ABSTRACT

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| Title of Thesis: | **ANALYSIS OF FIRE CONDITIONS IN A CLOSED-END TUNNEL** |
| | **Joelle DeJoseph, Master of Science, 2004** |
| Thesis Directed By: | **Associate Professor Frederick W. Mowrer Department of Fire Protection Engineering** |

Many studies have addressed fires in tunnels. For the most part, these previous studies have addressed fires that might occur during operation of the tunnel, when the tunnel has openings at both ends. During construction of a tunnel, the tunnel has only one opening as the tunnel is being bored. Analysis of fire conditions that might develop during construction of a tunnel is addressed here. A number of analyses are presented to assess tenability conditions in a closed-end subsurface environment as a result of different postulated fire scenarios. The purpose of these analyses is to develop fire tenability criteria for use in evaluating subsurface life and fire safety.

ANALYSIS OF FIRE CONDITIONS IN A CLOSED-END TUNNEL


By


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# Acknowledgements

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| | |
|---|---|
| $A_{ConveyorBelt}$ | Surface Area of Conveyor Belt (m²) |
| $A_{ElectricCables}$ | Surface Area of Electric Cables (m²) |
| $A_f$ | Surface Area of Fuel (m²) |
| $A_{HydraulicLines}$ | Surface Area of Hydraulic Lines (m²) |
| $A_{ts}$ | Surface Area of Tunnel Boundaries (m²) |
| $A_{xs}$ | Cross-sectional Area of Tunnel (m²) |
| $C_d$ | Orifice Discharge Coefficient |
| CFD | Computational Fluid Dynamics |
| $c_p$ | Average Specific Heat at Constant Pressure (kJ/kg K) |
| EPR | Ethylene-Propylene Rubber |
| FDS | Fire Dynamics Simulator |
| $f_i$ | Species Yield ($g_i/g_f$) |
| $f_s$ | Yield of Smoke($g_s/g_f$) |
| $g$ | Gravitational Constant (m/s²) |
| $\Delta H_c$ | Heat of Combustion (MJ/kg) |
| $\Delta H_g$ | Heat of Gasification (MJ/kg) |
| $h_k$ | Heat Transfer Coefficient (kW/m²K) |
| $H_n$ | Neutral Plane Elevation (m) |

| | |
|---|---|
| $H_o$ | Tunnel Height (m) |
| $k$ | Conductivity (kW/mK) |
| $K$ | Extinction Coefficient (1/m) |
| $k\beta$ | Extinction-Absorption Coefficient (1/m) |
| K-H | Kelvin-Helmholtz |
| LES | Large Eddy Simulation |
| LHD | Diesel-Powered Load-Haul-Dump Vehicle |
| $\dot{m}_{ext}$ | Mass Extraction Rate of Ventilation System (kg/s) |
| $m_f$ | Mass of Fuel (kg) |
| $\dot{m}_f$ | Mass Loss Rate of Fuel (kg/s) |
| $\dot{m}''_f$ | Mass Loss Rate of Fuel per Unit Area (kg/m$^2$s) |
| $\dot{m}_i$ | Mass Flow Rate of Species (kg/s) |
| $\dot{m}_{inj}$ | Mass Injection Rate of Ventilation System (kg/s) |
| $\dot{m}_{nat}$ | Mass Rate of Natural Ventilation System (kg/s) |
| $\dot{m}_s$ | Mass Flow Rate of Smoke (kg/s) |
| $\dot{m}_{tot}$ | Total Mass Flow Rate (kg/s) $= \dot{m}_a + \dot{m}_f$ |
| NIST | National Institute of Standards and Technology |
| NFPA | National Fire Protection Association |
| $\Delta p_I$ | Pressure Differences Due to Inertia |
| $\Delta p_B$ | Pressure Differences Due to Buoyancy |

| | |
|---|---|
| $q_e''$ | External Heat Flux (kW/m$^2$) |
| $\dot{Q}_f$ | Heat Release Rate of Fuel (MW) |
| $\dot{Q}_{max}$ | Maximum Heat Release Rate (MW) |
| $q_{rr}''$ | Surface Re-Radiation Loss (kW/m$^2$) |
| $\dot{Q}_{tot}$ | Total Heat Release Rate (MW) |
| $r$ | Stoichiometric Fuel to Oxygen Mass Ratio |
| $S$ | Visibility Estimate (m) |
| SBR | Styrene Butadiene Rubber |
| SFPE | Society of Fire Protection Engineers |
| $\Delta T$ | Temperature Change (ºC, K) |
| $\Delta T_c$ | Characteristic Temperature Change (ºC, K) |
| $t$ | Simulation Time (s) |
| $t_b$ | Burning Time (s, min, hr) |
| TBM | Tunnel Boring Machine |
| $T_o$ | Ambient Temperature (ºC, K) |
| $t_p$ | Thermal Penetration Time (s) |
| $T_s$ | Smoke Temperature (ºC, K) |
| US | United States |
| $v_a$ | Air Speed (m/s) |
| $\dot{V}_{ext}$ | Extraction Volumetric Flow Rate (m$^3$/s) |

| | |
|---|---|
| $V_f$ | Volume of Fuel ($m^3$) |
| $\dot{V}_{inj}$ | Injection Volumetric Flow Rate ($m^3$/s) |
| $Y_s$ | Mass Fraction of Smoke ($g_s$/$g_{tot}$) |
| | |
| $\alpha$ | Thermal Diffusivity ($m^2$/s) |
| $\chi_{ch}$ | Combustion Efficiency |
| $\delta$ | Thickness (m) |
| $\phi_{gl}$ | Global Equivalency Ratio |
| $v$ | Rate of Smoke Propagation (m/s) |
| $v_{ext}$ | Extraction Rate of Smoke Propagation (m/s) |
| $v_{inj}$ | Injection Rate of Smoke Propagation (m/s) |
| $v_{nat}$ | Natural Ventilation Rate of Smoke Propagation (m/s) |
| $\rho$ | Density (kg/$m^3$) |
| $\rho_f$ | Density of Fuel (kg/$m^3$) |
| $\rho_o$ | Density of Air at Ambient Conditions (kg/$m^3$) |
| $\rho_s$ | Smoke Density (kg/$m^3$) |
| $\sigma_s$ | Mass Specific Extinction Coefficient ($m^2$/g) |

# Chapter 1: Introduction

Tunnels are a pervasive part of modern life. They are used for the transport of people

and goods on roadways, railways and subways as well as for the transport of utilities,

including water, gas and electricity. Fires in tunnels during normal operations are

particularly hazardous due to the confined environment and the limited access to and

egress from a tunnel. Several fires throughout the world during the past decade have

focused considerable attention on fires in tunnels. Table 1 presents a partial list of

significant tunnel fires, dating back to 1995 [1].

| Tunnel | Country | Date | Type | Deaths |
|--------|---------|------|------|--------|
| Jungango | S. Korea | 18 Feb 2003 | Metro | 189 |
| St. Gotthard | Switzerland | 24 Oct 2001 | Road | 11 |
| Kitzsteinhorn | Austria | 11 Nov 2000 | Funicular | 155 |
| Tauern | Austria | 29 May 1999 | Road | 12 |
| Mont Blanc | France/Italy | 24 March 1999 | Road | 39 |
| Gueizhou | China | 10 July 1998 | Rail | 80 |
| Baku Subway | Azerbaijan | 28 Oct 1995 | Metro | 260+ |

Table 1. Major Tunnel Fires Throughout the World Over the Past Decade

Most of the focus on tunnel fires has been on fires that occur during operation of the

tunnel. This period will generally be the longest period in the life cycle of a tunnel

and frequently constitutes the greatest risk to people and property, both in terms of

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the probability as well as the consequences of a fire. But it is not the only risky period in the life cycle of a tunnel. Fires can also occur during construction of a tunnel. Such fires are the topic of this thesis.

One of the distinguishing features of a tunnel during construction is its single-ended geometry. As a tunnel is being bored, whether from one end or simultaneously from both ends, the tunnel will have only a single opening. This will have an influence on both the dynamics of any fires that might occur during tunnel boring operations as well as the life safety of workers in the tunnel, who will have only one direction in which to evacuate the tunnel.

In this thesis, a number of analyses are presented to assess conditions resulting from fires in closed-end tunnels as a result of postulated fire scenarios. The purpose of these analyses is to develop fire tenability criteria for use in evaluating subsurface life and fire safety conditions for closed-end tunnels.

In general, the approach presented here includes the following steps:
1. Estimate the intensity and duration of the fire source term for the postulated fire scenario;
2. Calculate the fire-induced conditions, including visibility, temperature and oxygen concentrations, resulting from the specified fire source as a function of time and location.

The scenario analysis addresses three different ventilation conditions, two separate fire locations, and two possible locations for workers to be located within the tunnel. The first ventilation condition assumes that air is being injected into the tunnel through a ventilation duct suspended from the top of the tunnel. The second ventilation condition assumes that air (or smoke) is being extracted through the same duct at the same rate. The third ventilation condition assumes that there is no forced ventilation at the time of the postulated fire. The first location for a fire is near the closed-end of the tunnel where the tunnel boring machine is operating. If the fire is in this location, workers can only be up tunnel of the fire. Up-tunnel refers to a position closer to the vent opening than the reference location while down-tunnel refers to a position between the reference location and the closed end of the tunnel. The second fire location being examined is at the midpoint of the tunnel. For a fire in this location, workers could be on either side of the fire. For a fire at the midpoint of the tunnel, the integrity of the ventilation duct is assumed, although this might not be a realistic assumption.

The first ventilation scenario is forced injection. The first location of the fire is located at the closed-end, down tunnel of the end of the ventilation duct. There is only one possible location for the workers to be located, up tunnel from the fire. Figure 1 shows this case schematically. The second two forced injection cases have the fire located at the midpoint of the tunnel, with workers on either side of the fire. Figures 2 and 3 show these cases schematically.

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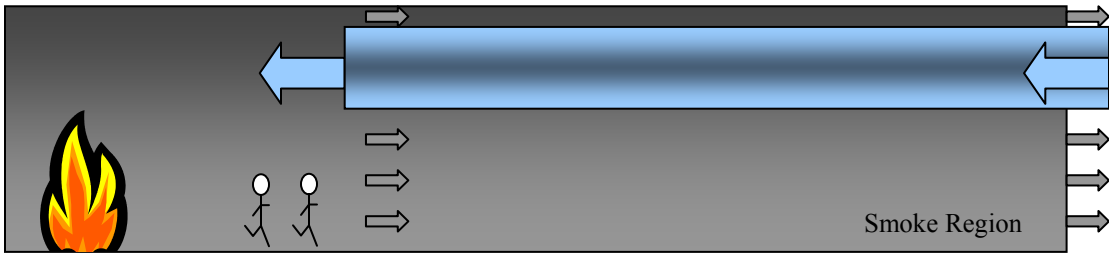
Figure 1. Schematic Illustration of Fire at Closed-End of Tunnel with Forced Injection of Air with Workers Up Tunnel
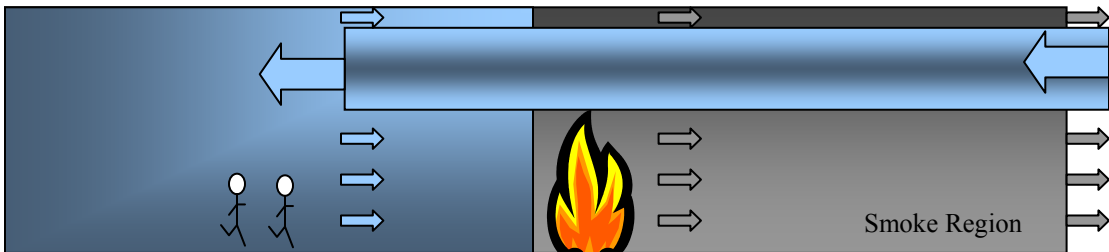


Figure 2. Schematic Illustration of Fire at Midpoint of Tunnel with Forced Injection of Air with Workers Down Tunnel
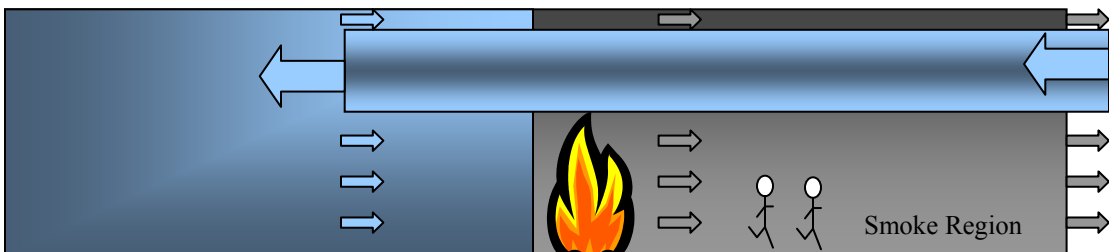


Figure 3. Schematic Illustration of Fire at Midpoint of Tunnel with Forced Injection of Air with Workers Up Tunnel

