' A$$ (Reference 2.2.8, Eq. 1) **Equation 4.5-11**

where:

$\dot{Q}$ = energy release rate (kW)

Δh_c = heat of combustion (kJ/kg)

$\dot{m}''$ = mass loss rate (kg/m² s) (See Section 4.5.8)

A = surface burning area

4.5.11 Rubber Carcass Burning Time

$$t_b = \frac{W}{\dot{m}''A}$$ (Derived from **Equation 4.5-10** and units used) **Equation 4.5-12**

where:
t_b = burning time (s)
W = weight of rubber carcass (kg)
$\dot{m}''$ = initial mass burning rate of fuel (kg/m² s)
A = exposed area of material burning (m²)
and

$$\dot{m}'' = \frac{\dot{q}''_e - \dot{q}''_{rr}}{\Delta H_g}$$ (Reference 2.2.24, Page 3–67, Eq. 14) **Equation 4.5-13**

where;
$\dot{q}''_e$ = external heat flux
$\dot{q}''_{rr}$ = surface re-radiation heat flux
ΔH_g = heat of gasification at ambient temperature

5. LIST OF ATTACHMENTS

None used.

6. BODY OF CALCULATION

Three basic fire scenarios are postulated for this calculation. These are:

- Surface Fire Exposure (Section 6.1)
- Subsurface Repository Emplacement Area Fire Exposure (Section 6.2)
- Subsurface Repository Development Area Fire Exposure (Section 6.3)

Surface Fire Exposure Scenarios-Fire exposure to a WP onboard the TEV on the surface, prior to entering the North Portal, is calculated (Section 6.1) at three locations: 1) on the rail pathway adjacent to site buildings (Section 6.1.1); 2) on the rail pathway adjacent to equipment (Section 6.1.2); and 3) exposure to offsite wildfires (Section 6.1.3).

Subsurface Repository Emplacement Area Fire Exposure-Fire exposure to a WP in the operations (emplacement) area of the subsurface repository is calculated (Section 6.2) at a single location: 1) onboard the TEV in an access main (Section 6.2.1), evaluated at this location; and 2) the impact of this exposure evaluated for a WP emplaced in an emplacement drift (Section 6.2.2).

Subsurface Repository Development Area Fire Exposure-Fire exposure to a ventilation/isolation barrier separating the development area from the repository operations area is calculated (Section 6.3). The fire is postulated to occur in the development area onboard typical construction equipment (Sections 6.3.1 and 6.3.2).

6.1 SURFACE TRANSIT FIRE EXPOSURE SCENARIOS

6.1.1 TEV Rail Pathway To Site Buildings

The TEV is exposed on the surface to structures, other mobile equipment, and on-site and off-site yard hazards.

Assumption 3.1.1 provides a range of distances to the TEV from fixed site facilities. The least separation distance shown is to the building face of the Heavy Equipment Maintenance Facility (Area 220) of 34-m (112-ft) (Assumption 3.1.1.1). Any exposures from a facility that the TEV exits are considered as dealt with as a function of that facility and are not addressed here.

Table 4.3.8.2 of NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures* (Reference 2.2.21), lists separation distances for buildings with non-rated roof assemblies (Note: this is used as a guide and not a representation of actual roof conditions, which are fire-resistant). For a three-story building with a fire through the roof, the minimum distance is listed as 12.5-m (41-ft).

Based on the 12.5-m (41-ft) distance, and the fact that building hazards are protected by automatic fire suppression systems, a 34-m (112-ft separation distance from the closest TEV rail to a facility should provide adequate separation distance from a building exposure. Building fire exposure to the TEV is therefore, not a concern.

6.1.2 TEV Rail Pathway To Equipment

Assumption 3.1.1.2 provides the approximate center-to-center track rail spacing between adjacent tracks from the TEV to the Site Locomotive as 83-m (273-ft). The adjacent locomotive spills diesel fuel in an accident scenario (Assumption 3.2.4).

An example calculation for radiant heat from a burning pool fire is given in Section 2.2.6.3 of *Guidelines for Chemical Process Quantitative Risk Analysis* (Reference 2.2.2). The thermal flux is calculated to a receiver 50-m away from a diked pool fire. Two models are used; point source and solid plume radiative heat. The calculated heat flux at the receiver is 6.11-kW/m² and 1.3-kW/m² respectively. Table 2.35 of *Guidelines for Chemical Process Quantitative Risk Analysis* (Reference 2.2.2) shows that the minimum energy required for piloted ignition of wood, and melting of plastic tubing is 12.5-kw/m², and to cause damage to process equipment is 37.5-kW/m².

A pool fire resulting from a diesel-fueled locomotive on an adjacent rail track is not anticipated to reach these heat flux levels at the TEV. The 83-m (273-ft) separation distance would result in incidental heat flux to the TEV, adjacent to the Heavy Equipment Maintenance Facility (Area 220), less than these numbers. Therefore, the heat energy being radiated towards the shielded WP onboard the TEV would be insufficient to damage the WP.

6.1.3 TEV Exposure To Offsite Wildfires

A minimum separation distance of the TEV to offsite natural vegetation of 15-m (49-ft) (Assumption 3.1.1.3) is bounded by the results of the *Wildfire Exposure Calculation* (Reference 2.2.3). The wildfire calculation requires a minimum 10-m (33-ft) perimeter separation (Reference 2.2.3, Section 7) between the boundary of the protected area and the edge of cleared vegetation.

The 15-m (49-ft) distance to the TEV exceeds the established minimum distance. Wildfire exposure to the TEV therefore, is not a concern.

6.2 SUBSURFACE REPOSITORY EMPLACEMENT AREA FIRE EXPOSURE SCENARIOS

The emplacement phase of the repository represents the operational emplacement of nuclear waste into Yucca Mountain, the completion of construction activities for a given subsurface area, and the initiation of monitoring and preparation for post-closure activities. During this phase, it is anticipated that combustible content is limited to that necessary to support electrically-driven TEV operation, provide for ventilation operations, or to provide for various control and monitoring functions.

A review of available literature from the Federal Railway Administration and the National Institute of Standards and Technology (NIST) does not show any significant historical fire data or losses from fires originating in electrically-driven locomotives. (This should not be judged to include electrically-driven commuter railcars, which are of modular design and individually powered). The only remaining significant combustible source that may provide a fire exposure threat is the cabling providing power, control, and instrumentation to the subsurface.

This exposure fire is postulated to occur in Panel 3, adjacent to the emplacement drifts with the shortest distance to the ventilation doors in the drift turnout (Assumption 3.1.3).

