THE CALDECOTT TUNNEL FIRE THERMAL ENVIRONMENTS, REGULATORY CONSIDERATIONS AND PROBABILITIES

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INTRODUCTION

A fire occurred in the Caldecott Tunnel on April 7, 1982. This fire was one of five major highway tunnel fires involving large shipments of hazardous materials that have happened worldwide since 1949. In the Caldecott Tunnel fire, approximately 32,000 liters (8,500 gallons) of gasoline were burned causing about three million dollars in damage to the tunnel (which was reopened approximately 135 hours after the fire), the loss of seven lives, and the destruction of eight vehicles. Shortly after the Caldecott Tunnel fire occurred, Sandia National Laboratories obtained permission from the California Highway Patrol to send observers to the fire scene before the debris and other evidence had been removed from the tunnel.

In designing transport systems to withstand the effects of a major fire, it is important to know the potential thermal environment. Designing a system that will survive a severe fire environment is difficult because of the limited information available on actual fires and because many variables can have a strong influence on a fire. A tunnel fire is unique because it confines the fire somewhat like a furnace and provides physical constraints or boundary conditions not usually encountered in fire events. This limits the assumptions needed to analyze the fire environment. In addition, the tunnel retains significant information on the behavior of the materials involved in the fire.

The observations made at the scene and the analyses of the information gathered there form the basis of this study. The paper describes the thermal environment, discusses the predicted response of a Type B package to that environment and to the environment resulting from the conditions specified in 10CFR71, Appendix B (1). The probability of a Type B package being involved in a major tunnel fire is also examined.

TUNNEL DESCRIPTION

The Caldecott Tunnel Complex consists of three nearly parallel tunnels located on California State Highway 24 between Oakland and Walnut Creek. The east-west daily flow of traffic averages 110,000 vehicles, including 1219 tractor trailers with five axles or more. The north bore, in which the fire occurred, is dedicated to westbound traffic and was opened in 1964. The tunnel is constructed of a steel frame encased with reinforced concrete. The tunnel has a nearly constant downslope along its 1027 meter (3371 feet) length which results in an elevation change of 49 meters (160 feet) between entrance and exit.

An isometric drawing of the cross-section of the north bore (an eastward view) is shown in Figure 1. Features of the tunnel that are useful in determining the fire environment are the concrete ceiling, the tile lined concrete walls, the ventilation system, the emergency call boxes, the lighting system, and the tunnel dimensions (5.5 meters (18 feet) high and 10.5 meters (34.5 feet) wide).

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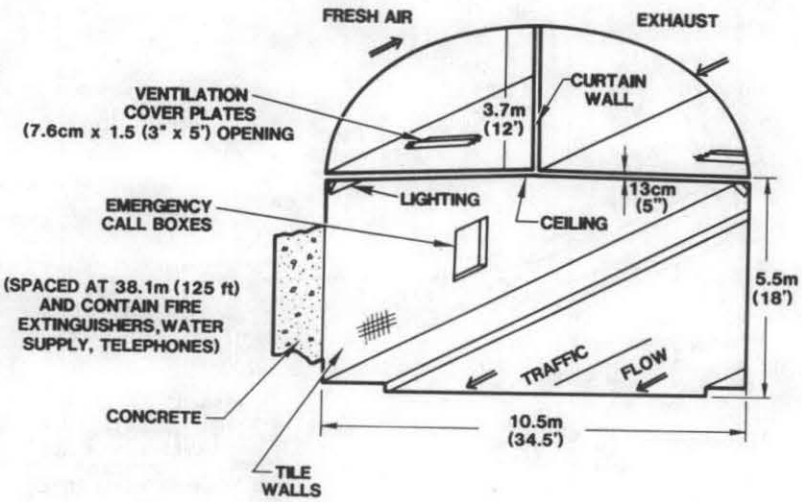

Fig. 1. Isometric cross-section of north bore of Caldecott Tunnel (looking east).