The second ventilation condition to be examined is forced extraction. The fire and worker locations are the same as the forced injection case. Figures 4, 5, and 6 shows each case schematically.
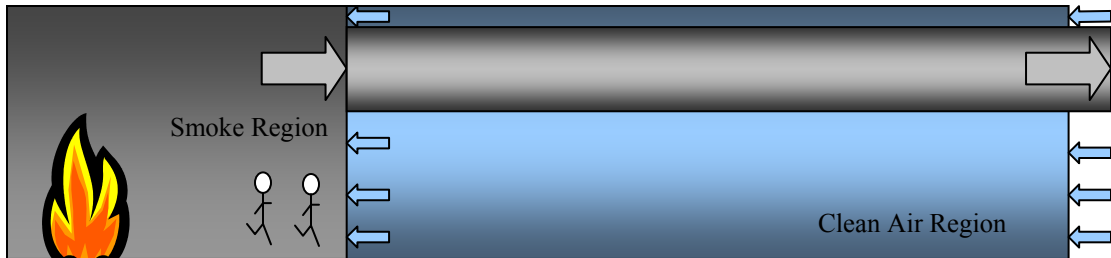
Figure 4. Schematic Illustration of Fire at Closed-End of Tunnel with Forced Extraction of Air with Workers Up Tunnel
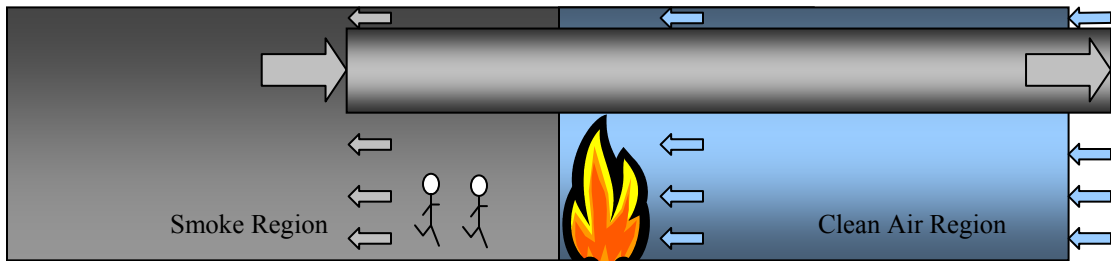
Figure 5. Schematic Illustration of Fire at Midpoint of Tunnel with Forced Extraction of Air with Workers Down Tunnel
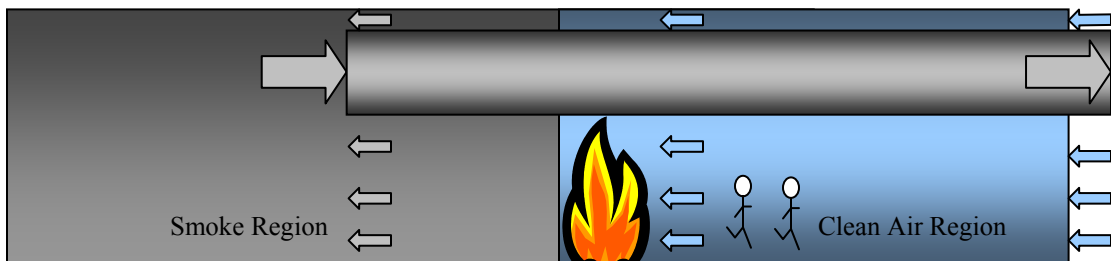
Figure 6. Schematic Illustration of Fire at Midpoint of Tunnel with Forced Extraction of Air with Workers Up Tunnel

The final ventilation condition is natural ventilation.  The fire and worker locations are the same as in the forced ventilation scenarios and each case is schematically shown below in Figures 7, 8, and 9.
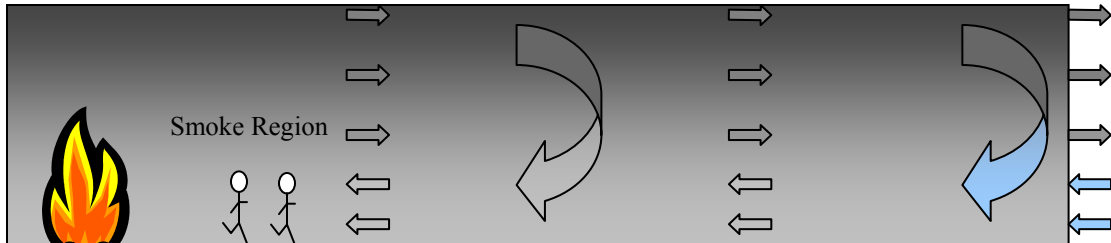


Figure 7. Schematic Illustration of Fire at Closed-End of Tunnel with Natural Ventilation of Air with Workers Up Tunnel
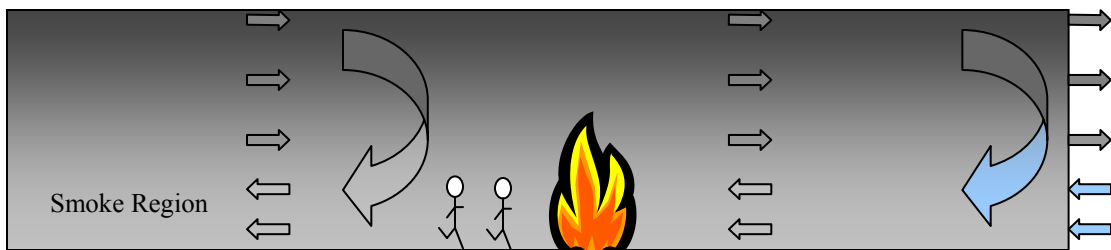


Figure 8. Schematic Illustration of Fire at Midpoint of Tunnel with Natural Ventilation of Air with Workers Down Tunnel
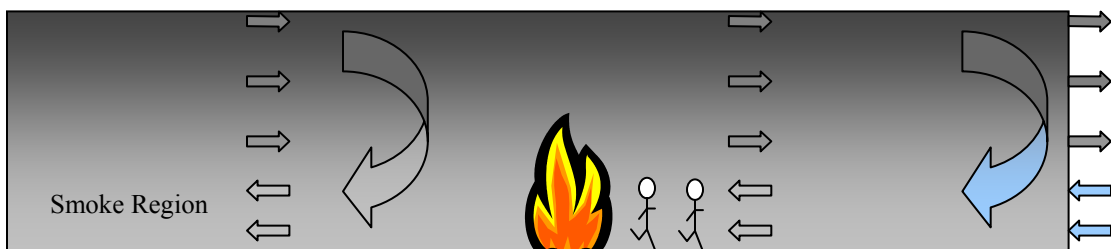


Figure 9. Schematic Illustration of Fire at Midpoint of Tunnel with Natural Ventilation of Air with Workers Up Tunnel

There are significant differences between an open-ended tunnel and a closed-ended tunnel. An open-ended tunnel allows egress and air flow to occur in both directions, although the fire conditions that develop may obstruct one or both egress paths. If an open-ended tunnel has a slope, the buoyant smoke will tend to move upward along the sloped surface. The tunnel will act as a chimney, carrying the smoke up the tunnel and away from the fire. For this situation, the only safe egress is down the tunnel, upstream of the fire.

An example of this type of chimney effect in a sloping open-ended tunnel was observed in the devastating Kaprun tunnel fire in the Kitzsteinhorn Mountain that claimed the lives of 155 people. The fire started in a funicular vehicle near the low end of the tunnel. As the fire burned, the smoke moved upward through the tunnel towards the upper, open-end. All of the fatalities occurred above the fire. [13]

In a closed-end tunnel with only a single opening, construction workers in the tunnel can move in only one direction to evacuate the tunnel. The fire and smoke conditions to which these people might be subjected depends on a number of variables, including:

- The intensity of the fire and the quality and quantity of smoke produced;
- The locations of the workers relative to the fire and the tunnel entrance;
- The ventilation configuration for the tunnel.

This thesis will examine fire scenarios in a tunnel during construction. The tunnel geometry is such that there is a closed-end and no slope. The three different ventilation conditions described previously will be considered, along with two different fire locations with workers being on either side of the fire. Tables 2 and 3 summarize each scenario being investigated in this thesis.

| | Worker Location | |
|---|---|---|
| **Ventilation Condition** | **Up Tunnel** | **Down Tunnel** |
| Forced Injection | | ● |
| Forced Extraction | | ● |
| Natural | | ● |

Table 2. Scenarios Considered for a Fire Located at the Closed-End of Tunnel

| | Worker Location | |
|---|---|---|
| **Ventilation Condition** | **Up Tunnel** | **Down Tunnel** |
| Forced Injection | ● | ● |
| Forced Extraction | ● | ● |
| Natural | ● | ● |

Table 3. Scenarios Considered for a Fire Located at the Midpoint of Tunnel

# Chapter 2: Literature Review

A major obstacle created by a fire in a tunnel is the production and flow of smoke. There have been several studies that analyze smoke movement, both in tunnels and in corridors, which are similar to tunnels. The tunnel studies typically examine tunnel geometries where both ends of the tunnel are open. A fire in a closed-end tunnel can be considered an enclosure fire where there is a wall vent at one end. The building studies examine enclosures with a single wall vent and are relevant to the closed-end tunnel encountered during construction and will be utilized.

Safety concerns about evacuation force the examination of ventilation systems and their effects on fire size and smoke flow in tunnels. Longitudinal forced ventilation is a common system studied and used to address these safety concerns. Longitudinal ventilation is addressed for tunnels by NFPA 502, the Standard for Road Tunnels, Bridges, and Other Limited Access Highways. Longitudinal ventilation (examples diagramed in Figures 1 through 6) is defined as a system that "introduces air into, or removes air from (a tunnel,) thus creating a longitudinal flow of air within the (tunnel), with discharge at the exiting portal." [2] Tunnels with forced ventilation have a controlled air flow rate. This air flow rate can regulate the heat release rate of the fire, the smoke movement, and the temperature increases.

Thomas investigated the impact of smoke and heat generation in a tunnel with forced air flow on evacuation and fire fighting. He examined how velocity differences between the hot upper layer of smoke and the cool lower layer of air affect backflow [3]. Backflow occurs when smoke travels upstream against the longitudinal air flow. The prevention of backflow allows a safe, smoke-free means of egress and fire fighting in an open-ended tunnel. In the situation where a tunnel is closed-ended, backflow creates a protected pocket of air allowing safe evacuation and fire fighting. Thomas explored the critical velocity needed to prevent backflow. He did this analytically by using the Froude Number, and supported this claim through small-scale experiments. The Froude Number, or Internal Froude Number, is defined as the ratio of pressure differences due to inertia, $\Delta p_I$, to the pressure differences due to buoyancy, $\Delta p_B$. These pressure differences are defined as follows:

$$\Delta p_I = \frac{v^2}{2g} \tag{1}$$

$$\Delta p_B = \frac{H_o \Delta T_c}{\left(T_o + \Delta T_c\right)} \tag{2}$$

The characteristic temperature change, $\Delta T_c$, refers to the ambient temperature change driven by the fire size and neglecting all losses. The Internal Froude Number is defined below and is used to address how the two layers interact with one another.

$$Fr_I = \frac{\Delta p_I}{\Delta p_B} = \frac{v^2\left(T_o + \Delta T_c\right)}{2gH_o\Delta T_c} \qquad (3)$$

Thomas suggested that when the Internal Froude Number is greater than or equal to 1, backflow would be prevented. The Internal Froude Number is used to characterize the smoke movement in each ventilation scenario.

The work done in the field of building fire research is similar to the closed-end tunnel scenario. Ideally, a building corridor could represent a closed-end tunnel under natural ventilation conditions. This concept was used in researching the vast amount of information [7, 8, 18] written on the subject of fires in building corridors. Thomas examined the effect that incoming air has on preventing upstream smoke propagation, backflow, in horizontal passages [7]. In his scenario, a horizontal corridor has a bulk flow of air. The smoke flow is mainly downstream, but some smoke will flow upstream. This upstream flow would be undesirable because this is the direction used for egress and fire fighting. He was able to show how the critical velocity preventing backflow against the upstream smoke movement is dependent upon the fire's heat release rate.

Under naturally ventilated fire conditions, smoke flow propagates up tunnel towards the open-end, while fresh air moves down tunnel towards the fire. The boundary of these two opposing flows is shared. It is important to know the extent to which these two opposing layers mix with one another. The Overall Richardson Number can be

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used to describe the mixing efficiency [4]. The Overall Richardson Number represents the ratio of potential energy to kinetic energy, where the potential energy is indicative of gravitational or buoyancy effects and the kinetic energy is indicative of inertial effects of the opposing flows.

$$Ri = \left( \frac{T_s - T_o}{T_o} \right) \frac{gH_o}{v^2} \qquad (4)$$

Comparison of the Overall Richardson Number to a Critical Richardson Number can help describe the stability of the flow. For a situation where the Overall Richardson Number is greater than the Critical Richardson Number, the flow is stable. A high Overall Richardson Number indicates that the buoyancy force will dominate the inertial force and minimize mixing between the hot and cold layers [4, 5, 6]. Ellison and Turner [5] suggest a Critical Richardson Number of 0.8; above this value, stratification occurs, while below this number mixing is expected.

Work done by Quintiere [8] for a fire in a building compartment is similar to a tunnel fire under natural ventilation conditions. This work models an enclosure fire with a single opening. For a steady-state analysis, an enclosure will consist of two zones, an upper smoke layer and a lower ambient air layer. This two-zone analysis is used to do hand calculations for the tunnel under natural ventilation conditions. Quintiere derives equations to determine air flow rate and neutral plane height. The neutral plane height is indicative of where the hot and cool layers separate. The significance

of the neutral plane is for egress and fire fighting.

These works will be used to help determine the fire conditions for each fire scenario for a fire in a tunnel and the conditions an escaping worker might be under. FDS will be used in conjunction with hand calculations to verify findings and for better understanding of conditions along the length of the tunnel.

# Chapter 3: Description of Fire Scenario

*3.1 Scenario*

The scenario addressed is a postulated fire involving a 5.0 m tunnel boring machine (TBM) located near the end of a 600 m long tunnel. The tunnel is assumed to be perfectly horizontal, without any slope. In this scenario, workers operating on the TBM or elsewhere within the same tunnel can only evacuate in one direction because the TBM has not yet bored through to the opposite end.