6.2.1 Waste Package Onboard the TEV in an Access Main

Horizontal cable trays are used in a wide variety of installations including cable vaults, tunnels, and for large facilities. Cable trays can be used for the routing of power, control, and instrument cabling. Cable loading in trays can vary from a single layer to trays that may be loaded up to the full height of their sidewall. A single vertical column of three 18-in-wide cable trays are used to calculate loading for this calculation (Assumption 3.1.7).

The HRR for horizontal cable trays, determined by fire test data, is given by:

$$\dot{Q}_{\max} = N_{tray} A_{tray} \dot{Q}'' \qquad \textbf{(Equation 4.5-1)}$$

Heat release data for free burn cable tray tests is provided in (Reference 2.2.25, Table 9.4. The only fire test cited that identifies the use of IEEE 383 and non-IEEE 383 cables is the test conducted by Sumitra, done in 1982 (Reference 2.2.25, Table 9.4). The peak HRR for this cable test was 2600-4600 kW (200–370 kW/m^2). For a 400-kW ignition source, the identified flame spread rate is 9-33 cm/min horizontally, the flame spread vertically to top tier trays was from 6.5-40 min depending on cables tested (Reference 2.2.25, Table 9.4).

Previous significant nuclear power plant cable-tray fires were reviewed to aid in prediction of what may be a representative subsurface cable-tray fire.

A cable-tray fire at the Browns Ferry Nuclear Plant extended approximately 30 to 40 feet from the point of ignition near a barrier wall (Reference 2.2.20, Page I-1). This burning occurred where: “a complex system of trays, some of which continue southward, others extend vertically, and others are orientated in an east-west direction.” The cable-tray fire involved 65 different type cables (Reference 2.2.20, Exhibit C-1, Page 6 and Attachment 7, Sheet 1). The Nuclear Regulatory Commission (NRC) Inspection Report suggests that some of these cables may have been flame tested, but the cited Standard Test Reference (Reference 2.2.20, Exhibit C-1, Page 48) is no longer in active use or circulation. The fire burned for about three and one-half hours (Reference 2.2.20, Page 8).

NUREG-0050 also states about the Browns Ferry fire that: “There was very little other equipment in the fire area, and the only damage, other than that to cables, trays, and conduits, was the melting of a soldered joint on an air line and some spalling of concrete” (Reference 2.2.13, Section 1.2).

NUREG/CR-6738 continues on to state: “in classical fire protection terms, the Browns Ferry fire was not especially severe; that is, the fire remained confined to a relatively small area and did not threaten either the plant structure nor the intact fire barriers” (Reference 2.2.22, Page 30).

The only other well-documented U.S. Nuclear Power plant cable fire occurred at Waterford, Unit 3. The fire started inside a switchgear panel and ignited vertical cable-tray risers above the panel. “Cables in a 5-foot (1.5-m) diameter column up to a height of about 10 feet (3-m) above the panel top were damaged by the fire.” The fire eventually reached a horizontal cable tray about 17 feet (5.2-m) above the floor (10 feet (3-m) above the top of the panel) and propagated horizontally up to a fire stop in the tray about 8 feet (2.4-m) from the junction with the vertical trays (Reference 2.2.22, Page A24-2).

Based on this cable-tray fire experience and the likelihood that an ignition source will not be as extreme as the 400-kW case (Reference 2.2.25, Table 9.4), a flame-spread rate of 9-cm/min is selected. As the burn time per meter length of cable tray will vary depending on the tray fill, use a resident burn time of 30-min for a given meter length of cable tray. This represents the period that the peak HRR is generated. (Note: Peak HRR is NOT equal to maximum HRR).

Based on a spread rate of 9-cm/min (0.09-m/min), the fire will expand to 2.7-m in one direction from the point of ignition or **5.4-m** in two directions. The ventilation velocities have no apparent effect on flame-spread rate for velocities in the 0.5-1.6 m/s range (Reference 2.2.25, p. 313).

The cable tray fire area is then given by:

$$A_{tray} = L_{tray} w_c$$

where:

L_{tray} = tray length (m) = 5.4-m (from above)

w_c = cable width (m) = 0.46-m (Assumption 3.1.7)

$$A_{tray} = (5.4)(0.46) \quad = 2.48 \sim \mathbf{2.5\text{-}m^2}$$

$\dot{Q}''$ = **370-kW/m²** **(Peak HRR)** (Section 4.4.4)

$$\dot{Q}_{\max} = (3)(2.5)(370) \quad = \mathbf{2{,}775\text{-}kW\ (Maximum\ HRR)}$$

A 30-min effective burn time for a given square meter of cable tray can be expressed in terms of combustible content. The burn time for a solid combustible is given by:

$$t_{solid} = \frac{m_{fuel}\Delta H_c}{\dot{Q}'' A_{fuel}} \qquad \textbf{(Equation 4.5-2)}$$

where:

t_{solid} = 30-min (1,800-s) (from above)

m_{fuel} = mass of solid fuel (kg)

ΔH_c = 24,000-kJ/kg (Section 4.4.5)

$\dot{Q}''$ = 370-kW/m² (from above)

A_{fuel} = 1.0-m² (unit area)

$$m_{fuel} = \frac{t_{solid}\dot{Q}''A_{fuel}}{\Delta H_c} = \frac{(1800)(370)(1.0)}{(24000)}$$ = **27.8-kg/m²** of cable tray

Length of tray (1.0-m², 0.46-m (18-in) wide) is:

$$\frac{1.0}{0.46}$$ = **2.2-m** (7.2-ft)

Weight of combustible cable (insulation and jacketing weight only) per unit length of tray:

$$\frac{(27.8)}{(2.2)}$$ = **12.6-kg/m** (8.5-lb/ft)

For a 3-high vertical tray array, this equals 37.8-kg/m (25.5-lb/ft).

The cable insulation available for combustion may be greater, but the fire would likely become deep-seated and would burn at a lower HRR due to char formation, heat losses to the conductors themselves, and lower levels of fire re-radiation back to a given burned area. (Note: The results will need to be revised should actual cable tray fills exceed these values).

6.2.1.1 Fire Exposure to TEV

The TEV will run parallel to the cable trays which are assumed to be mounted along the access main sidewall approximately mid-way between the spring line and the crown of the drift (Assumption 3.1.2, Figure 2). For fire modeling purposes, the TEV with WP onboard is located as shown in the access main (Assumption 3.1.2, Figure 2). Allowing for cable tray mounting hardware and its assumed width of 18-in (Assumption 3.1.7), a distance of 2.1-m (7-ft) is used as the distance from a cable tray fire to the exposed surface of the TEV shielding (Assumption 3.1.2, Figure 2).

It is likely that the fire could be considered ventilation-aided, but due to tunnel configuration, any ventilation effects would tilt flaming from a cable tray fire along the cable tray and not toward the TEV. The ventilation would assist in maintaining this parallel orientation between the cable tray (fire source) and the TEV (target). The presence of ventilation will assist in maintaining this 2.1-m distance.