The ventilation system can be described as two tubes, open on the west end and closed on the east end, with vents along the tube lengths. The tube walls are formed by a false ceiling over the roadway, a curtain wall separating the fresh air from the exhaust and the upper portion of the tunnel walls. When in operation, the ventilation system is designed to have fresh air flow up one tube and exhaust gases down the other. The vents are spaced at 4.6 meters (15 feet) and are covered with a 6.5 millimeter (0.25 inch) thick steel plate restricting the vent opening to 0.075 meters by 1.5 meters (3 inches by 5 feet). Although the ventilation system was not in operation during the fire, it provided a source of air to support combustion and retained evidence (thermally buckled cover plates) of the environment after the fire was extinguished.

ACCIDENT DESCRIPTION

The fire was caused by nearly simultaneous collisions of a transit bus (no passengers) and a tank truck and trailer with a stalled automobile. The collisions caused the trailer of the tank truck to become unstable and overturn. (The trailer was attached to the truck by a draw bar not by a fifth wheel.) The trailer was dragged for about 75 meters (250 feet) and eventually came to rest on its side midway through the tunnel. The tank truck remained upright. The overturned trailer released gasoline at a rate of about 75 to 375 liters (20 to 100 gallons) per minute. The first people on the scene stated that burning gasoline flowed down the gutters of the roadway into the drop inlets for drainage. Approximately five minutes after the truck and trailer had come to rest and the driver had made his way to safety by running downhill and out of the tunnel, the characteristics of the fire changed dramatically; the fire changed from a localized conflagration to one whose combustion products engulfed the vehicles that had entered the tunnel from the east. The fire burned unabated for up to 40 minutes consuming the 18,120 liters (4800 gallons) of gasoline in the trailer and 15,140 liters (4000 gallons) of gasoline in the tank truck, except for approximately 750 to 1150 liters (200 to 300 gallons), which drained into the gutters in the first few minutes of the fire or remained in the damaged tanks after the fire was extinguished.

Figure 2 shows the locations of the vehicles involved and the extent of: spalled wall tiles, spalled concrete from the walls and ceiling, and thermally induced deformations of the ventilation cover plates.

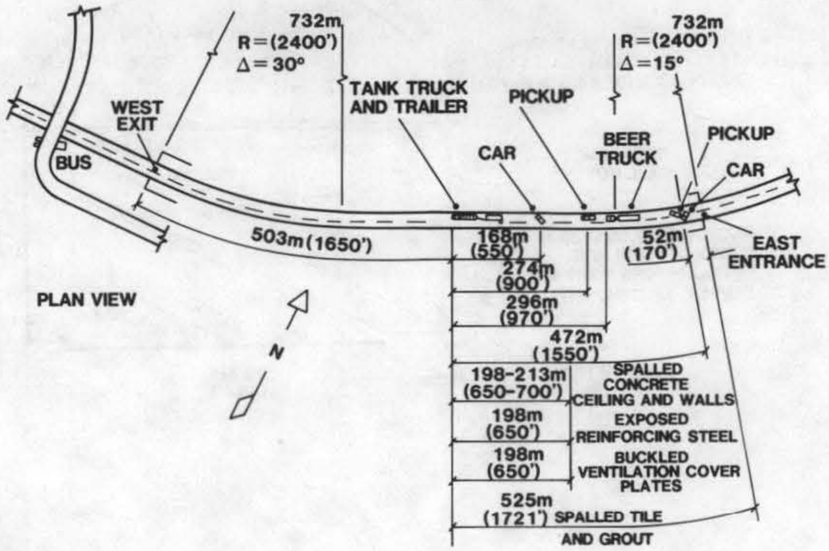

Fig. 2. Schematic of accident location and damage evidence.

PHYSICAL EVIDENCE AND WITNESS OBSERVATIONS

There were four main sources of information about the fire environment: (1) the damage to the tunnel, (2) the damage to the vehicles, (3) the gasoline fuel source, and (4) the observations of the first responders.