The postulated fire for this scenario assumes a fire involving hydraulic and lubricating oils for the TBM. The fire is assumed to occur near the lead end of the TBM. It is assumed that there is a loss of containment of the hydraulic and lubricating oils, resulting in a pool fire at the base of the TBM. The pool fire then ignites other combustibles associated with the TBM, including electric cables and the TBM conveyor belt, which is used to move bored materials from the front of the TBM to its rear, where they can be removed from the tunnel. The details of the postulated fire are addressed in the next section.

The fire-induced conditions within the tunnel resulting from the postulated fire are estimated with hand calculations as well as with simulations using version 3.1 of the FDS model developed by the NIST [11]. The FDS model is a CFD model based on

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the concept of LES.  For this scenario, 3-dimensional FDS simulations are performed
to address the fire-induced conditions that develop as a function of time, longitudinal
position and elevation within the tunnel.  The fire-induced conditions addressed in
this scenario include temperature, visibility and oxygen concentrations. Variations in
conditions across the width of the tunnel are neglected for this analysis because they
are expected to be relatively minor.

Three ventilation conditions are addressed for this scenario.  The first ventilation
condition assumes that air is being injected into the tunnel through a 1.2 m diameter
duct suspended from the top of the tunnel, the second ventilation condition assumes
that air or smoke are being extracted through the duct, while the third ventilation
condition assumes that the forced ventilation system is not operating.  For the
injection case, air is injected at a set volumetric flow rate of 30 $m^3$/s at a point 70 m
back from the closed-end of the tunnel. For the extraction case, air (or smoke under
fire conditions) is extracted at the same volumetric flow rate and at the same location.
The injection/extraction location is assumed to be representative of the progress of the
ventilation duct construction near the back end of the TBM as it progresses through
the tunnel.

### *3.2 Postulated Fire*

#### 3.2.1 Location of Fire on TBM

The intensity and duration of a postulated fire involving the TBM are estimated.  For

this estimate, it is assumed that there is loss of containment of hydraulic fluid, for example from a ruptured hose, near the leading end of the TBM.  It is assumed that all of the hydraulic fluid flows from the TBM and accumulates in a pool on the floor of the tunnel.  It is assumed that the ensuing fire consumes the entire stored capacity of the hydraulic fluid, with the heat release rate governed by the surface area of the liquid pool and the burning duration governed by the quantity of fluid as well as the burning rate of the fluid.  It is assumed that the initial fire will spread and additionally consume the conveyor belt, hydraulic hose, and electric cables in the vicinity of the liquid pool fire.

### 3.2.2 Fuel for Fire

A 5.0 m TBM can typically carry approximately 2,954 l of Hydraulic Fluid.  To account for extra fuel that may be in the hydraulic lines, this quantity is increased by 5%.  Thus, the total quantity of Hydraulic Fluid assumed to be available to burn in a fire is 3,102 l, as indicated in Table 4.

| TBM Fuel | Capacity (l) | 5% adjustment for fuel in lines (l) |
|---|---|---|
| Hydraulic Fluid | 2954 | 3102 |

Table 4. TBM Fuel Capacity and Effective Fuel Capacity

The Hydraulic Fluid used on the TBM is typically a synthetic hydrocarbon.  The

burning characteristics of this particular material are not known.  For the present

analysis, the Hydraulic Fluid is assumed to have the same burning characteristics as

the transformer oil identified by Babrauskas [12] in the SFPE Handbook of Fire

Protection Engineering.  Both materials are synthetic hydrocarbons.  The associated

burning rate data for transformer oil from the SFPE Handbook is provided in Table 5.

| TBM Material | Assigned Material Match | Density of Fuel $\rho_f$ (kg/m$^3$) | Heat of Combustion $\Delta H_c$ (MJ/kg) | Mass Loss Rate per Unit Area m"$_f$ (kg/m$^2$s) | Extinction-Absorption Coefficient k$\beta$ (1/m) |
|---|---|---|---|---|---|
| Hydraulic Fluid | Transformer Oil | 760 | 46.4 | 0.039 | 0.7 |

Table 5. Assigned Burning Rate Data for TBM Hydraulic Fluid

The selection of a fuel surface area for a liquid spill is difficult to determine

accurately in the absence of curbs, dikes or other impediments to contain such spills

within a specific area.  For this analysis, a spill width at the base of the 5.0 m tunnel is

assumed to be approximately 2.4 m.  If the fuel area is assumed to be square, then the

liquid pool would have an area of 5.76 m$^2$.  Using a combustion efficiency for

hydrocarbon liquid fuels of 0.84 [14], the fire heat release rate is estimated to be:

$$\dot{Q}_f = A_f \dot{m}_f^{"} \chi_{ch} \Delta H_c = 5.76 m^2 \cdot 0.039 \, kg/m^2 s \cdot 0.85 \cdot 46.4 \, MJ/kg = 8.7 MW \quad (5)$$

The conveyor belt used on a TBM is typically made up of styrene butadiene rubber

(SBR).  The burning characteristics of SBR are reported in the literature [14].  The

hydraulic hose line material is not known, but is assumed to be the same material as

the conveyor belt.  The electric cables used in the drift are assumed to be ethylene-

propylene rubber (EPR).  Burning rate data of EPR is not available in the literature,

but smoke yield data is available.  For the present analysis, the conveyor belt,

hydraulic hose, and electric cables are assumed to have the same burning

characteristics as SBR, identified by Tewarson [14] in the SFPE Handbook of Fire

Protection Engineering.  The associated heat of gasification and surface re-radiation

loss are provided in Table 6.  An external heat flux of 75kW/m$^2$ is assumed,

representative of fully developed fire exposure conditions.

| Material | Assigned Material Match | Heat of Gasification $\Delta H_g$ (kJ/g) | Surface Re-Radiation Loss $q''_{rr}$ (kW/m$^2$) | External Heat Flux $q''_e$ (kW/m$^2$) | Heat of Combustion $\Delta H_c$ (kJ/g) |
|---|---|---|---|---|---|
| Conveyor Belt, Hydraulic Hose, Electric Cables | SBR | 2.7 | 10 | 75 | 35.6 |

Table 6. Assigned Burning Characteristic Data for Other Combustibles

The unit mass loss rate of the SBR fuel is calculated as:

$$\dot{m}''_f = \frac{q''_e - q''_{rr}}{\Delta H_g} = \frac{(75-10)kW/m^2}{2.7kJ/g} = 0.024 kg/m^2 s \tag{6}$$

The surface area for each material is determined assuming a 3-m length. This length is based on the assumption that only cables and hoses immersed in the pool fire flame will burn, i.e., the fire will not propagate on these additional materials. The conveyor belt is assumed to have a width of 0.61 m and be 0.013 m thick. The electric cables and hydraulic lines are assumed to have a diameter of 0.05 m with an insulation/covering thickness of 0.006 m. Three electric cables and three hydraulic lines are assumed to burn. The heat release rate of these additional fuels can be estimated using the following expression:

$$\dot{Q}_f = \dot{m}''_f \Delta H_c A_f = 0.024 kg/m^2 s \cdot 35.6 MJ/kg \cdot 10 m^2 = 8.5 MW \qquad (7)$$

where

$$A_f = A_{ConveyorBelt} + A_{ElectricCables} + A_{HydraulicLines} = 7.2 m^2 + 1.4 m^2 + 1.4 m^2 = 10 m^2 \quad (8)$$

The burning duration for each fuel is estimated by dividing the total mass of fuel by the estimated fuel mass burning rate. For the hydraulic oil:

$$t_b = \frac{m_f}{\dot{m}_f} = \frac{\rho_f V_f}{\dot{m}_f} = \frac{760 kg/m^3 \cdot 3.101 m^3}{0.22 kg/s} = 10713 s \, (\approx 3 \, hrs) \qquad (9)$$

For the other combustibles:

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$$t_b = \frac{m_f}{\dot{m}_f} = \frac{\rho_f V_f}{\dot{m}_f'' A_f} = \frac{1300\,kg\,/\,m^3 \cdot 0.10m^3}{0.024\,kg\,/\,m^2 s \cdot 10m^2} = 542s\,(\approx 9\,min) \qquad (10)$$

The yield for smoke is estimated in terms of yield factors in accordance with the following equation:

$$\dot{m}_i = f_i \dot{m}_f \qquad (11)$$

For the analysis, the conveyor belt, hydraulic hose, and electric cables are assumed to have the same yield factors as EPR/Hypalon 4, identified by Tewarson [14] in the SFPE Handbook of Fire Protection Engineering. Yield factors for smoke are provided in Table 7 [14]. These yield factors are based on well-ventilated fire conditions. Such conditions will be justified on the basis of the ventilation conditions for the scenario being evaluated in the next chapter.

| TBM Material | Assigned Material Match | Yield Factor $f_s$ ($g_s/g_f$) |
|---|---|---|
| Hydraulic Fluid | Transformer Oil | 0.059 |
| Conveyor Belt, Hydraulic Hose, Electric Cables | EPR/Hypalon 4 | 0.082 |

Table 7. Yield factors for smoke species.

# Chapter 4: Analysis

## 4.1 Overview of Conditions Resulting from Postulated Fires

The heat and smoke conditions that would develop within the tunnel as a result of the postulated fire are addressed in this chapter.  These conditions depend on the ventilation conditions as well as the fire location within the tunnel.  Six different conditions are addressed here:


- Forced injection of air through the ventilation duct at a constant rate with the fire located at closed-end of tunnel

- Forced injection of air through the ventilation duct at a constant rate with the fire located at midpoint of tunnel

- Forced extraction of air through the ventilation duct at a constant rate with the fire located at closed-end of tunnel

- Forced extraction of air through the ventilation duct at a constant rate with the fire located at midpoint of tunnel

- Natural ventilation of the tunnel, with no forced ventilation with the fire located at closed-end of tunnel

- Natural ventilation of the tunnel, with no forced ventilation with the fire located at midpoint of tunnel

For the hand calculations, each ventilation scenario will be calculated as an enclosure with a single wall vent. Several FDS simulations have been conducted to evaluate the smoke and heat conditions within the tunnel as a result of the postulated fire under the three different ventilation conditions. A 3-dimensional simulation has been conducted for simulation times of 600 s (10 minutes). For these simulations, conditions vary along the length and height of the tunnel, but not across the width. Temperature, visibility distance and oxygen concentration have been recorded at the 30 m intervals along the tunnel length at elevations of 0.5 m, 1.5 m, 2.5 m, 3.5 m and 4.5 m above the floor. The 10-minute simulation time is sufficient to permit the propagation of the smoke front down the entire length of the tunnel where such propagation occurs.

The FDS model uses rectilinear coordinates. To model a 5.0 m diameter tunnel with the FDS model, the tunnel was represented as having a height of 5.0 m and a width of 4.0 m. This gives the simulated tunnel the same height and approximately the same cross-sectional area as the circular tunnel. Properties of concrete were used to represent the thermal properties of the tunnel boundaries in the simulations.

In the FDS simulations, the fire was represented as a pool fire at each location. The fire near the closed-end of the tunnel and at the midpoint had a heat release rate per unit area of 1,075 kW/m$^2$ and a surface area of 16 m$^2$ to yield the specified heat release rate of 17.2 MW. The actual heat release rate of at any particular time was determined by the FDS calculations and oscillates around this specified value. For

the fire at the closed-end of the tunnel, the heat release rate varied between

approximately 10 and 20 MW. For the fire at the midpoint of the tunnel, the heat

release rate varied between approximately 12 and 22 MW.


## *4.2 Fire Located at the Closed-End of the Tunnel*

### 4.2.1 Hand Calculations for Forced Injection

For the forced injection scenario where the fire is located at the closed-end of the

tunnel, air is injected through the 1.2 m diameter ventilation duct located near the top

of the tunnel. Air is injected at a volumetric flow rate of 30 m³/s at a location

approximately 70 m back from the closed-end of the tunnel. Assuming an ambient

temperature of 30°C, the density of the injected air will be 1.18 kg/m³. The mass

flow rate of the air is calculated to be:

$$\dot{m}_{inj} = \rho_o \dot{V}_{inj} = (1.18 kg/m^3) \cdot (30 m^3/s) = 35.4 kg/s \tag{12}$$

The maximum size fire that could be supported by this air flow rate is estimated as:

$$\dot{Q}_{max} = \dot{m}_{inj}(\Delta H_c/r) = (35.4 kg/s) \cdot (3.0 MJ/kg) = 106.2 MW \tag{13}$$

The global equivalence ratio can be determined as the ratio between the postulated

heat release rate and the maximum fire size that can be supported by the ventilation

rate:

$$\Phi_{gl} = \frac{\dot{Q}_{tot}}{\dot{Q}_{max}} = \frac{(8.7 + 8.5)MW}{106.2\,MW} = 0.16 \tag{14}$$

This value suggests that the fire would be over-ventilated by a factor of approximately six. The global equivalence ratio also indicates that the oxygen concentration will decrease by approximately $\frac{1}{6}$ to a level of 19%. This value is above 13%, the oxygen concentration needed to sustain fire [10].

To determine the heat transfer coefficient, the thermal penetration time, $t_p$, needs to be calculated. The thermal penetration time indicates the time at which approximately 15% of the temperature increase will reach the outer edge of the boundary. In this scenario, the tunnel walls are very thick, minimally 1.0 m.

$$t_p = \frac{\delta^2}{4\alpha} = \frac{(1m)^2}{4 \cdot 5.7 \times 10^{-7} m^2 / s} = 438596s \tag{15}$$

This large thickness drives the thermal penetration time to be on the order of 100 hours. Our simulation time, t, is 600 s. Because our simulation time is less than the thermal penetration time, the heat transfer coefficient is calculated using the equation below [19]. This heat transfer coefficient is similar to concrete being used in FDS.