The TEV is not expected to be effectively exposed for a distance (area) much greater than the area of the cable tray fire.

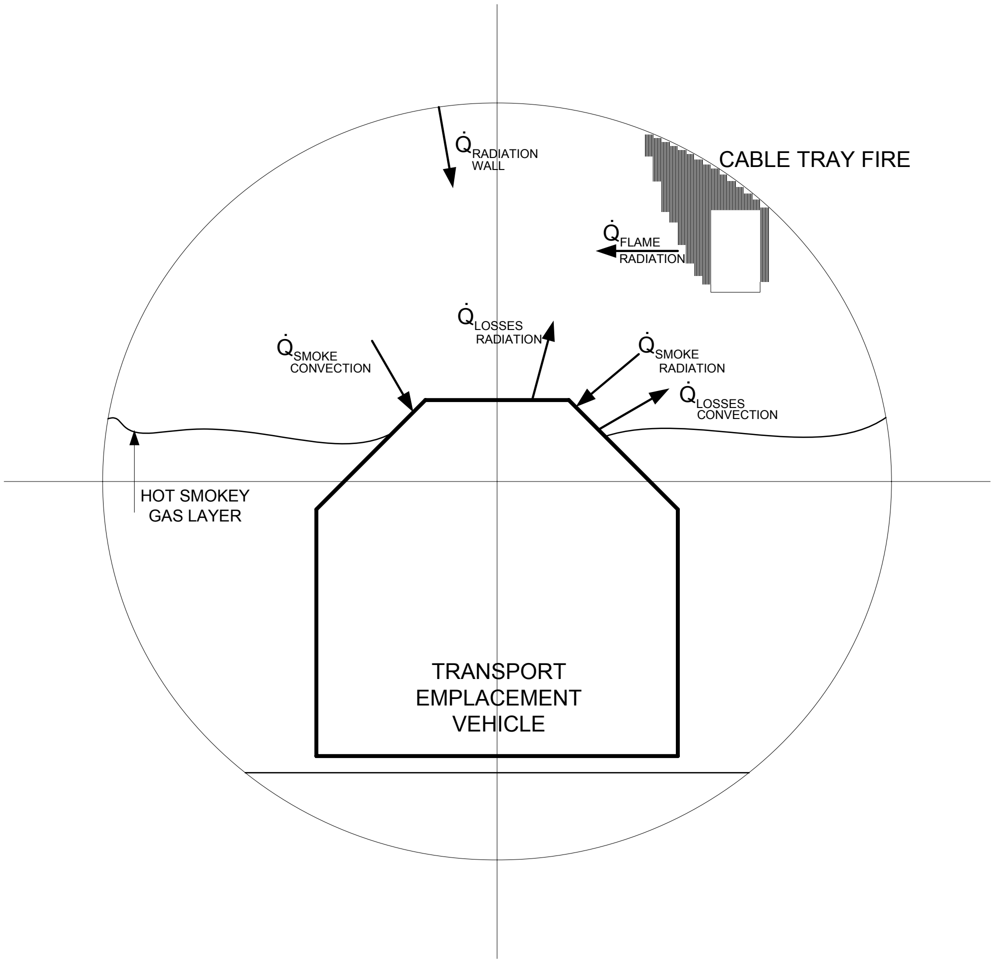


Figure 8. Simplified Fire and Target Presentation – Access Main Adjacent to TEV

6.2.1.2 Radiative Exposure

The radiant heat of the cable tray flame to the TEV through an upper smoke layer is given by:

$$\dot{q}''_r = \varepsilon_{g,u}\sigma T^4_{g,u} + F_{12}(1-\varepsilon_{g,u})\sigma T^4_{w,u} + F_{13}(1-\varepsilon_{g,u})\sigma T^4_a - \sigma T^4_s \qquad \textbf{(Equation 4.5-3)}$$

where:

σ = Stephan-Boltzmann constant = $5.67 \cdot 10^{-11}$ kW/m²·K⁴ (Section 4.4.6)

$F_{12} = 1$ (Section 4.4.7)

$F_{13} = 0$ (Section 4.4.7)

The emissivity (ε_g) of the upper smoke layer can be determined by:

$$\varepsilon = 1 - e^{-KL} \qquad \textbf{(Equation 4.5-4)}$$

where:

K = 1.8-m^{-1} (Section 4.4.8)

L = 2.1-m (the path length is the distance from the flame to the TEV surface (Section 6.2.1.1))

$\varepsilon_g = 1 - e^{-(1.8)(2.1)}$ = **0.98** (dimensionless)

The 2,775-kW HRR (Section 6.2.1) of the fire is distributed over a 5.4-m length. For any given location on the upper surface of the TEV, using the mean beam length can approximate the effective fire exposure from the cable tray. For two parallel surfaces of infinite length, the mean beam distance is 2.0 D, or two times the separation distance (Reference 2.2.19, Table 7.3). For a 2.1-m separation distance, the mean beam length is 4.2-m.

The net emissive flame power is a function of the flame thickness (or mean beam length) (Reference 2.2.15, Section 2.4.3, p. 69). This states that the effective exposure to a given point on the outer TEV surface is effectively limited to directly opposite a cable tray fire 2.0-m in length; one meter downstream and one meter upstream. The field-of-view from any flaming outside this range is sufficiently small that it will not produce a significant radiative effect at the point of measurement on the TEV surface.

6.2.1.3 TEV Exposure Temperature

Ventilation rates in the Panel 3 access mains vary from 2.7 to 254.1-m³/s (5,700 to 538,300-cfm) (Reference 2.2.7, Attachment C, Branches 435 and 417). These numbers represent extremes that may be difficult to achieve in practical terms, but will serve as lower and upper bounding values in which to define a fire scenario.

6.2.1.3.1 Upper Smoke Layer Temperature – Higher Ventilation Rate Case

The temperature rise for the forced ventilation case is given by:

$$\frac{\Delta T_g}{T_\infty} = 0.63\left(\frac{\dot{Q}}{\dot{m}c_p T_\infty}\right)^{0.72}\left(\frac{h_k A_T}{\dot{m}c_p}\right)^{-0.36}$$ (**Equation 4.5-5**)

where:

ΔT_g = upper gas temperature rise above ambient (K)

c_p = 1.0-kJ/kg·K (Section 4.4.9)

$$h_k = \left(k\rho c / t\right)^{1/2} \quad \text{for } t \le t_p$$ (**Equation 4.5-6**)

where:

Note: Concrete properties are used to approximate rock properties.