The thermally induced spall patterns of the tile, grout, and concrete were uniform for about 230 meters (750 feet) east of the fire source. The concrete walls were spalled to the reinforcing steel, which normally is from 50 to 75 millimeters (2 to 3 inches) below the surface. The false ceiling concrete spalled to a depth of 50 to 100 millimeters (2 to 4 inches) and exposed the double reinforcment steel pattern used in the ceiling. The ventilation steel cover plates (see Fig. 1) were buckled by the heat for a distance of 205 meters (675 feet) east of the tank truck and trailer.

The seven vehicles remaining in the tunnel were destroyed. The tank truck was constructed of aluminum except for the engine, parts of the frame, and the axles. The aluminum parts were melted or partially melted and included the front wheels, which were 25 millimeters (1 inch) thick, the rear dual wheels, the truck frame, the large gasoline tanks, the truck cab, fenders, and hood. Brass fittings on the fuel distribution system for the engine were melted. The copper core of the radiator was exposed but did not melt. The window glass had melted and pooled. All of the combustible materials in the other vehicles (tires, seat covers and interior materials) were burned.

The damage to the tunnel indicated that significant over-pressure had not built up at any time during the fire. The false ceiling, while extensively damaged, did not show evidence of an explosion.

The behavior of the fire as a function of time and location can be deduced from the reports of the first responders. Their reports also include estimates of the air velocity in the tunnel at various times during the fire and supply other evidence used in the analyses to follow.

TEMPERATURE AND DURATION OF FIRE

The extensive aluminum melting (T_{melt} = 660°C (1220°F)), the glass melting and pooling (T_{melt} = 550-650°C (1022-1200°F)) and the melting of brass fittings (T_{melt} = 1000°C (1832°F)) indicate that a severe thermal environment was produced by the burning gasoline in the tunnel. The copper wiring in the lighting fixtures and on the vehicles showed formation of cuprite, which is an oxide of copper that requires local temperatures of approximately 1025°C (1877°F). However, the presence of the cuprite could have been caused by the burning of the wire insulation which could create high localized temperatures. A bound on the maximum temperature in the tunnel was determined by the absence of melted copper (T_{melt} = 1083°C (1981° F)). From this evidence an average temperature of approximately 1000°C (1832°F) was assumed for these analyses. This assumption was verified by other evidence and analyses.

A 1000°C (1832°F) blackbody fire that would heat and melt the 38-millimeter (1.5 inch) total thickness of the trailer dual wheels (oxide-covered aluminum, emissivity = 0.19), must last for approximately 29 minutes if it heated the wheels from both sides. Convective heating was not considered since it is small compared to the radiative heating for sooty flames at this temperature. A lower temperature fire environment, i.e. 802°C (1475°F), would require over 2 hours to melt the dual wheels. The time required to melt various thickness of aluminum for various fire temperatures is shown in Figure 3.

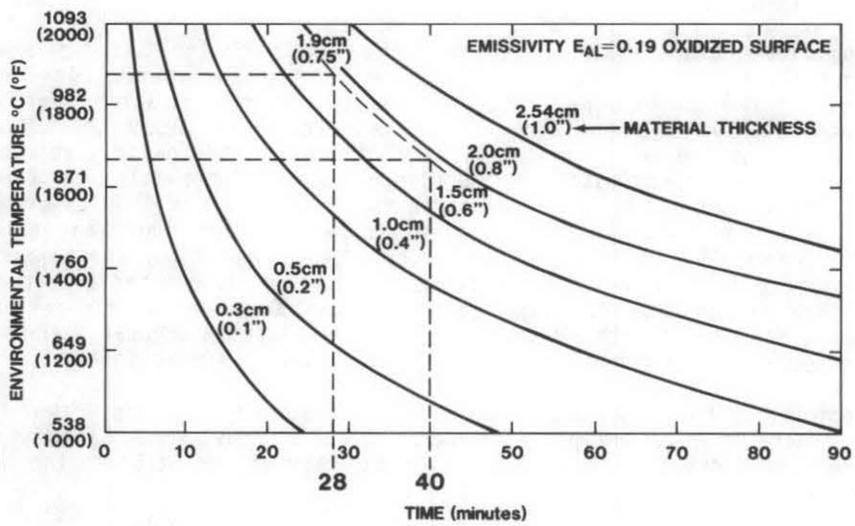

Fig. 3. Time required to heat and melt aluminum (insulated back face) in a thermal radiation environment.