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$$h_k = \sqrt{\frac{k\rho c_p}{t}} = \sqrt{\frac{2 \times 10^6 W^2 s / m^4 K^2}{600 s}} = 57.7 W / m^2 K = 0.058 kW / m^2 K \quad (16)$$

The average temperature of the smoke can be estimated using the Foote, Pagni, and Alveres method for mechanical ventilation [18]. The temperature change is a function of tunnel length embedded in the surface area term, $A_s$. The temperature rise will depend on the position within the tunnel, with the smoke cooling as it moves through the tunnel as a result of heat transfer to the tunnel boundaries. A more detailed analysis of these heat losses is included in the FDS simulations.

$$\Delta T = T_o \cdot 0.63 \left[ \frac{\dot{Q}_{tot}}{\dot{m}_{inj} c_p T_o} \right]^{0.72} \left[ \frac{h_k A_{ts}}{\dot{m}_{inj} c_p} \right]^{-0.36}$$

$$= 303 K \cdot 0.63 \left[ \frac{17200 kW}{35.4 kg / s \cdot 1.0 kJ / kgK \cdot 303 K} \right]^{0.72} \left[ \frac{0.058 kW / m^2 K \cdot 10820 m^2}{35.4 kg / s \cdot 1.0 kJ / kgK} \right]^{-0.36} \quad (17)$$

$$= 95^\circ C$$

The average smoke yields [14] resulting from the postulated fire under these ventilation conditions are calculated as follows.

For the hydraulic oil:

$$\dot{m}_s = f_s \dot{m}_f = 0.059 \cdot 0.22 kg / s = 1.30 \times 10^{-2} kg / s \quad (18)$$

For the other combustibles:

$$\dot{m}_s = f_s \dot{m}_f = 0.082 \cdot 0.24 kg/s = 1.97 \times 10^{-2} kg/s \qquad (19)$$

The optical characteristics of the smoke are estimated in terms of an extinction coefficient as:

$$
\begin{aligned}
K &= \rho_s \cdot \sigma_s = \rho \sum Y_s \cdot \sigma_s = \frac{\rho_o T_o}{T_s} \frac{\sum (f_s \dot{m}_f)}{\dot{m}_{tot}} \cdot \sigma_s = \\
&= \frac{353}{398}(kg/m^3)\frac{(1.30 \times 10^{-2} + 1.97 \times 10^{-2})}{(0.22 + 0.24 + 35.4)} \cdot (8{,}700 m^2/kg_s) = 7.0 m^{-1}
\end{aligned}
\qquad (20)
$$

Mulholand and Croarkin [15] suggest the mass specific extinction coefficient, $\sigma_s$, has a mean value of 8.7 $m^2/g_s$ for flaming combustion conditions. This value is used for these calculations.

Visibility through smoke generally varies inversely with the extinction coefficient. For light-reflecting surfaces, S = 3/K is used [16] as an estimate for the relationship between visibility distance and the extinction coefficient. For this case, the visibility distance generated by the fire would be:

$$S = \frac{3}{K} = \frac{3}{7.0\,m^{-1}} = 0.4m \qquad (21)$$

For the forced injection case where the fire is at the closed-end of the tunnel, the smoke would be pushed through the tunnel by the forced injection.  The rate of smoke propagation along the tunnel for this case is estimated as:

$$v_{inj} = \frac{\dot{V}_{inj}}{A_{xs}} = \frac{30\,m^3\,/\,s}{20m^2} = 1.5\,m\,/\,s \tag{22}$$

Due to gas expansion, the actual velocity of gases moving down the tunnel is expected to be somewhat higher than this, but the importance of the gas expansion diminishes, as heat is lost to the boundaries.

### 4.2.2 FDS Calculations for Forced Injection

The FDS simulations produced results for the injection case for temperature, visibility distance, and oxygen concentrations along the length of the tunnel at several elevations.  These results illustrate the highly transient nature of CFD calculations based on the LES concept, but some important aspects of these results can be pointed out.

To determine the conditions an escaping worker would experience, results for temperature, visibility distance, and oxygen concentrations are reviewed at the 1.5 m elevation.  At the location furthest downstream of the air injection point (30 m and 60 m stations) the temperature generally falls within the range of 300 to 500°C, with an

average value of approximately 400°C.  Temperatures at stations upstream within the tunnel generally fall within the range of approximately 80 to 225°C, with an average value of approximately 125°C.

The FDS results show the visibility distance at the 1.5 m elevation at all stations falls dramatically to a value 1.1 m upon arrival of the smoke front.  From the visibility data, the smoke propagation rate will be calculated.  The first evidence of a decrease in visibility at the open-end of the tunnel occurs 222 s after the fire is started.  Over the 600 m length of the tunnel, this represents an average smoke front velocity of 2.7 m/s over the length of the tunnel.

The oxygen concentration generally remains around 20%, which is more than enough to sustain the fire.  It is interesting to note that the oxygen concentration at the 30 m point fluctuates between 0 and 17%.  It should again be noted that this point is down tunnel of the duct, but up tunnel of the fire.  A reason for this fluctuation is the large eddy motion that mixes the fresh oxygen rich injected air and the hot oxygen deprived smoke.  The fire does not extinguish itself because the oxygen concentration only briefly dips below the limitation, which is generally considered to be 13% [10].

### 4.2.3 Hand Calculations for Forced Extraction

Analysis of the forced extraction case is similar to analysis of the forced injection case.  The primary difference is that the mass flow rate through the ventilation system

will be lower for the extraction case than for the injection case due to the higher

temperatures of the smoky gases being extracted.  In order to calculate a smoke

temperature and mass flow rate at the extraction point of the ventilation duct, an

iteration needs to occur using the Foote, Pagni, and Alveres method [18] to determine

temperature and an equation for the mass flow rate.

$$\Delta T = T_o \cdot 0.63 \left[ \frac{\dot{Q}_{tot}}{\dot{m}_{ext} c_p T_o} \right]^{0.72} \left[ \frac{h_k A_{ts}}{\dot{m}_{ext} c_p} \right]^{-0.36} \tag{23}$$

$$\dot{m}_{ext} = \frac{\rho_o T_o}{T_s} \dot{V}_{ext} \tag{24}$$

The average temperature rise needs to be recalculated over the entire length of the

tunnel using the known extraction mass flow rate of 18.6 kg/s.

$$\Delta T = T_o \cdot 0.63 \left[ \frac{\dot{Q}_{tot}}{\dot{m}_{ext} c_p T_o} \right]^{0.72} \left[ \frac{h_k A_{ts}}{\dot{m}_{ext} c_p} \right]^{-0.36}$$

$$= 303K \cdot 0.63 \left[ \frac{17200kW}{18.6kg/s \cdot 1.0kJ/kgK \cdot 303K} \right]^{0.72} \left[ \frac{0.058kW/m^2 K \cdot 10820m^2}{18.6kg/s \cdot 1.0kJ/kgK} \right]^{-0.36} \tag{25}$$

$$= 120^\circ C$$

The maximum size fire that could be supported by this air flow rate is estimated as:

$$\dot{Q}_{max} = \dot{m}_{ext}\left(\Delta H_c \, / \, r\right) = \left(18.6 \, kg \, / \, s\right) \cdot \left(3.0 MJ \, / \, kg\right) = 55.8 \, MW \tag{26}$$

The global equivalence ratio between the postulated heat release rate and the maximum fire size that can be supported by the ventilation rate:

$$\Phi_{gl} = \frac{\dot{Q}_{tot}}{\dot{Q}_{max}} = \frac{\left(8.7 + 8.5\right) MW}{55.8 \, MW} = 0.31 \tag{27}$$

While higher than the injection case due to the reduced air flow rate for this case, this global equivalence ratio is still representative of an over-ventilated fire by a factor of approximately three. The global equivalence ratio indicates that the oxygen concentration will decrease by approximately ⅓ to a level of 15%. This value is above 13%, the oxygen concentration to sustain fire [10].

The optical characteristics of the smoke for each fuel are estimated in terms of an extinction coefficient as:

$$
\begin{aligned}
K &= \rho_s \cdot \sigma_s = \rho \sum Y_s \cdot \sigma_s = \frac{\rho_o T_o}{T_s} \frac{\sum\left(f_s \dot{m}_f\right)}{\dot{m}_{tot}} \cdot \sigma_s = \\
&= \frac{353}{423}\left(kg \, / \, m^3\right) \frac{\left(1.30 \times 10^{-2} + 1.97 \times 10^{-2}\right)}{\left(0.22 + 0.24 + 18.6\right)} \cdot \left(8,700 m^2 \, / \, kg_s\right) = 12.5 m^{-1}
\end{aligned}
\tag{28}
$$

For this case, the visibility distance would be:

$$S = \frac{3}{K} = \frac{3}{12.5\,m^{-1}} = 0.2\,m \tag{29}$$

The air and smoke extracted through the duct will help pull the smoke layer away from the open-end and aid in egress and fire fighting.  The flow of the incoming fresh is:

$$v_{ext} = \frac{\dot{m}_{ext}}{\rho_o A_{xs}} = \frac{18.6\,kg\,/\,s}{1.18kg\,/\,m^3 \cdot 20m^2} = 0.8\,m\,/\,s \tag{30}$$

The Internal Froude Number is used to determine the air velocity needed to prevent backflow.  The characteristic temperature rise based on fire size and air flow rate, but neglects the fraction of heat lost to the tunnel boundaries.

$$\Delta T_c = \frac{\dot{Q}_{tot}}{\dot{m}_{ext}c_p} = \frac{17,200kW}{18.6kg\,/\,s \cdot 1.0kJ\,/\,kgK} = 924K \tag{31}$$

Thomas suggests that Internal Froude Numbers is greater than or equal to one, backlayering should be prevented.

$$Fr_I = \frac{v_{ext}^2\left(T_o + \Delta T_c\right)}{2gH_o\Delta T_c} = \frac{\left(0.79m\,/\,s\right)^2 \cdot \left(303K + 924K\right)}{2 \cdot 9.81m\,/\,s^2 \cdot 5.0m \cdot 924K} = 0.01 \tag{32}$$

This low Internal Froude Number indicates that the smoke front will propagate along the tunnel towards the open-end. FDS simulations will be used to verify this observation.

### 4.2.4 FDS Calculations for Forced Extraction

For the extraction case, the FDS calculations suggest that most of the smoke generated by the postulated fire is captured and exhausted through the ventilation system. As a consequence, the temperature upstream of the extraction point remains just above the ambient temperature at approximately 40°C. The visibility remains at the default value of 30 m at all stations except those below the 240 m stations. From the visibility data, the first evidence of a decrease in visibility at 240 m station occurs at 491 s after the fire is started. Over the 240 m length segment of the tunnel, this represents an average smoke front velocity of 0.5 m/s to the 240 m station. After this point, the smoke layer does not descend below the 1.5 m height. At the 30 m and 60 m stations, the temperatures and visibility distances bounce significantly. This variability in the temperature and visibility data at these two stations is due to the large eddy motion of the smoke in the region downstream of the extraction location. The oxygen concentrations, shown in Figure 18, in the extraction case generally remain around 22%, enough to sustain the fire. Table 10 shows a summary of the results calculated thus far.

### 4.2.5 Hand Calculations for Natural Ventilation

Analysis of the naturally ventilated case models the tunnel after an enclosure. To determine the average temperature rise, the method of McCaffrey, Quintiere, and Harkleroad [9] was used. This temperature rise will depend on the position within the tunnel, with the smoke cooling as it moves through the tunnel as a result of heat transfer to the tunnel boundaries. A more detailed analysis of these heat losses is included in the FDS simulations.

$$
\Delta T = 6.85 \left( \frac{\dot{Q}_{tot}^2}{A_{xs} \sqrt{H_o} h_k A_{ts}} \right)^{\frac{1}{3}} =
$$

$$
= 6.85 \left( \frac{(17,200 kW)^2}{20 m^2 \sqrt{5m} \cdot 0.05 kW/m^2 K \cdot 10820 m^2} \right)^{\frac{1}{3}} = 158°C
$$

(33)

The neutral plane height is representative of the height at which the hot smoke layer and cooler fresh air layer separate and can be estimated below.

$$
H_n = \frac{H_o}{1 + \left( \dfrac{T_s}{T_o} \right)^{\frac{1}{3}}} = \frac{5m}{1 + \left( \dfrac{461K}{303K} \right)^{\frac{1}{3}}} = 2.3m
$$

(34)

As a result of a fire in a tunnel, the hot gases and combustion products will naturally rise to the top. This hot layer and the cool layer at the bottom of the tunnel are kept separated by buoyant forces. Fresh air is drawn into the tunnel due to pressure

differences created between the tunnel and the outside air.  The orifice constriction

coefficient, $C_d$, is typically valued at 0.7 [18].  In air flow rate into the tunnel is:

$$
\begin{aligned}
\dot{m}_{nat} &= \frac{2}{3}\rho_o C_d A_{xs}\sqrt{H_o}\sqrt{2g\frac{T_o}{T_s}\left(1-\frac{T_o}{T_s}\right)\cdot\left(1-\frac{H_n}{H_o}\right)^{\frac{3}{2}}} = \\
&= \frac{2}{3}1.18kg/m^3\cdot 0.7\cdot 20m^2\sqrt{5m}\sqrt{2\cdot 9.81m/s^2\frac{303K}{461K}\left(1-\frac{303K}{461K}\right)\cdot\left(1-\frac{2.3m}{5m}\right)^{\frac{3}{2}}} \quad (35) \\
&= 20.6kg/s
\end{aligned}
$$

The maximum fire size supported by the open-end of the tunnel is based on the

ventilation factor.  The $0.53A_{xs}\sqrt{H_o}$ term is defined as the ventilation factor and is

commonly used and found in the literature [18].

$$
\dot{Q}_{\max} = 0.53A_{xs}\sqrt{H_o}\left(\Delta H_c/r\right) = 0.53\cdot 20m^2\sqrt{5.0m}\left(3.0MJ/kg\right) = 71.1MW \quad (36)
$$

The global equivalence ratio between the postulated heat release rate and the

maximum fire size that can be supported by the ventilation rate:

$$
\Phi_{gl} = \frac{\dot{Q}_{tot}}{\dot{Q}_{\max}} = \frac{17.2\,MW}{71.1\,MW} = 0.24 \quad (37)
$$

The global equivalence ratio is representative of an over-ventilated fire by a factor of

approximately four. The global equivalence ratio also indicates that the oxygen

concentration will decrease by approximately ¼ to a level of 17%. This value is above 13%, the oxygen concentration to sustain fire [10].