ρ = 2,100-kg/m³ (Section 4.4.10)

k = 1.4·10^{-3}-kW/m·K (Section 4.4.11)
c = 0.88-kJ/kg·K (Section 4.4.12)

Using a time of 1800 seconds burn duration (Section 6.2.1), once all trays have been involved:

$$h_k = [(0.0014)(2100)(0.88)/1800]^{1/2} = \mathbf{0.038\text{-}kW/m^2{\cdot}K}$$

This exposure fire is postulated to occur in Panel 3, adjacent to the emplacement drifts with the shortest distance to the ventilation doors in the drift turnout (Assumption 3.1.3).

The airflow quantity in the access main is: **254.1-m³/s** (Section 4.4.1)

Ambient air temperature is: 23.8ºC (**296.8-K**) (Section 4.4.2)

Density of air at 296 K is: **1.18-kg/m³** (Reference 2.2.24, Table B-2)

Compartment mass ventilation rate:

$$\dot{m} = (254.1)(1.18) = \mathbf{299.8\text{-}kg/s}$$

Total area of the compartment-enclosing surfaces:
Drift perimeter is: 23.94-m (Section 4.4.3)
Tray length is: 5.4-m (Section 6.2.1)

$$A_T = (23.94)(5.4) = \mathbf{129.3\text{-}m^2}$$

Solving for ΔT_g:

$$\Delta T_g = 296.8\left[0.63\left(\frac{(2775)}{(299.8)(1.0)(296.8)}\right)^{0.72}\left(\frac{(0.038)(129.3)}{(299.8)(1.0)}\right)^{-0.36}\right]$$

$$= 67.6 \quad \sim \mathbf{68\text{-}K}$$ Temperature change – Higher Ventilation Rate Case

Based on this airflow rate, this represents a modest increase in the upper layer temperature exterior to the TEV surface.

6.2.1.3.2 Upper Smoke Layer Temperature – Lower Ventilation Rate Case

The access main supplies ventilation flow to each emplacement drift. At the remote points of ventilation supply, the ventilation rate in the access main approaches that for the emplacement drift, approximately 15.1-m³/s (32,000-cfm) (Section 4.4.1).

At a ventilation rate of 15.1- m³/s and 23.8 C, the mass flow rate in kg/s is given by:

$$\dot{m} = (15.1)(1.18) = \mathbf{17.8\text{-}kg/s}$$

$\dot{m}$ = 17.8-kg/s and A_T = 129.3-m² (as before)

Solving for ΔT_g:

$$\Delta T_g = 296.8\left[0.63\left(\frac{(2775)}{(17.8)(1.0)(296.8)}\right)^{0.72}\left(\frac{(0.038)(129.3)}{(17.8)(1.0)}\right)^{-0.36}\right]$$

$= \mathbf{187\text{-}K}$ Temperature change – Lower Ventilation Rate Case

A temperature increase of 187-K (483.8-K absolute) is used for T_g.

6.2.1.3.3 Radiative Flux at TEV

Let T_w (wall temperature) equal T_g:

$T_w = T_g = 483.8$-K (Section 6.2.1.3.2)

Let $T_a = 296.8$-K (also known as T_∞)

Initially the TEV surface temperature is at ambient temperature, so:
$T_s = T_a = T_\infty = 296.8$-K.

Solving for the radiative flux (Section 6.2.1.2) gives:

$$\begin{aligned}\dot{q}_r'' &= (0.98)(5.67\cdot 10^{-11})(483.8)^4 + (1)(1-0.98)(5.67\cdot 10^{-11})(483.8)^4 + \\ &\quad (0)(1-0.98)(5.67\cdot 10^{-11})(483.8)^4 - (5.67\cdot 10^{-11})(296.8)^4 \\ &= \mathbf{2.7\text{-}kW/m^2}\end{aligned}$$

This flux at 2.7-kW/m² is not a significant threat to a steel object (a radiant heat intensity of 12.5-kW/m² is the minimum energy required for piloted ignition of wood, and melting of plastic tubing (Reference 2.2.2, Table 2.35)). This flux is also confined to a relatively small view area of the TEV surface directly adjacent to the burning cable trays.

6.2.1.3.4 Convective Flux at TEV

The convective flux exposure to the TEV can be determined by:

$$\dot{q}'' = h_c(T_f - T_s) \qquad \textbf{(Equation 4.5-7)}$$

where:

$h_c = 25$-W/m²·K (Section 4.4.13)

Let $T_f = T_g = 483.8$-K (Section 6.2.1.3.3)

$T_s = 296.8$-K (Section 6.2.1.3.3)

Let $\dot{q}'' = \dot{q}_c''$

$$\dot{q}_c'' = (0.025)(483.8 - 296.8)$$
$$= \mathbf{4.7\text{-}kW/m^2}$$

This convective flux exists only in the assumed 5.4-m long control volume. Convective exposure outside this volume would be less and decrease with distance from the seat of the fire.

6.2.1.4 Total Fire Exposure to TEV

The fire exposure to the TEV is the sum of the heat input from all sources.

$$\dot{Q}_{exposure} = \dot{Q}_{rad} + \dot{Q}_{conv}$$

where:
$\dot{Q}_{rad}$ = HRR due to radiative heat (kW)
$\dot{Q}_{conv}$ = HRR due to convective heat (kW)

Simplify the calculation by considering the entire upper half of the TEV surface area (an octagon) as in the control volume in the upper gas layer.

Area of exposed TEV shielding:

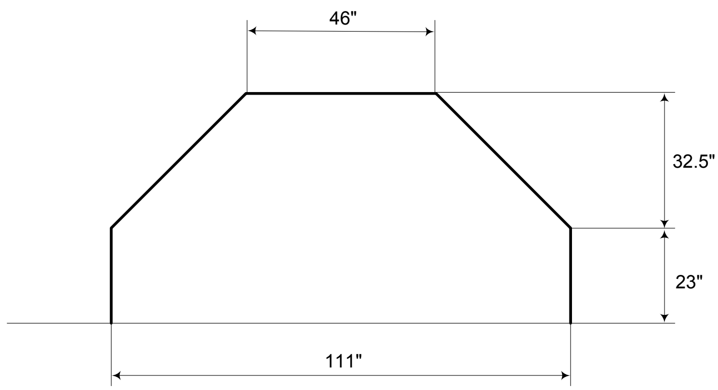


Figure 9. Partial Cross-Section of Outer Surface of TEV Shielding

Source: Reference 2.2.9, Sections 6.3.3.2.6 and 7.2

TEV exposed area = [((23+46+46+46+23)/12)(0.3048)](5.4)
= **25.2-m²**

Using:
$\dot{q}_r''$ = 2.7-kW/m² (Section 6.2.1.3.3)
$\dot{q}_c''$ = 4.7-kW/m² (Section 6.2.1.3.4)

The bounding fire exposure within the control volume to the upper half of the TEV is then:

$$\dot{Q}_{\exp osure} = (2.7)(25.2) + (4.7)(25.2)$$
$$= 186.5 \qquad \mathbf{\sim 187\text{-}kW}$$

Ignoring the shielding effect of the thermal barrier provided by the TEV itself, the WPs have been analyzed to a 10 CFR 71 exposure of 800ºC (1,073-K) for 30 minutes (Reference 2.2.1, Part 73(c)(4)), bounded by it, and found acceptable (Assumption 3.2.15).

The emissive power of the regulatory defined fire can be estimated by:

$$\dot{q}'' = \varphi\varepsilon\sigma T_e^{\,4} \qquad \textbf{(Equation 4.5-8)}$$

where:
$\dot{q}''$ = radiant heat flux at a point on receiving surface (kW/m²)
φ = 1.0 (worst-case factor)
ε = 0.9 (Section 4.4.14)
T_e = absolute temperature of the emitting surface (K)

$$\dot{q}'' = (1.0)(0.9)(5.67 \cdot 10^{-11})(1073)^4$$
$$= 67.6\text{-kW/m}^2$$

For an identical control volume surface area of 25.2-m² determined above:

$$Q = (25.2)(67.6)$$
$$= \mathbf{1{,}704\text{-}kW}$$

The heat input from the regulatory fire to a bare WP exceeds the calculated exposure by a factor of **9 times** (1704/187 = 9.1)

Based on this comparison, the postulated cable tray fire is not a significant fire threat to a WP either, directly exposed, or, in the TEV. This comparison is true for fire exposures to a WP either in a TEV in the access main or to a remotely located WP in an emplacement drift.

6.2.2 Waste Package Emplaced in an Emplacement Drift

As stated in Section 6.2, this exposure fire is postulated to occur in Panel 3, in the access main adjacent to a turnout with the shortest distance to the face of an emplacement drift (Assumption 3.1.3). This provides the worst-case (i.e., shortest) dimension for radiant heat from a main drift fire to an emplaced WP. This distance is greater than 71-m (232.5-ft) (Assumption 3.1.3), the distance from the emplacement access door to the first emplaced WP.

The postulated exposure fire to an emplaced WP is the same fire calculation presented in Section 6.2.1. Since installation of insulated cables is not planned in the turnouts, the electrical fire hazard in the access main is used to evaluate a fire exposure to an emplaced WP.

A cable tray fire in the access main could be less than 27-m (89-ft) (Assumption 3.1.3) distant from the turnout emplacement access doors, behind which are the emplaced WPs. This distance is significantly greater than the distance calculated for radiative heat effects to the TEV in the access main. Therefore heat input to a WP in the emplacement drift is much less and need not be considered further.

This scenario is bounded by the calculation performed for fire exposure to a TEV in an access main (Section 6.2.1.4).

6.3 SUBSURFACE REPOSITORY DEVELOPMENT AREA FIRE EXPOSURE SCENARIOS

6.3.1 Initial Fire Event

The worst-case development (construction) drift fire event is postulated to start on the MRC (Assumption 3.2.11). The MRC consists of a railcar, with secondary containment tank, storage tanks, barrel, pumps, and hose reels, that is used to transport fuel, lubricating oil, hydraulic oil, waste oil, and grease into the development area to service and refuel equipment (Assumption 3.1.4, Figure 4 and Figure 5). The storage unit would be field fabricated from steel and sit on the railcar. Air-operated pumps would be used to transfer the materials from the tanks to the serviced equipment. An external source of compressed air would be required to power the pumps. Fire protection, provided by an onboard automatic fire extinguishing system, is assumed to fail (Assumption 3.2.8).

The fire event occurs in a main drift at an unspecified distance from the ventilation isolation bulkhead/fire barrier between the development and emplacement areas (Assumption 3.2.7).

The MRC has no built-in motive power and is moved to its assigned location by a locomotive. This calculation excludes any of the locomotive's onboard fuel (diesel) (Assumption 3.2.10)

Total calculated fuel capacities for each container are shown in Assumption 3.1.4, Figure 5. These capacities are noted in Table 2. This fire is postulated as initiating from an electrostatic discharge during fuel or lubricant transfer operations (Assumption 3.2.11) and consumes all available fuel (Assumptions 3.2.5, 3.2.6 and 3.2.9).

6.3.1.1 MRC Total Fuel Capacities

Table 2 shows the calculated total fuel capacities of the MRC's onboard storage tanks (Assumption 3.1.4, Figure 5). These capacities reflect total volume without allowance for filling shutoff, expansion, and overfilling.

Table 2. Typical Maintenance Railcar – Total Fuel Capacities

Material	Calculated Capacity (gal)	Calculated Capacity (l)
Motor Oil	75.4	285.5
Compressor Oil	75.4	285.5
Hydraulic Oil	75.4	285.5
Waste Oil	75.4	285.5
Diesel Fuel	123.6	467.8
Grease	120 (lb)	54.4 (kg)

6.3.1.2 MRC Effective Fuel Capacities

The effective capacities of the fuel containers from Table 2 are as noted in Table 3. For this reason, the effective capacity of each container is 95 percent of total capacity (Assumption 3.2.5). This adjustment affects the burn time to a minor extent, but does not change the heat release rate (kW) output of the postulated fire event.

Table 3. Typical Maintenance Railcar – Effective Fuel Capacities

Material	Effective Capacity (l)
Motor Oil	271.0
Compressor Oil	271.0
Hydraulic Oil	271.0
Waste Oil	271.0
Diesel Fuel	444.0
Grease	51.7 (kg)

6.3.1.3 MRC Fuel Burning Rate Data

Burning rate parameters for large pools can be obtained from the *Technical Report on Nuclear Facility Fire Heat Release Rates* (Reference 2.2.8, Section 6.2.4) and the *SFPE Handbook of Fire Protection Engineering*, Table 3-1.2 (Reference 2.2.24). Both these sources provide the parameters shown in Table 4 and Table 5 and are based on the best match to published and available data.

Table 4. Assigned Burning Rate Data

MRC Material	Assigned Material Match	Density (kg/m³)	Heat of Combustion Δh_c (MJ/kg)	Mass Loss Rate $\dot{m}''_\infty$ (kg/m²·s)	Extinction-Absorption Coefficient $k\beta$ (m⁻¹)
Motor Oil [1,2]	Hydrocarbon Transformer Oil	760	46.0	0.039	0.7
Compressor Oil [1,2]	Hydrocarbon Transformer Oil	760	46.0	0.039	0.7
Hydraulic Oil [1,2]	Hydrocarbon Transformer Oil	760	46.0	0.039	0.7
Waste Oil [1,2]	Hydrocarbon Transformer Oil	760	46.0	0.039	0.7
Grease [2]	Heavy Fuel Oil	970 (avg.)	39.7	0.035	1.7

Source: [1] Reference 2.2.8, Section 6.2.4.2
[2] Reference 2.2.24, Table 3-1.2

where:
Δh_c = heat of combustion (MJ/kg)
$\dot{m}''_\infty$ = mass loss rate per unit area for very large pool diameters (kg/m²·s)
k = extinction-absorption coefficient (m⁻¹)
β = mean-beam-length corrector (-)

Burning rate parameters for diesel fuel are shown in Table 5.