The optical characteristics of the smoke for each fuel are estimated in terms of an extinction coefficient as:

$$K = \rho_s \cdot \sigma_s = \rho \sum Y_s \cdot \sigma_s = \frac{\rho_o T_o}{T_s} \frac{\sum (f_s \dot{m}_f)}{\dot{m}_{tot}} \cdot \sigma_s =$$
$$= \frac{353}{461}(kg/m^3)\frac{(1.30 \times 10^{-2} + 1.97 \times 10^{-2})}{(0.22 + 0.24 + 20.6)} \cdot (8,700 m^2/kg_s) = 10.3 m^{-1}$$

(38)

For this case, the visibility distance would be:

$$S = \frac{3}{K} = \frac{3}{10.3\,m^{-1}} = 0.3\,m.$$

(39)

For the natural ventilation case, the rate of smoke propagation along the tunnel is estimated as:

$$v_{nat} = \frac{\dot{m}_{nat}}{\rho_o A_{xs}} = \frac{20.6\,kg/s}{1.18 kg/m^3 \cdot 20m^2} = 0.9\,m/s$$

(40)

The actual velocity of gases moving down the tunnel is expected to be somewhat higher due to gas expansion. FDS simulations will be used to verify this observation.

### 4.2.6 FDS Calculations for Natural Ventilation

The temperature and visibility data for the naturally ventilated case show that the smoke front fills a large fraction of the tunnel height as it progresses down the tunnel, extending down at least to the 1.5 m elevation.  The temperature at the upstream locations of the fire generally falls within the range of 30 to 225°C, with an average value of approximately 100°C.  The smoke front reaches the end of the tunnel at an average smoke front speed of approximately 1.1 m/s with a visibility distance of 0.8 m.  As in the other simulations, arrival of the smoke front at a particular station was noted by the very rapid loss of visibility distance upon smoke front arrival.  The FDS simulations do not indicate a gradual degradation of visibility conditions.  They do indicate dramatic bounces in the visibility distance, particularly at the tunnel entrance as the smoke front moves up and down with the formation of large eddies of smoke being drawn back into the tunnel at the entrance.  The oxygen concentration at all stations decrease throughout the duration of the fire to approximately 16%.  Although the fire is approaching its oxygen concentration limitation for extinction, it does not reach it.  Table 8 shows a summary of the results calculated.

| Fire at Closed-End | Forced Injection | | Forced Extraction | | Natural Ventilation | |
|---|---|---|---|---|---|---|
| | Hand Calculation | FDS Simulation | Hand Calculation | FDS Simulation | Hand Calculation | FDS Simulation |
| $\Delta T$ (°C) | 95 | 95 | 120 | 10 | 158 | 70 |
| v (m/s) | 1.5 | 2.7 | 0.8 | 0.5 | 0.9 | 1.1 |
| S (m) | 0.4 | 1.1 | 0.2 | 3.0 | 0.3 | 0.8 |
| $O_2$ (%) | 19 | 20 | 15 | 22 | 17 | 17 |

Table 8.  Summary of Results for Fire at Closed-End of Tunnel

## 4.3 Fire Located at the Midpoint of the Tunnel

### 4.3.1 Hand Calculations for Forced Injection

For the forced injection scenario where the fire is located at the midpoint of the

tunnel, the calculations done for the fire located at the closed-end of the tunnel are

similar to the fire conditions on the up tunnel side of the fire.

On the down tunnel side of the fire, the fresh air injected into the tunnel will

counteract the smoke layer movement produced by the fire. The conditions for a

worker trapped on the down tunnel side of the fire could be helped by preventing the

backflow of smoke with the injected fresh air. The Internal Froude Number derived

by Thomas [3] is used to determine the air velocity needed to prevent backflow.

Recall that the Internal Froude Number is defined as:

$$Fr_I = \frac{v_{inj}^2 \left(T_o + \Delta T_c\right)}{2gH_o \Delta T_c} \tag{41}$$

The is the characteristic temperature, $\Delta T_c$, rise based on fire size and air flow rate,

but neglects the fraction of heat lost to the tunnel boundaries.

$$\Delta T_c = \frac{\dot{Q}_{tot}}{\dot{m}_{inj}c_p} = \frac{17,200 kW}{35.4 kg/s \cdot 1.0 kJ/kgK} = 486K \tag{42}$$

Thomas suggests that for Internal Froude Numbers greater than or equal to one, backlayering should be prevented.

$$Fr_I = \frac{v_{inj}^2 (T_o + \Delta T_c)}{2 g H_o \Delta T_c} = \frac{(1.5 m/s)^2 \cdot (303K + 486K)}{2 \cdot 9.81 m/s^2 \cdot 5.0 m \cdot 486K} = 0.04 \qquad (43)$$

This low Internal Froude Number indicates that the smoke front will propagate along the tunnel towards the closed-end and possibly trap workers. FDS simulations are used to verify this observation.

### 4.3.2 FDS Calculations for Forced Injection

For the fire at the midpoint of the tunnel, the temperature, visibility distance, and oxygen concentration data are taken at the 1.5 m elevation. The temperature and visibility data show that the smoke front fills a large fraction of the tunnel height as it progresses in the up tunnel direction, extending down at least to the 1.5 m elevation. The temperature on the up tunnel side of the fire generally falls within the range of 150 to 400°C, with an average value of approximately 250°C. The temperature on the down tunnel side of the fire generally falls within the range of 30 to 40°C, with an average value of approximately 35°C. As the smoke front moves at approximately 0.5 m/s towards the closed-end of the tunnel, the visibility distance drops to 10 m. As the smoke front moves at approximately 4.2 m/s towards the open-end of the tunnel, the visibility distance drops to 1.3 m. The oxygen concentration at all stations up

tunnel decrease throughout the duration of the fire.  On the down tunnel side of the fire, the oxygen concentration drops to approximately 22.5%.  On the up tunnel side of the fire, the oxygen concentration drops to approximately 19%.

### 4.3.3 Hand Calculations for Forced Extraction

For the forced extraction scenario where the fire is located at the midpoint of the tunnel, the calculations done for the fire located at the closed-end of the tunnel are the same as the fire conditions on the up tunnel side of the fire.

On the down tunnel side of the fire, the air extracted through the duct will aid the smoke layer's propagation.  The conditions for a worker trapped on the down tunnel side of the fire are extremely unfavorable as it is assumed a well-mixed smoke front will travel down tunnel towards the duct's extraction point.  FDS simulations will be used to verify this observation.

### 4.3.4 FDS Calculations for Forced Extraction

The temperature and visibility data show that the smoke front fills a large fraction of the tunnel height as it progresses towards the closed-end, extending down at least to the 1.5 m elevation.  The temperature on the down tunnel side of the fire generally falls within the range of 100 to 300°C, with an average value of approximately 192°C.  The temperature on the up tunnel side of the fire generally falls within the

range of 30 to 100°C, with an average value of approximately 55°C. As the smoke front moves at approximately 2.3 m/s towards the closed-end of the tunnel, the visibility distance drops to 0.8 m. As the smoke front moves at approximately 0.4 m/s towards the open-end of the tunnel, the visibility distance drops to 1.5 m. The oxygen concentration at all stations decrease throughout the duration of the fire. On the down tunnel side of the fire, the oxygen concentration drops to approximately 17%. On the up tunnel side of the fire, the oxygen concentration drops to approximately 22%. Table 11 shows a summary of the results calculated thus far.

### 4.3.5 Hand Calculations for Natural Ventilation

For the natural ventilation scenario where the fire is located at the midpoint of the tunnel, the calculations done for the fire located at the closed-end of the tunnel are the same as the fire conditions on the up tunnel side of the fire.

On the down tunnel side of the fire, the conditions for a worker trapped are extremely unfavorable as it is assumed a well-mixed smoke front will travel down tunnel towards the closed-end. FDS simulations will be used to verify this observation.

### 4.3.6 FDS Calculations for Natural Ventilation

The temperature and visibility data show that the smoke front fills a large fraction of the tunnel height as it progresses along the tunnel in both directions, extending down at least to the 1.5 m elevation. The temperature on the up tunnel side of the fire

41

generally falls within the range of 30 to 150°C, with an average value of approximately 90°C. The temperature on the down tunnel side of the fire generally falls within the range of 60 to 150°C, with an average value of approximately 115°C. The average smoke front speed of approximately 1.5 m/s moves towards the closed-end of the tunnel and approximately 2.3 m/s towards the open-end of the tunnel. The visibility distance on the down tunnel side drops to 0.5 m and on the up tunnel side, drops to 1.5 m. The oxygen concentration at all stations decrease throughout the duration of the fire. On the down tunnel side of the fire, the oxygen concentration drops to approximately 16%. On the up tunnel side of the fire, the oxygen concentration drops to approximately 21%. Although the fire is approaching its oxygen concentration limitation for extinction on the down tunnel side of the fire, it does not reach it during the 10-minute simulation. Table 9 shows a summary of the results calculated.

| Fire at Midpoint | Forced Injection | | Forced Extraction | | Natural Ventilation | |
|---|---|---|---|---|---|---|
| | Down Tunnel | Up Tunnel | Down Tunnel | Up Tunnel | Down Tunnel | Up Tunnel |
| $\Delta T$ (°C) | 5 | 180 | 162 | 25 | 85 | 60 |
| v (m/s) | 0.5 | 4.1 | 2.3 | 0.4 | 1.5 | 2.3 |
| S (m) | 10 | 1.3 | 0.8 | 1.5 | 0.5 | 1.5 |
| $O_2$ (%) | 22.5 | 19 | 18 | 22 | 16 | 21 |

Table 9. Summary of Results for Fire at Midpoint of Tunnel

# Chapter 5:  Discussion

## *5.1 Fire Located at Closed-End of Tunnel Scenario Results*

### 5.1.1 Forced Injection

For the case where the fire was at the closed-end of the tunnel, smoke is forced down

the length of the tunnel by the forced injection.  The hand calculations determined

that the average smoke temperature rise was 95°C.  The smoke propagated up the

tunnel at 1.5 m/s with the visibility distance being 0.4 m.  The oxygen concentration

was calculated to diminish to approximately 19%.  The FDS simulations captured

data at the 1.5 m elevation.  It determined that the average smoke temperature rise

was 95°C.  The smoke propagated up the tunnel at 2.7 m/s with the visibility distance

being approximately 1.1 m.  The oxygen concentration was shown to diminish to

approximately 20%.

### 5.1.1 Forced Extraction

In the forced extraction case where the fire was at the closed-end of the tunnel, smoke

is forced down tunnel.  The hand calculations determined that the average smoke

temperature rise was 120°C.  The smoke propagated up the tunnel at 0.8 m/s with the

visibility distance being 0.2 m.  The oxygen concentration was calculated to diminish

to approximately 15%.  The FDS simulations captured data at the 1.5 m elevation.  It

determined that the average smoke temperature rise was 10°C.  The smoke

propagated up the tunnel at 0.5 m/s with the visibility distance being approximately

3.0 m.  The oxygen concentration was shown to diminish to approximately 22%.


### 5.1.3 Natural Ventilation

In the natural ventilation case where the fire was at the closed-end of the tunnel, the

hand calculations determined that the average smoke temperature rise was 158°C.

The smoke propagated up the tunnel at 0.9 m/s with the visibility distance being 0.3

m.  The oxygen concentration was calculated to diminish to approximately 17%.  The

FDS simulations determined that the average smoke temperature rise was 50°C.  The

smoke propagated up the tunnel at 1.1 m/s with the visibility distance being

approximately 0.8 m.  The oxygen concentration was shown to diminish to

approximately 17%.


## 5.2 Fire Located at Midpoint of Tunnel Scenario Results

### 5.1.1 Forced Injection

For the case where the fire was at the midpoint of the tunnel, smoke is forced in the

up tunnel direction by the forced injection.  The hand calculations conducted for the

closed-end case were assumed to be the approximate conditions seen in the up tunnel

portion on the tunnel. On the up tunnel side of the fire, the FDS simulations

determined that the average smoke temperature rise was 180°C.  The smoke

propagated towards the open-end of the tunnel at 4.1 m/s with the visibility distance being approximately 1.3 m.  The oxygen concentration was shown to diminish to approximately 19%.  For the conditions on the down tunnel side of the fire at the midpoint of the tunnel, the hand calculations suggested that the injected air would not be able to prevent backlayering.  This was not completely shown in the FDS simulations because the simulation time was not long enough.  The FDS simulations determined that the average smoke temperature rise was 5°C.  The smoke propagated towards the closed-end of the tunnel at 0.5 m/s with the visibility distance being approximately 10 m.  The oxygen concentration was shown to diminish to approximately 22.5%.