Table 5. Diesel Fuel Assigned Burning Rate Data

MRC Material	Assigned Material Match	Density (kg/m³)	Heat of Combustion Δh_c (MJ/kg)	Mass Loss Rate $\dot{m}''$ (kg/m²·s)
Diesel Fuel	Diesel	918 [1]	44.4 [1]	0.045 [2]

Source: [1] Reference 2.2.8, Section 6.2.4.1
[2] Reference 2.2.18, p.5-29

where:
Δh_c = heat of combustion (MJ/kg)
$\dot{m}''$ = mass loss rate per unit area for pool diameters>0.2-m (kg/m²·s) (Reference 2.2.24, p.3-3)

6.3.1.4 MRC Burning Time

A pool fire is postulated to occur in the MRC secondary containment. The fire area is postulated across the full area of the secondary containment (Assumption 3.2.6). From Figure 5 this area is calculated to be:

A = (5′-7″ x 8′-0″) = (44.7-ft²) = **4.15-m²**

An equivalent circular diameter for this rectangular area can be found as follows:

A = 0.785 D²

$$D = \sqrt{\frac{A}{0.785}} = \sqrt{\frac{4.15}{0.785}} = 2.3\text{-m}$$

For D>0.2m, the mass loss rate (burning rate) (kg/m²·s) can be expressed as

$$\dot{m}'' = \dot{m}''_{\infty}\left(1 - e^{-k\beta D}\right)$$ (**Equation 4.5-9**)

The burning time for each of these materials is calculated from the following equation:

$$t_b = \frac{V\rho}{\dot{m}'' A}$$ (**Equation 4.5-10**)

Applying the data from Table 4 and Table 5, the burning times are calculated and shown in Table 6.

Table 6. Calculated Burning Times

Material	Burning Rate $\dot{m}''$ (kg/m² s)	Burning Time (s)	Burning Time (min)
Motor Oil	0.031	1600	27
Compressor Oil	0.031	1600	27
Hydraulic Oil	0.031	1600	27
Waste Oil	0.031	1600	27
Diesel Fuel	0.045 [1]	2183	36
Grease	0.034	366	6
Total		8949 = ~ 9000	150 = 2.5 hours

Source: [1] Table 5

The burning time calculation assumes 100 percent consumption of all available fuel (Assumption 3.2.9), as listed in Table 3.

Adding a 30-minute allowance for uncertainty due to data match:

Fire Duration for MRC is postulated as **3.0-hours.**

Effects on materials combining during burning and at what time they would combine are not addressed and this information or an approach is not known to exist. Further refinements of MRC burn-time can only be obtained through a fire test program that would also have a good means to predict fuel material container-failure.

6.3.1.5 MRC Heat Release Rate

The HRR for the MRC is approximated by using the following equation:

$$\dot{Q} = \Delta h_c \, \dot{m}'' A \qquad \textbf{(Equation 4.5-11)}$$

where:

A = surface burning area = 4.15-m² (Section 6.3.1.4)

In order to model the HRR from this fire, a single fuel is selected. The largest single fuel quantity on the railcar is diesel. Diesel fuel is selected to model various fire parameters other than the total burning time previously determined.

$$\dot{Q} = (44400)(0.045)(4.15) \qquad \text{(Table 5)}$$
$$\dot{Q} = 8{,}292\text{-kW} \sim \textbf{8.3-MW Fire}$$

An 8.3-MW fire for a pool size of 4.15-m² is consistent with values obtained through testing. In *Aerodynamics and Ventilation of Vehicle Tunnels* (Reference 2.2.16) it is reported, "a large petrol fire in the open will burn at a linear rate of about 4-mm/min, some 2-MW/m²." (Reference 2.2.16, p. J1-5).

Using the MRC pool size of 4.15-m², this equates to a fire size of 8.3-MW. This is a good correlation to the MRC fire size of 8.3-MW, allowing for differences in fuel (petrol-gasoline) and different test conditions.

6.3.2 Alternative Fire Event

An alternative fire event is reviewed to check if the DBF actually bounds the "worst-case" fire event. The scenario evaluated is when the LHD is in use over the railroad tracks in a development (construction) drift. No other vehicles are involved in this fire event.

The alternative fire event is postulated to start on a small (one cubic yard) LHD (Assumption 3.1.5). This LHD is used to muck-out the rock removed during construction. The fire event is assumed to result from a small puncture to the vehicle's fuel tank (Assumption 3.2.12) that pools under the rear of the vehicle, ignites, and burns the tires.

6.3.2.1 One-Yard LHD Fuel Capacity

The fuel capacity is shown in Assumption 3.1.5 and noted in Table 7. This fire is postulated to consume all available fuel (Assumption 3.2.12).

Table 7. One-Yard Load-Haul-Dump Fuel Capacities

Material	Capacity (gal)	Capacity (l)
Diesel Fuel	22	83
Hydraulic Oil	22	83
Hydraulic Transmission	15	57

6.3.2.2 One-Yard LHD Fuel Burning Rate Data

The following parameters, shown in Table 8, are assigned, based on best match to published and available data (See Table 4 and Table 5).

Table 8. One-Yard LHD Assigned Burning Rate Data

LHD Material	Assigned Material Match	Density (kg/m³)	Heat of Combustion Δh_c (MJ/kg)	Mass Loss Rate $\dot{m}''_\infty$ (kg/m²·s)	Extinction-Absorption Coefficient $k\beta$ (m⁻¹)	Mass Loss Rate $\dot{m}''$ (kg/m²·s)
Hydraulic Oil [1]	Hydrocarbon Transformer Oil	760	46.0	0.039	0.7	(See Table 9)
Diesel Fuel [2]	Diesel	918	44.4	N.A.	N.A.	0.045

Source: [1] Table 4, [2] Table 5

6.3.2.3 One-Yard LHD Burning Time

In case of the LHD's fuel tank puncture and the subsequent fire occurring in or near the ventilation isolation bulkhead, only onboard fuels and vehicle tires are the primary contributors to the postulated fire event. The resulting pool fire occurs on the unobstructed floor of an excavated area.