### 5.1.1 Forced Extraction

For the case where the fire was at the midpoint of the tunnel, smoke is forced in the down tunnel direction by the forced extraction.  The hand calculations conducted for the closed-end case were assumed to be the approximate conditions seen in the up tunnel portion on the tunnel. On the up tunnel side of the fire, the FDS simulations determined that the average smoke temperature rise was 25°C.  The smoke propagated towards the open-end of the tunnel at 0.4 m/s.  The visibility distance was approximately 1.5 m.  The oxygen concentration was shown to diminish to approximately 22%.  For the conditions on the down tunnel side of the fire at the midpoint of the tunnel, it was suggested that the conditions would be highly unfavorable.  The FDS simulations determined that on the down tunnel side of the

fire, the average smoke temperature rise was 162°C.  The smoke propagated towards

the closed-end of the tunnel at 2.3 m/s with the visibility distance being

approximately 0.8 m.  The oxygen concentration was shown to diminish to

approximately 18%.

### 5.1.3 Natural Ventilation

For the case where the fire was at the midpoint of the tunnel, the hand calculations

conducted for the closed-end case were assumed to be the approximate conditions

seen in the up tunnel portion on the tunnel. On the up tunnel side of the fire, the FDS

simulations determined that the average smoke temperature rise was 60°C.  The

smoke propagated towards the open-end of the tunnel at 2.3 m/s with a visibility

distance being approximately 1.5 m.  The oxygen concentration was shown to

diminish to approximately 21%.  For the conditions on the down tunnel side of the

fire at the midpoint of the tunnel, it was suggested that the conditions would be highly

unfavorable.  The FDS simulations determined that on the down tunnel side of the

fire, the average smoke temperature rise was 85°C.  The smoke propagated towards

the closed-end of the tunnel at 1.5 m/s with the visibility distance being

approximately 0. 5 m.  The oxygen concentration was shown to diminish to

approximately 16%.

## 5.3 Future Application of the Richardson Number

Under naturally ventilated fire conditions, smoke flow propagates up tunnel towards the open-end, while fresh air moves down tunnel towards the fire. The smoke front movement along the top of the tunnel may behave like Kelvin-Helmholtz (K-H) billows. K-H billows are produced by the vertical velocity shear at the interface of two opposing flows and is associated with the instability formed at the interface due to density differences. In this case, the density differences between the layers are significant because of the large temperature difference [20]. Once this front passes a particular point, the boundary layer needs to be addressed. This can be done using the Overall Richardson Number that can show if the opposing flows are stratified or mixed [4].

The importance of stratification is essential to evacuation and fire fighting. Several salt-water experiments have been conducted pertaining to the flow of smoke in corridors and were run under open-ended conditions [21, 22, 23]. For smoke and air flow in a close-end tunnel, the effect of the closed-end is not known. Comparison of the Overall Richardson Number to the Critical Richardson Number of 0.8 suggested by Ellison and Turner [5] may still pertain to this situation. A high Overall Richardson Number should still indicate that the buoyancy force would dominate the inertial force and minimize mixing [4, 5, 6]. Further consideration should be taken through experiments and FDS modeling to verify these theories in a closed-end tunnel.

# Chapter 6:  Summary / Conclusions

A methodology has been developed to assess tenability in the subsurface environment in a tunnel in response to postulated fire and ventilation scenarios.  This analysis has been performed to demonstrate application of the tunnel tenability methodology.  For this analysis, a fire has been postulated at the closed-end and the midpoint of a 5.0 m diameter tunnel during boring operations.  Conditions within the tunnel resulting from the postulated fire have been calculated for three different ventilation scenarios: forced injection of air into the tunnel, forced extraction of air/smoke from the tunnel and natural ventilation with no forced ventilation.

The postulated fire for this analysis contemplates ignition of fuel/hydraulic oil from the tunnel boring machine and consequent ignition of conveyor belt, electrical cables and hydraulic hoses in the vicinity of the oil fire.  The postulated fire has a magnitude of approximately 17.2 MW.

Based on the postulated fire and the different ventilation scenarios for a fire at the closed-end of the tunnel, it appears that the forced extraction ventilation case provides for the best conditions to aid in escape and fire fighting within the tunnel.  For this ventilation condition and the postulated fire, a majority of the smoke produced by the fire would be extracted through the ventilation system.  It should be recognized, however, that the potential effects of heat and smoke on continued operation of the

ventilation system has not been assessed, so the actual reliability of this extraction through the duct under fire conditions is not known.

The forced injection of air near the closed-end of the tunnel causes the smoke produced by a fire to be pushed through the tunnel at a rate that would be likely to outpace evacuating workers traveling at approximately 1.0 m/s [17]. Similarly, the rate of smoke propagation through the tunnel under naturally ventilated conditions would occur at a rate comparable to the expected travel speed of evacuating workers. For these scenarios, workers would be more likely to become immersed in the smoke cloud.

The visibility in the smoke cloud is expected to be on the order of a half meter, indicative of poor visibility conditions. The temperature of the smoke cloud would vary with position along the tunnel, but could be within the range that would pose potential health consequences to workers immersed in the smoke.

Based on the postulated fire and the different ventilation scenarios for a fire at the midpoint of the tunnel, it appears that the no ventilation conditions provide for tenable condition if a worker is trapped on the down tunnel side. The forced injection ventilation case gives the trapped worker the most favorable chance for rescue. If workers are located on the up tunnel side of the fire, it appears that the forced extraction ventilation case would again provide the most tenable conditions to escape and fight the fire within the tunnel. For this ventilation condition and the postulated

fire, virtually all of the smoke produced by the fire would be extracted through the ventilation system.  It should be recognized, however, that the integrity of the ventilation duct has not been assessed, so the actual reliability of this extraction through the duct under fire conditions is not known.

The forced injection of air near the closed-end of the tunnel and the natural ventilation case would cause the smoke produced by a fire to be pushed through the tunnel at a rate that would be likely to outpace evacuating workers. For these scenarios, workers would be more likely to become immersed in the smoke cloud.

The visibility in the smoke cloud is expected to be on the order of a half meter, indicative of poor visibility conditions.  The temperature of the smoke cloud would vary with position along the tunnel, but could be within the range that would pose potential health consequences to workers immersed in the smoke.

# Appendices

Note: The following appendix sections (A.1, A.2, and A.3) only contain FDS data files pertaining to the fire at the closed-end of the tunnel case as an example of work done. For the fire at the midpoint of the tunnel case, the fire was located at 300 m to 304 m with the same width.

### *A.1 FDS Input Data for Forced Injection Case for Fire for at Closed-End*

```
&HEAD CHID='injection-end',TITLE='3D Tunnel Simulation - Forced
Injection Ventilation Case-Fire at Closed-End of Tunnel' /

&GRID IBAR=2000,JBAR=3,KBAR=16 / defines the number of grids in each
direction
&PDIM XBAR0=0.0,XBAR=600,YBAR0=0.0,YBAR=4.0,ZBAR0=0.0,ZBAR=5.0 / defines
the tunnel size

&MISC
TMPA=30.0,REACTION='KEROSENE',SURF_DEFAULT='CONCRETE',DATABASE_DIRECTORY
='c:\nist\fds\database3\' / defines ambient temperature, fuel, and
tunnel surface

&TIME TWFIN=600.0 / 10 minute simulation

&SURF ID='FIRE',HRRPUA=1075. / 17 MW fire over 16m2 area
&SURF ID='HVAC',VOLUME_FLUX=-30.0 / air flow rate injected through duct

&OBST XB=70,600,1.33,2.66,3.75,4.6875 / location of duct in tunnel
&VENT XB=70,70,1.33,2.66,3.75,4.6875 ,SURF_ID='HVAC' / duct is open
&VENT CB='XBAR' ,SURF_ID='OPEN' /

&VENT XB=10,14,0,4,0.0,0.0,SURF_ID='FIRE' / location of fire
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where fire is

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&THCP XYZ=240,0.67,4.5,QUANTITY='visibility',LABEL='S-240-4.5' /
&THCP XYZ=360,0.67,4.5,QUANTITY='visibility',LABEL='S-360-4.5' /
&THCP XYZ=480,0.67,4.5,QUANTITY='visibility',LABEL='S-480-4.5' /
&THCP XYZ=600,0.67,4.5,QUANTITY='visibility',LABEL='S-600-4.5' /

&SLCF PBX=30,QUANTITY='TEMPERATURE' /
&SLCF PBX=60,QUANTITY='TEMPERATURE' /
&SLCF PBX=70,QUANTITY='TEMPERATURE' /
&SLCF PBX=120,QUANTITY='TEMPERATURE' /
&SLCF PBX=240,QUANTITY='TEMPERATURE' /
&SLCF PBX=360,QUANTITY='TEMPERATURE' /
&SLCF PBX=480,QUANTITY='TEMPERATURE' /
&SLCF PBX=600,QUANTITY='TEMPERATURE' /

&SLCF PBX=30,QUANTITY='U-VELOCITY' /
&SLCF PBX=60,QUANTITY='U-VELOCITY' /
&SLCF PBX=70,QUANTITY='U-VELOCITY' /
&SLCF PBX=120,QUANTITY='U-VELOCITY' /
&SLCF PBX=240,QUANTITY='U-VELOCITY' /
&SLCF PBX=360,QUANTITY='U-VELOCITY' /
&SLCF PBX=480,QUANTITY='U-VELOCITY' /
&SLCF PBX=600,QUANTITY='U-VELOCITY' /

&SLCF PBX=30,QUANTITY='oxygen mass fraction' /
&SLCF PBX=60,QUANTITY='oxygen mass fraction' /
&SLCF PBX=70,QUANTITY='oxygen mass fraction' /
&SLCF PBX=120,QUANTITY='oxygen mass fraction' /
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&SLCF PBX=240,QUANTITY='oxygen mass fraction' /
&SLCF PBX=360,QUANTITY='oxygen mass fraction' /
&SLCF PBX=480,QUANTITY='oxygen mass fraction' /
&SLCF PBX=600,QUANTITY='oxygen mass fraction' /

&SLCF PBX=30,QUANTITY='visibility' /
&SLCF PBX=60,QUANTITY='visibility' /
&SLCF PBX=70,QUANTITY='visibility' /
&SLCF PBX=120,QUANTITY='visibility' /
&SLCF PBX=240,QUANTITY='visibility' /
&SLCF PBX=360,QUANTITY='visibility' /
&SLCF PBX=480,QUANTITY='visibility' /
&SLCF PBX=600,QUANTITY='visibility' /

&SLCF PBY=0.67,QUANTITY='TEMPERATURE' /
&SLCF PBY=0.67,QUANTITY='U-VELOCITY' /
&SLCF PBY=0.67,QUANTITY='oxygen mass fraction' /
&SLCF PBY=0.67,QUANTITY='visibility' /

&SLCF PBY=2,QUANTITY='TEMPERATURE' /
&SLCF PBY=2,QUANTITY='U-VELOCITY' /
&SLCF PBY=2,QUANTITY='oxygen mass fraction' /
&SLCF PBY=2,QUANTITY='visibility' /
```