6.3.2.3.1 Diesel Fuel

The steady state leak-rate for a 5-mm diameter hole (Assumption 3.2.12) in an atmospheric storage tank is approximately 1.0-l/min (Reference 2.2.23, Figure 5). The pool diameter for this flow rate is approximately 0.5-m (Reference 2.2.23, Figure 6). These values are based on gasoline pool fire characteristics and should reasonably bound the diesel fuel tank spill postulated.

The area of the pool is calculated to be:

$$A_D = 0.785\ (0.5)^2 = \mathbf{0.196\text{-}m^2} \qquad \text{(Section 6.3.1.4)}$$

6.3.2.3.2 Hydraulic Oil

Catastrophic failure of both the hydraulic oil tank and the hydraulic transmission containment spreads into a pool of 10-mm thickness (Assumption 3.2.13).

Total Volume (V_H) = 83 + 57 = 140-l (**0.140-m³**) (Table 7)
Thickness (t_H) = 0.010-m
Area (A_H) = 0.140 ÷ 0.010 = **14.0-m²**

Pool Diameter (D_H) = $\sqrt{\dfrac{4\times 0.140}{\pi\times 0.010}}$ = 4.22 m ~ **4.2-m**

6.3.2.3.3 Diesel and Hydraulic Oil Burning Times

For D>0.2m, the mass loss rate (kg/m²·s) can be expressed as

$$\dot{m}'' = \dot{m}''_{\infty}\left(1-e^{-k\beta D}\right)$$ (**Equation 4.5-9**)

The burning time for each of these materials is calculated from the following equation:

$$t_b = \frac{V\rho}{\dot{m}''A}$$ (**Equation 4.5-10**)

Applying the data from Table 8 and Sections 6.3.2.3.1 and 6.3.2.3.2, the burning rate and time are calculated and shown in Table 9.

Table 9. One-Yard LHD Calculated Burning Time for Combustible Liquids

Material	Volume m³	Density kg/m³	Burning Rate $\dot{m}''$ (kg/m² s)	Area m²	Burning Time (s)	Burning Time (min)
Hydraulic Oil & Transmission Oil	0.140	760	0.037	14.0	205	3.4
Diesel Fuel	0.083	918	0.045	0.196	8639	144

The burning time calculation assumes 100-percent consumption of all available fuel (Assumption 3.2.12). These burning rates differ from those calculated in Table 6 due to different pool sizes. These fuels burn simultaneously, therefore the burning time is equal to the longer of the two calculated times, i.e., 144-min ~ **2.4-hours**.

Adding a 30-minute allowance for uncertainty due to data match:

Fire duration for LHD fuels is postulated as **3.0-hours**.

6.3.2.3.4 Tires Burning Time

A typical LHD is shown in Assumption 3.1.5, Figure 6. Tire dimensions and weights are shown in Assumption 3.1.5, Figure 6.

Tire Size = 229-mm (9-in) wide by 965-mm (38-in) (outside diameter)
Rim Size = 508-mm (20-in) (tire inside diameter)

Exposed Area of each tire sidewall = $\frac{\pi}{4}\left\{(0.965)^2 - (0.508)^2\right\}$
= 0.53-m²

Exposed Area of each tire tread = π (0.965)(0.229) = 0.694-m²

Total Tire Exposed Area = 8(0.53) + 4(0.694) = **7.02-m²** (using twelve exposed surfaces, four tires exposed on each side plus four exposed tread surfaces)

Tire Weights:
(Note: tire weights include foam filling, which is typical for tunneling equipment)
Total Rubber (Carcass) Weight = 4 x 49 = **196-kg** (432-lb)
Total Foam Fill Weight = 4 x 107 = **428-kg** (944-lb)

Rubber Carcass Burning Time:

$$t_b = \frac{W}{\dot{m}''A} \quad \textbf{(Equation 4.5-12)}$$

where:
Total weight = 196-kg

$$\dot{m}'' = \frac{\dot{q}''_e - \dot{q}''_{rr}}{\Delta H_g} \quad \textbf{(Equation 4.5-13)}$$

where;
$\dot{q}''_e$ = external heat flux = 56-kW/m² (Section 4.4.15)
$\dot{q}''_{rr}$ = surface re-radiation heat flux = 10-kW/m² (Section 4.4.16)
ΔH_g = heat of gasification at ambient temp. = 2.7-kJ/g (Section 4.4.17)

$$\dot{m}'' = \frac{(56)-(10)}{(2.7)} = 17.04\text{-g/m}^2\text{ s}$$
= **0.017-kg/m² s**

A = exposed area of material burning
= 7.02-m²

$$\text{Time (s)} = \frac{196}{(0.017)\times(7.02)} = 1{,}642 \qquad = \mathbf{27.4\text{-min}}$$

Foam Fill Burning Time:

Total weight = 428-kg
$\dot{m}''$ = 0.025-kg/m² s (Section 4.4.18)
A = 7.02-m² (Using the same exposed area as rubber carcass)

$$\text{Time (s)} = \frac{428}{(0.025)\times(7.02)} = 2{,}439 \qquad = \mathbf{40.7\text{-min}}$$

Total tire (and foam fill) burning time = 27.4 + 40.7 = **68-min**

6.3.2.3.5 Pool Sizes

The diesel tank spill and the hydraulic oil tank failure will spill into the space between adjacent ties. The volume between adjacent ties will depend on the extent of muck filling the spaces around the ties. For this calculation, the voids under the ties and along the sides of the ties are assumed filled, leaving pockets between the ties for fuel to pool in (Assumption 3.2.14).

Cross-sectional Area of Tie: = 1.524-m (5′) x 0.1524-m (6″) = 0.23-m²
(Assumption 3.1.6)

Volume Tie-to-Tie: = Area x Separation Distance
= 0.23 x (0.762 – 0.2032) (Assumption 3.1.6)
= 0.129-m³

Catastrophic failure of the hydraulic oil tank and hydraulic transmission containment spills into this space.

Total Volume (V_H) = **0.140-m³** (Section 6.3.2.3.2)

Since the volume between adjacent ties is essentially the same as the spill volume (0.129-m³ and 0.140-m³), the smallest pool size and thus the longest burning time is 0.140-m³.