## *A.2 FDS Input Data for Forced Extraction Case for Fire for at Closed-End*

```
&HEAD CHID='extraction-end',TITLE='3D Tunnel Simulation - Forced
Extraction Ventilation Case-Fire at Closed-End of Tunnel' /

&GRID IBAR=2000,JBAR=3,KBAR=16 / defines the number of grids in each
direction
&PDIM XBAR0=0.0,XBAR=600,YBAR0=0.0,YBAR=4.0,ZBAR0=0.0,ZBAR=5.0 / defines
the tunnel size

&MISC
TMPA=30.0,REACTION='KEROSENE',SURF_DEFAULT='CONCRETE',DATABASE_DIRECTORY
='c:\nist\fds\database3\' / defines ambient temperature, fuel, and
tunnel surface

&TIME TWFIN=600.0 / 10 minute simulation

&SURF ID='FIRE',HRRPUA=1075. / 17 MW fire over 16m2 area
&SURF ID='HVAC',VOLUME_FLUX=30.0 / air flow rate extracted through duct

&OBST XB=70,600,1.33,2.66,3.75,4.6875 / location of duct in tunnel
&VENT XB=70,70,1.33,2.66,3.75,4.6875 ,SURF_ID='HVAC' / duct is open
&VENT CB='XBAR' ,SURF_ID='OPEN' /

&VENT XB=10,14,0,4,0.0,0.0,SURF_ID='FIRE' / location of fire
&OBST XB= 10,14,0,4,0.4,0.6,SURF_ID='STEEL' / representation of TBM base
where fire is

&THCP XYZ=30,2,0.5,QUANTITY='TEMPERATURE',LABEL='T-30-0.5' /
&THCP XYZ=60,2,0.5,QUANTITY='TEMPERATURE',LABEL='T-60-0.5' /
&THCP XYZ=120,2,0.5,QUANTITY='TEMPERATURE',LABEL='T-120-0.5' /
&THCP XYZ=240,2,0.5,QUANTITY='TEMPERATURE',LABEL='T-240-0.5' /
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```
&THCP XYZ=360,2,0.5,QUANTITY='TEMPERATURE',LABEL='T-360-0.5'  /
&THCP XYZ=480,2,0.5,QUANTITY='TEMPERATURE',LABEL='T-480-0.5'  /
&THCP XYZ=600,2,0.5,QUANTITY='TEMPERATURE',LABEL='T-600-0.5'  /

&THCP XYZ=30,2,1.5,QUANTITY='TEMPERATURE',LABEL='T-30-1.5'  /
&THCP XYZ=60,2,1.5,QUANTITY='TEMPERATURE',LABEL='T-60-1.5'  /
&THCP XYZ=120,2,1.5,QUANTITY='TEMPERATURE',LABEL='T-120-1.5'  /
&THCP XYZ=240,2,1.5,QUANTITY='TEMPERATURE',LABEL='T-240-1.5'  /
&THCP XYZ=360,2,1.5,QUANTITY='TEMPERATURE',LABEL='T-360-1.5'  /
&THCP XYZ=480,2,1.5,QUANTITY='TEMPERATURE',LABEL='T-480-1.5'  /
&THCP XYZ=600,2,1.5,QUANTITY='TEMPERATURE',LABEL='T-600-1.5'  /

&THCP XYZ=30,2,2.5,QUANTITY='TEMPERATURE',LABEL='T-30-2.5'  /
&THCP XYZ=60,2,2.5,QUANTITY='TEMPERATURE',LABEL='T-60-2.5'  /
&THCP XYZ=120,2,2.5,QUANTITY='TEMPERATURE',LABEL='T-120-2.5'  /
&THCP XYZ=240,2,2.5,QUANTITY='TEMPERATURE',LABEL='T-240-2.5'  /
&THCP XYZ=360,2,2.5,QUANTITY='TEMPERATURE',LABEL='T-360-2.5'  /
&THCP XYZ=480,2,2.5,QUANTITY='TEMPERATURE',LABEL='T-480-2.5'  /
&THCP XYZ=600,2,2.5,QUANTITY='TEMPERATURE',LABEL='T-600-2.5'  /

&THCP XYZ=30,2,3.5,QUANTITY='TEMPERATURE',LABEL='T-30-3.5'  /
&THCP XYZ=60,2,3.5,QUANTITY='TEMPERATURE',LABEL='T-60-3.5'  /
&THCP XYZ=120,2,3.5,QUANTITY='TEMPERATURE',LABEL='T-120-3.5'  /
&THCP XYZ=240,2,3.5,QUANTITY='TEMPERATURE',LABEL='T-240-3.5'  /
&THCP XYZ=360,2,3.5,QUANTITY='TEMPERATURE',LABEL='T-360-3.5'  /
&THCP XYZ=480,2,3.5,QUANTITY='TEMPERATURE',LABEL='T-480-3.5'  /
&THCP XYZ=600,2,3.5,QUANTITY='TEMPERATURE',LABEL='T-600-3.5'  /

&THCP XYZ=30,0.67,4.5,QUANTITY='TEMPERATURE',LABEL='T-30-4.5'  /
&THCP XYZ=60,0.67,4.5,QUANTITY='TEMPERATURE',LABEL='T-60-4.5'  /
&THCP XYZ=120,0.67,4.5,QUANTITY='TEMPERATURE',LABEL='T-120-4.5'  /
&THCP XYZ=240,0.67,4.5,QUANTITY='TEMPERATURE',LABEL='T-240-4.5'  /
&THCP XYZ=360,0.67,4.5,QUANTITY='TEMPERATURE',LABEL='T-360-4.5'  /
&THCP XYZ=480,0.67,4.5,QUANTITY='TEMPERATURE',LABEL='T-480-4.5'  /
&THCP XYZ=600,0.67,4.5,QUANTITY='TEMPERATURE',LABEL='T-600-4.5'  /

&THCP XYZ=600,0.67,1.0,QUANTITY='TEMPERATURE',LABEL='T-600-1.0'  /
&THCP XYZ=600,0.67,2.0,QUANTITY='TEMPERATURE',LABEL='T-600-2.0'  /
&THCP XYZ=600,0.67,3.0,QUANTITY='TEMPERATURE',LABEL='T-600-3.0'  /
&THCP XYZ=600,0.67,4.0,QUANTITY='TEMPERATURE',LABEL='T-600-4.0'  /

&THCP XYZ=30,2,0.5,QUANTITY='U-VELOCITY',LABEL='U-30-0.5'  /
&THCP XYZ=60,2,0.5,QUANTITY='U-VELOCITY',LABEL='U-60-0.5'  /
&THCP XYZ=120,2,0.5,QUANTITY='U-VELOCITY',LABEL='U-120-0.5'  /
&THCP XYZ=240,2,0.5,QUANTITY='U-VELOCITY',LABEL='U-240-0.5'  /
&THCP XYZ=360,2,0.5,QUANTITY='U-VELOCITY',LABEL='U-360-0.5'  /
&THCP XYZ=480,2,0.5,QUANTITY='U-VELOCITY',LABEL='U-480-0.5'  /
&THCP XYZ=600,2,0.5,QUANTITY='U-VELOCITY',LABEL='U-600-0.5'  /

&THCP XYZ=30,2,1.5,QUANTITY='U-VELOCITY',LABEL='U-30-1.5'  /
&THCP XYZ=60,2,1.5,QUANTITY='U-VELOCITY',LABEL='U-60-1.5'  /
&THCP XYZ=120,2,1.5,QUANTITY='U-VELOCITY',LABEL='U-120-1.5'  /
&THCP XYZ=240,2,1.5,QUANTITY='U-VELOCITY',LABEL='U-240-1.5'  /
&THCP XYZ=360,2,1.5,QUANTITY='U-VELOCITY',LABEL='U-360-1.5'  /
&THCP XYZ=480,2,1.5,QUANTITY='U-VELOCITY',LABEL='U-480-1.5'  /
&THCP XYZ=600,2,1.5,QUANTITY='U-VELOCITY',LABEL='U-600-1.5'  /

&THCP XYZ=30,2,2.5,QUANTITY='U-VELOCITY',LABEL='U-30-2.5'  /
&THCP XYZ=60,2,2.5,QUANTITY='U-VELOCITY',LABEL='U-60-2.5'  /
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&THCP XYZ=120,2,2.5,QUANTITY='U-VELOCITY',LABEL='U-120-2.5' /
&THCP XYZ=240,2,2.5,QUANTITY='U-VELOCITY',LABEL='U-240-2.5' /
&THCP XYZ=360,2,2.5,QUANTITY='U-VELOCITY',LABEL='U-360-2.5' /
&THCP XYZ=480,2,2.5,QUANTITY='U-VELOCITY',LABEL='U-480-2.5' /
&THCP XYZ=600,2,2.5,QUANTITY='U-VELOCITY',LABEL='U-600-2.5' /

&THCP XYZ=30,2,3.5,QUANTITY='U-VELOCITY',LABEL='U-30-3.5' /
&THCP XYZ=60,2,3.5,QUANTITY='U-VELOCITY',LABEL='U-60-3.5' /
&THCP XYZ=120,2,3.5,QUANTITY='U-VELOCITY',LABEL='U-120-3.5' /
&THCP XYZ=240,2,3.5,QUANTITY='U-VELOCITY',LABEL='U-240-3.5' /
&THCP XYZ=360,2,3.5,QUANTITY='U-VELOCITY',LABEL='U-360-3.5' /
&THCP XYZ=480,2,3.5,QUANTITY='U-VELOCITY',LABEL='U-480-3.5' /
&THCP XYZ=600,2,3.5,QUANTITY='U-VELOCITY',LABEL='U-600-3.5' /

&THCP XYZ=30,0.67,4.5,QUANTITY='U-VELOCITY',LABEL='U-30-4.5' /
&THCP XYZ=60,0.67,4.5,QUANTITY='U-VELOCITY',LABEL='U-60-4.5' /
&THCP XYZ=120,0.67,4.5,QUANTITY='U-VELOCITY',LABEL='U-120-4.5' /
&THCP XYZ=240,0.67,4.5,QUANTITY='U-VELOCITY',LABEL='U-240-4.5' /
&THCP XYZ=360,0.67,4.5,QUANTITY='U-VELOCITY',LABEL='U-360-4.5' /
&THCP XYZ=480,0.67,4.5,QUANTITY='U-VELOCITY',LABEL='U-480-4.5' /
&THCP XYZ=600,0.67,4.5,QUANTITY='U-VELOCITY',LABEL='U-600-4.5' /

&THCP XYZ=600,0.67,1.0,QUANTITY='U-VELOCITY',LABEL='T-600-1.0' /
&THCP XYZ=600,0.67,2.0,QUANTITY='U-VELOCITY',LABEL='T-600-2.0' /
&THCP XYZ=600,0.67,3.0,QUANTITY='U-VELOCITY',LABEL='T-600-3.0' /
&THCP XYZ=600,0.67,4.0,QUANTITY='U-VELOCITY',LABEL='T-600-4.0' /

&THCP XYZ=30,2,0.5,QUANTITY='oxygen mass fraction',LABEL='O2-30-0.5' /
&THCP XYZ=60,2,0.5,QUANTITY='oxygen mass fraction',LABEL='O2-60-0.5' /
&THCP XYZ=120,2,0.5,QUANTITY='oxygen mass fraction',LABEL='O2-120-0.5' /
&THCP XYZ=240,2,0.5,QUANTITY='oxygen mass fraction',LABEL='O2-240-0.5' /
&THCP XYZ=360,2,0.5,QUANTITY='oxygen mass fraction',LABEL='O2-360-0.5' /
&THCP XYZ=480,2,0.5,QUANTITY='oxygen mass fraction',LABEL='O2-480-0.5' /
&THCP XYZ=600,2,0.5,QUANTITY='oxygen mass fraction',LABEL='O2-600-0.5' /

&THCP XYZ=30,2,1.5,QUANTITY='oxygen mass fraction',LABEL='O2-30-1.5' /
&THCP XYZ=60,2,1.5,QUANTITY='oxygen mass fraction',LABEL='O2-60-1.5' /
&THCP XYZ=120,2,1.5,QUANTITY='oxygen mass fraction',LABEL='O2-120-1.5' /
&THCP XYZ=240,2,1.5,QUANTITY='oxygen mass fraction',LABEL='O2-240-1.5' /
&THCP XYZ=360,2,1.5,QUANTITY='oxygen mass fraction',LABEL='O2-360-1.5' /
&THCP XYZ=480,2,1.5,QUANTITY='oxygen mass fraction',LABEL='O2-480-1.5' /
&THCP XYZ=600,2,1.5,QUANTITY='oxygen mass fraction',LABEL='O2-600-1.5' /

&THCP XYZ=30,2,2.5,QUANTITY='oxygen mass fraction',LABEL='O2-30-2.5' /
&THCP XYZ=60,2,2.5,QUANTITY='oxygen mass fraction',LABEL='O2-60-2.5' /
&THCP XYZ=120,2,2.5,QUANTITY='oxygen mass fraction',LABEL='O2-120-2.5' /
&THCP XYZ=240,2,2.5,QUANTITY='oxygen mass fraction',LABEL='O2-240-2.5' /
&THCP XYZ=480,2,2.5,QUANTITY='oxygen mass fraction',LABEL='O2-480-2.5' /
&THCP XYZ=600,2,2.5,QUANTITY='oxygen mass fraction',LABEL='O2-600-2.5' /

&THCP XYZ=30,2,3.5,QUANTITY='oxygen mass fraction',LABEL='O2-30-3.5' /
&THCP XYZ=60,2,3.5,QUANTITY='oxygen mass fraction',LABEL='O2-60-3.5' /
&THCP XYZ=120,2,3.5,QUANTITY='oxygen mass fraction',LABEL='O2-120-3.5' /
&THCP XYZ=240,2,3.5,QUANTITY='oxygen mass fraction',LABEL='O2-240-3.5' /
&THCP XYZ=360,2,3.5,QUANTITY='oxygen mass fraction',LABEL='O2-360-3.5' /
&THCP XYZ=480,2,3.5,QUANTITY='oxygen mass fraction',LABEL='O2-480-3.5' /
&THCP XYZ=600,2,3.5,QUANTITY='oxygen mass fraction',LABEL='O2-600-3.5' /

&THCP XYZ=30,0.67,4.5,QUANTITY='oxygen mass fraction',LABEL='O2-30-4.5' /
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&THCP XYZ=60,0.67,4.5,QUANTITY='oxygen mass fraction',LABEL='O2-60-4.5' /
&THCP XYZ=120,0.67,4.5,QUANTITY='oxygen mass fraction',LABEL='O2-120-4.5' /
&THCP XYZ=240,0.67,4.5,QUANTITY='oxygen mass fraction',LABEL='O2-240-4.5' /
&THCP XYZ=360,0.67,4.5,QUANTITY='oxygen mass fraction',LABEL='O2-360-4.5' /
&THCP XYZ=480,0.67,4.5,QUANTITY='oxygen mass fraction',LABEL='O2-480-4.5' /
&THCP XYZ=600,0.67,4.5,QUANTITY='oxygen mass fraction',LABEL='O2-600-4.5' /

&THCP XYZ=30,2,0.5,QUANTITY='visibility',LABEL='S-30-0.5' /
&THCP XYZ=60,2,0.5,QUANTITY='visibility',LABEL='S-60-0.5' /
&THCP XYZ=120,2,0.5,QUANTITY='visibility',LABEL='S-120-0.5' /
&THCP XYZ=240,2,0.5,QUANTITY='visibility',LABEL='S-240-0.5' /
&THCP XYZ=360,2,0.5,QUANTITY='visibility',LABEL='S-360-0.5' /
&THCP XYZ=480,2,0.5,QUANTITY='visibility',LABEL='S-480-0.5' /
&THCP XYZ=600,2,0.5,QUANTITY='visibility',LABEL='S-600-0.5' /

&THCP XYZ=30,2,1.5,QUANTITY='visibility',LABEL='S-30-1.5' /
&THCP XYZ=60,2,1.5,QUANTITY='visibility',LABEL='S-60-1.5' /
&THCP XYZ=120,2,1.5,QUANTITY='visibility',LABEL='S-120-1.5' /
&THCP XYZ=240,2,1.5,QUANTITY='visibility',LABEL='S-240-1.5' /
&THCP XYZ=360,2,1.5,QUANTITY='visibility',LABEL='S-360-1.5' /
&THCP XYZ=480,2,1.5,QUANTITY='visibility',LABEL='S-480-1.5' /
&THCP XYZ=600,2,1.5,QUANTITY='visibility',LABEL='S-600-1.5' /

&THCP XYZ=30,2,2.5,QUANTITY='visibility',LABEL='S-30-2.5' /
&THCP XYZ=60,2,2.5,QUANTITY='visibility',LABEL='S-60-2.5' /
&THCP XYZ=120,2,2.5,QUANTITY='visibility',LABEL='S-120-2.5' /
&THCP XYZ=240,2,2.5,QUANTITY='visibility',LABEL='S-240-2.5' /
&THCP XYZ=360,2,2.5,QUANTITY='visibility',LABEL='S-360-2.5' /
&THCP XYZ=480,2,2.5,QUANTITY='visibility',LABEL='S-480-2.5' /
&THCP XYZ=600,2,2.5,QUANTITY='visibility',LABEL='S-600-2.5' /

&THCP XYZ=30,2,3.5,QUANTITY='visibility',LABEL='S-30-3.5' /
&THCP XYZ=60,2,3.5,QUANTITY='visibility',LABEL='S-60-3.5' /
&THCP XYZ=120,2,3.5,QUANTITY='visibility',LABEL='S-120-3.5' /
&THCP XYZ=240,2,3.5,QUANTITY='visibility',LABEL='S-240-3.5' /
&THCP XYZ=360,2,3.5,QUANTITY='visibility',LABEL='S-360-3.5' /
&THCP XYZ=480,2,3.5,QUANTITY='visibility',LABEL='S-480-3.5' /
&THCP XYZ=600,2,3.5,QUANTITY='visibility',LABEL='S-600-3.5' /

&THCP XYZ=30,0.67,4.5,QUANTITY='visibility',LABEL='S-30-4.5' /
&THCP XYZ=60,0.67,4.5,QUANTITY='visibility',LABEL='S-60-4.5' /
&THCP XYZ=120,0.67,4.5,QUANTITY='visibility',LABEL='S-120-4.5' /
&THCP XYZ=240,0.67,4.5,QUANTITY='visibility',LABEL='S-240-4.5' /
&THCP XYZ=360,0.67,4.5,QUANTITY='visibility',LABEL='S-360-4.5' /
&THCP XYZ=480,0.67,4.5,QUANTITY='visibility',LABEL='S-480-4.5' /
&THCP XYZ=600,0.67,4.5,QUANTITY='visibility',LABEL='S-600-4.5' /

&SLCF PBX=30,QUANTITY='TEMPERATURE' /
&SLCF PBX=60,QUANTITY='TEMPERATURE' /
&SLCF PBX=70,QUANTITY='TEMPERATURE' /
&SLCF PBX=120,QUANTITY='TEMPERATURE' /
&SLCF PBX=240,QUANTITY='TEMPERATURE' /
&SLCF PBX=360,QUANTITY='TEMPERATURE' /
&SLCF PBX=480,QUANTITY='TEMPERATURE' /
&SLCF PBX=600,QUANTITY='TEMPERATURE' /

&SLCF PBX=30,QUANTITY='U-VELOCITY' /
&SLCF PBX=60,QUANTITY='U-VELOCITY' /
&SLCF PBX=70,QUANTITY='U-VELOCITY' /
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```
&SLCF PBX=120,QUANTITY='U-VELOCITY' /
&SLCF PBX=240,QUANTITY='U-VELOCITY' /
&SLCF PBX=360,QUANTITY='U-VELOCITY' /
&SLCF PBX=480,QUANTITY='U-VELOCITY' /
&SLCF PBX=600,QUANTITY='U-VELOCITY' /

&SLCF PBX=30,QUANTITY='oxygen mass fraction' /
&SLCF PBX=60,QUANTITY='oxygen mass fraction' /
&SLCF PBX=70,QUANTITY='oxygen mass fraction' /
&SLCF PBX=120,QUANTITY='oxygen mass fraction' /
&SLCF PBX=240,QUANTITY='oxygen mass fraction' /
&SLCF PBX=360,QUANTITY='oxygen mass fraction' /
&SLCF PBX=480,QUANTITY='oxygen mass fraction' /
&SLCF PBX=600,QUANTITY='oxygen mass fraction' /

&SLCF PBX=30,QUANTITY='visibility' /
&SLCF PBX=60,QUANTITY='visibility' /
&SLCF PBX=70,QUANTITY='visibility' /
&SLCF PBX=120,QUANTITY='visibility' /
&SLCF PBX=240,QUANTITY='visibility' /
&SLCF PBX=360,QUANTITY='visibility' /
&SLCF PBX=480,QUANTITY='visibility' /
&SLCF PBX=600,QUANTITY='visibility' /

&SLCF PBY=0.67,QUANTITY='TEMPERATURE' /
&SLCF PBY=0.67,QUANTITY='U-VELOCITY' /
&SLCF PBY=0.67,QUANTITY='oxygen mass fraction' /
&SLCF PBY=0.67,QUANTITY='visibility' /

&SLCF PBY=2,QUANTITY='TEMPERATURE' /
&SLCF PBY=2,QUANTITY='U-VELOCITY' /
&SLCF PBY=2,QUANTITY='oxygen mass fraction' /
&SLCF PBY=2,QUANTITY='visibility' /
```