Surface Area of Pool = 1.524 x 0.5588 = **0.85-m²**

$$\text{Equivalent Diameter} = \sqrt{\frac{0.85}{0.785}} = \mathbf{1.04\text{-m}}$$

6.3.2.3.6 Revised One-Yard LHD Burning Time

If the hydraulic oil and transmission fluid spill pools to fill the available area between the two adjacent ties, then:

D = 1.04-m (A = 0.85-m²)

$$\dot{m}'' = 0.039\left(1 - e^{-(0.7)(1.04)}\right) \qquad = 0.02$$

$$\text{Time} = \frac{(0.140)(760)}{(0.02)(0.85)} \qquad = 6{,}259\text{-s} = \mathbf{104.3\text{-min}}$$

If the diesel spill pools to fill the available area between the two adjacent ties, then:

D = 1.04-m (A = 0.85-m²)

$\dot{m}'' = 0.045$ (Table 8)

$$\text{Time} = \frac{(0.083)(918)}{(0.045)(0.85)} \qquad = 1{,}992\text{-s} = \mathbf{33.2\text{-min}}$$

Check the diesel leak rate to see if this burn time is possible.

Leak Rate = 1.0-l/min (Section 6.3.2.3.1)

$$= \frac{0.001}{60} = 1.67 \times 10^{-5}\text{-m}^3/\text{s}$$

If Burn Rate = Leak Rate, then:

Burn Rate = $(1.67 \times 10^{-5}\ \text{m}^3/\text{s})(918\ \text{kg/m}^3)$ = 0.015-kg/s

$$\text{Burn Time} = \frac{(0.083)(60)}{(0.001)} \qquad = 4{,}980\text{-s} = \mathbf{83\text{-min}}$$

Since the diesel pool burn time cannot exceed the spill rate burn time, the calculated time of 33.2-min, based on using the total surface area between two adjacent ties, cannot be used. The burn time will therefore equal the leak rate of 83-min. Table 10 summarizes the burning times for the LHD fuels.

Table 10. Revised One-Yard LHD Calculated Burning Times

Material	Volume m^3	Density kg/m^3	Burning Rate $\dot{m}''$ (kg/m^2 s)	Area m^2	Burning Time (s)	Burning Time (min)
Hydraulic Oil & Transmission Oil	0.140	760	0.020	0.85	6,259	104
Diesel Fuel	0.083	918	N.A.	N.A.	4,980	83
Tires (1)					4,081	68

(1) See Section 6.3.2.3.4

These fuels burn simultaneously, therefore the burning time is equal to the longest of the three calculated times, i.e., 104-min ~ **1.7-hours.**

Adding a 30-minute allowance for uncertainty due to data match:

Fire duration for LHD fuels is postulated as **2.2-hours.**

7. RESULTS AND CONCLUSIONS

7.1 RESULTS

7.1.1 TEV Surface Fire Exposure Scenarios

7.1.1.1 TEV Rail Pathway To Site Buildings

Based on the 12.5-m (41-ft) distance required by code (Section 6.1.1), and the fact that building hazards are protected by automatic fire suppression systems, a 34-m (112-ft) separation distance from the closest TEV rail to a facility should provide adequate separation distance from a building exposure. Building fire exposure to the TEV is therefore, not a concern.

7.1.1.2 TEV Exposure to Equipment

A radiant heat intensity of 12.5-kW/m² is necessary to melt plastic tubing (Reference 2.2.2, Table 2.35). A radiant heat intensity of 37.5-kW/m² is necessary to cause damage to process equipment (Reference 2.2.2, Table 2.35). A pool fire resulting from a diesel-fueled locomotive on an adjacent rail track is not anticipated to reach these levels (Section 6.1.2). The 83-m (273-ft) separation distance results in incidental heat flux to the TEV, adjacent to the Heavy Equipment Maintenance Facility (Area 220), less than these numbers. Therefore, the heat energy being radiated towards the shielded WPs onboard the TEV is insufficient to damage the WP.

7.1.1.3 TEV Exposure To Offsite Wildfires

The 15-m (49-ft) distance to the TEV exceeds the established minimum distance (Section 6.1.3). Wildfire exposure to the TEV therefore, is not a concern.

7.1.2 TEV Subsurface Fire Exposure Scenarios

7.1.2.1 Total Fire Exposure to TEV

Based on the comparison of fire exposure to the TEV and the regulatory fire (Section 6.2.1.4), the postulated cable tray fire is not a significant fire threat to a WP either directly exposed or in the TEV. This comparison is true for fire exposures to a WP either in a TEV in the access main or to a remotely located WP in an emplacement drift.

7.1.2.2 WP Emplaced in an Emplacement Drift

As stated in Section 6.2.2, this scenario is bounded by the calculation performed for fire exposure to a TEV in an access main (Section 6.2.1).

7.1.3 Development Area Fire Exposure Scenarios

The MRC fire duration of 3.0-hours (Section 6.3.1.4) is bounding for the LHD combustible liquid (Section 6.3.2.3.6) and the rubber tire fire duration (Section 6.3.2.3.4) as summarized in Table 11.

Table 11. Summary - Development Area Fire Exposure Burn Times

Material	Burning Time (hours)	Source
MRC Fuels	3.0	Section 6.3.1.4
LHD Fuels	2.2	Section 6.3.2.3.6
LHD Tires	1.1	Section 6.3.2.3.4

The fire-resistance rating of a single ventilation isolation bulkhead/fire barrier needs to be a minimum of **3-hours**. This bounds an exposure fire from likely combustible liquid fire event scenarios in the development (construction) areas so as not to expose a WP in the emplacement area of the repository.

7.2 CONCLUSIONS

The results for each section of this calculation are summarized here. The output values from these calculations are reasonable compared to the input values and are suitable for their intended use.

7.2.1 Surface Fire Exposures

Three locations were evaluated for fire exposure to a TEV containing a WP:

- On the rail pathway adjacent to site buildings
- On the rail pathway adjacent to equipment
- Exposed to offsite wildfires

In each of these locations the separation distance from the postulated hazard to the WP onboard the TEV is sufficiently large to render surface fire exposures of no concern (Sections 6.1.1, 6.1.2, and 6.1.3).

7.2.2 Subsurface Repository Emplacement Area Fire Exposures

A single location was evaluated for fire exposure to a TEV containing a WP and the impact of the same fire exposure to an emplaced WP evaluated:

- In an access main adjacent to a turnout

The postulated cable tray fire is not a significant threat to a WP either directly exposed or onboard the TEV (Sections 6.2.1.4 and 6.2.2). The calculated heat input is approximately one-ninth of the bounding regulatory fire (Section 6.2.1.4).

7.2.3 Subsurface Repository Development Area Fire Exposures

Fire exposure to a ventilation isolation bulkhead/fire barrier from two pieces of construction equipment was evaluated. These were:

- Maintenance Railcar (MRC)
- Load-Haul-Dump (LHD)

The 3.0-hour fire duration for liquid fuel burning bounds all of the fire scenarios postulated (Section 7.1.3 and Table 11). To prevent an exposure fire in the development (construction) areas from exposing a WP in the repository, the fire-resistance rating of each ventilation isolation bulkhead/fire barrier needs to be 3-hours minimum.

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