## *A.3 FDS Input Data for Natural Ventilation Case for Fire for at Closed-End*

```
&HEAD CHID='natural-end',TITLE='3D Tunnel Simulation – Natural
Ventilation Case-Fire at Closed-End of Tunnel' /

&GRID IBAR=2000,JBAR=3,KBAR=16 / defines the number of grids in each
direction
&PDIM XBAR0=0.0,XBAR=600,YBAR0=0.0,YBAR=4.0,ZBAR0=0.0,ZBAR=5.0 / defines
the tunnel size

&MISC
TMPA=30.0,REACTION='KEROSENE',SURF_DEFAULT='CONCRETE',DATABASE_DIRECTORY
='c:\nist\fds\database3\' / defines ambient temperature, fuel, and
tunnel surface

&TIME TWFIN=600.0 / 10 minute simulation

&SURF ID='FIRE',HRRPUA=1075. / 17 MW fire over 16m2 area
&SURF ID='HVAC',VOLUME_FLUX=0.0 / no air flow rate through duct

&OBST XB=70,600,1.33,2.66,3.75,4.6875 / location of duct in tunnel
&VENT XB=70,70,1.33,2.66,3.75,4.6875 ,SURF_ID='HVAC' / duct is open
```

```
&VENT CB='XBAR' ,SURF_ID='OPEN' /

&VENT XB=10,14,0,4,0.0,0.0,SURF_ID='FIRE' / location of fire
&OBST XB= 10,14,0,4,0.4,0.6,SURF_ID='STEEL' / representation of TBM base
where fire is

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Note: This appendix section only contains FDS graphical results pertaining to the

forced injection case as an example of results obtained.

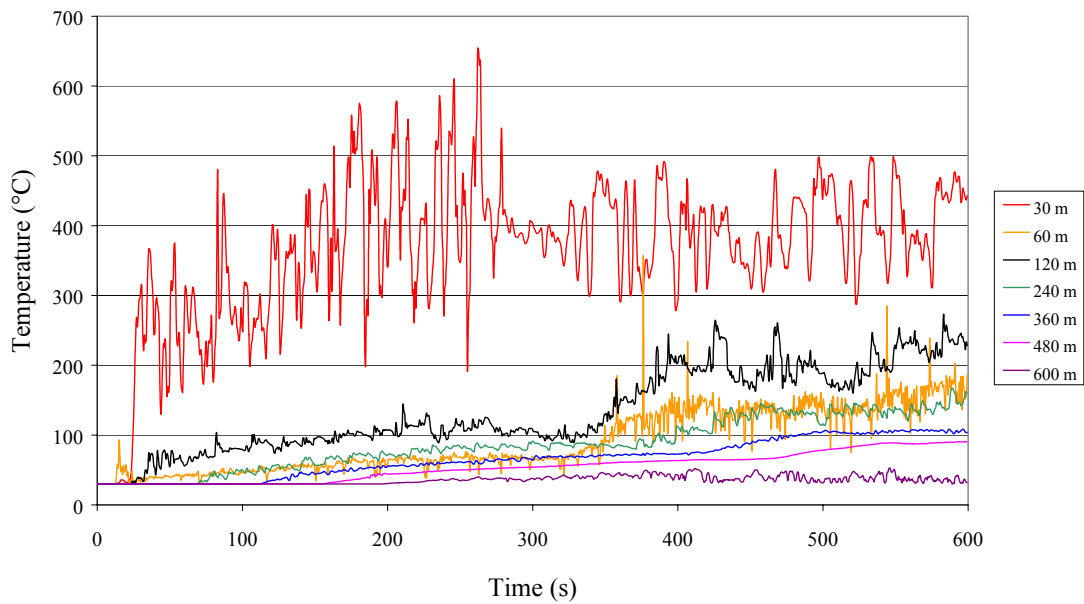*A.4 Graphical Results from FDS for Forced Injection Case for Fire at Closed-End*



Figure A1.  Temperatures at the 1.5 m Elevation for Fire at the Closed-End of a
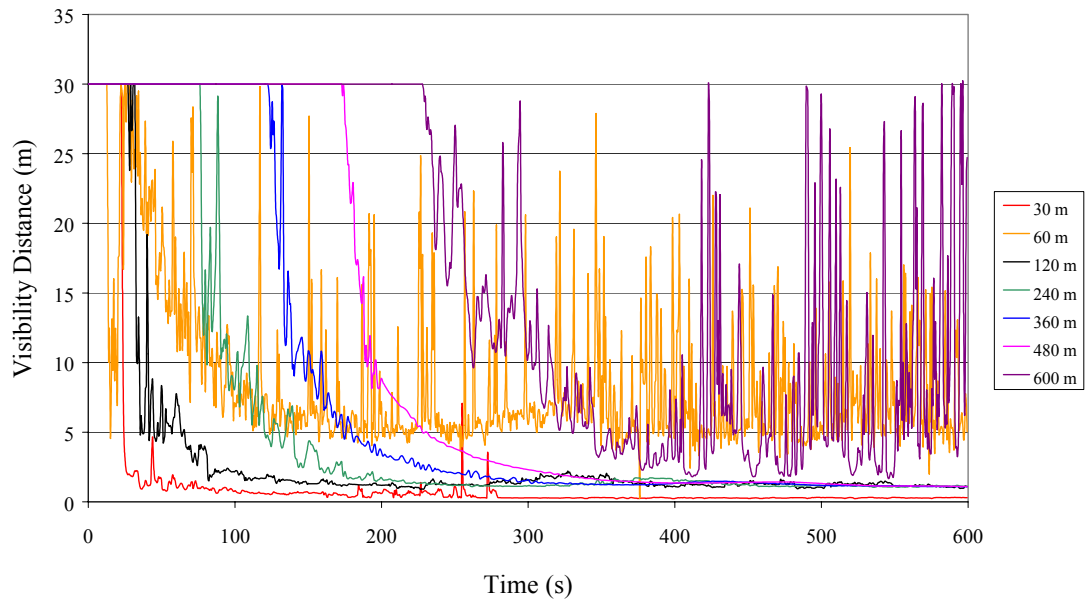
Tunnel for Forced Injection

Figure A2.  Visibility Distances at the 1.5 m Elevation for Fire at the Closed-End of a
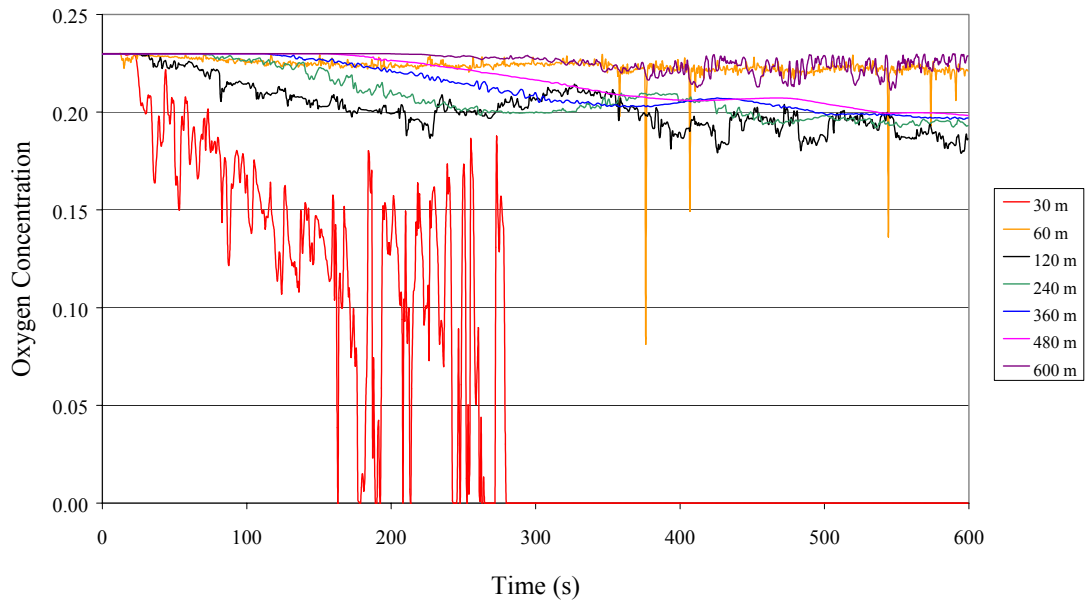
Tunnel for Forced Injection

Figure A3.  Oxygen Concentrations at the 1.5 m Elevation for Fire at the Closed-End

of a Tunnel for Forced Injection

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