Another approach to determing the duration of the fire was to calculate the energy input necessary to heat and vaporize the large quantity of gasoline contained in the two tanks. If it is assumed that the surfaces of the tanks were exposed to a 1000°C thermal environment, the unwetted portion of the 3.9 to 4.4 mm (0.15 to 0.17 inch) thick aluminum tank walls would melt in about seven minutes. Then, the fuel surface would be directly exposed to the radiating environment. With fuel assumed to be drained to the level of the fill ports, approximately 1455 liters (400 gallons) of fuel in the trailer tank would be vaporized during the seven minutes before the wall melted through. The remainder of the fuel would then be vaporized and burned in approximately 21 minutes (28 minutes into the fire). For the truck tank, 43 minutes would be required to melt the unwetted tank wall and to heat and vaporize the 14,550 liters (4000 gallons) of gasoline. However, this time could be reduced if gasoline were spilled. The post-fire condition of the truck tank indicates that the tank did tilt backwards when the aluminum frame of the truck lost its structural integrity. This information was used to establish a minimum burn time of approximately 28 minutes and a maximum burn time of approximately 40 minutes.

VELOCITIES OF AIR AND COMBUSTION PRODUCTS IN TUNNEL

A complete stoichiometric burn of 475 moles (8500 gallons) of gasoline would require 28,300 moles of air. If the combustion occurs over a 35-minute period, a tunnel inlet air velocity of 2.6 m/sec (5.8 miles per hour) is required, a value which is reasonable based on observers comments. After combustion, the heated products would have an average velocity of 15.5 m/sec (35 mph) which is not inconsistent with the observations. Of course, the combustion process could have been either fuel- or air-rich which would affect the total energy release and velocity conditions.

The "pumping" capacity of the flame was examined to determine what mass flow rates might be induced by the fire due to the high internal temperature and the 49 meter (160 feet) elevation change in the tunnel. Buoyancy/drag computations predict an average induced inlet velocity of only 0.8 m/sec (1.8 mph). Since this low velocity is not consistent with observer's comments and does not provide sufficient combustion air for the apparent energy release that occurred in the tunnel, it was concluded that local wind conditions controlled the inlet mass flow rate and that stoichiometric combustion occured.

TEMPERATURE PROFILE IN TUNNEL

The gas temperature distribution down the length of the tunnel was examined by coupled heat transfer and combustion-energy release considerations. The heat transfer to the walls of the tunnel would initially be governed by radiation, and later as the wall becomes hot, by the conduction in the concrete. Even though the adiabatic flame temperature of gasoline is approximately 2100°C, evidence indicates that local temperatures did not exceed approximately 1083°C (copper melt). Apparently, the thermal losses from the flame prevented higher temperatures from being reached. By examining the rate of energy loss that would occur at a flame temperature of 1000°C and balancing that against the energy production which would occur due to stoichiometric combustion, along with the estimated average velocity in the tunnel, it was determined that the combustion energy release had to be occurring over more than 100 meters of tunnel length. This would account somewhat for the evidence of a nearly uniform thermal environment in the tunnel for approximately 200 meters downwind (upslope) of the accident.

A predicted gas temperature versus tunnel length at various times is shown in Figure 4. These temperature profiles were calculated by assuming that the thermal losses were governed by the lower of either the thermal radiation to the wall or heat conduction in the concrete.

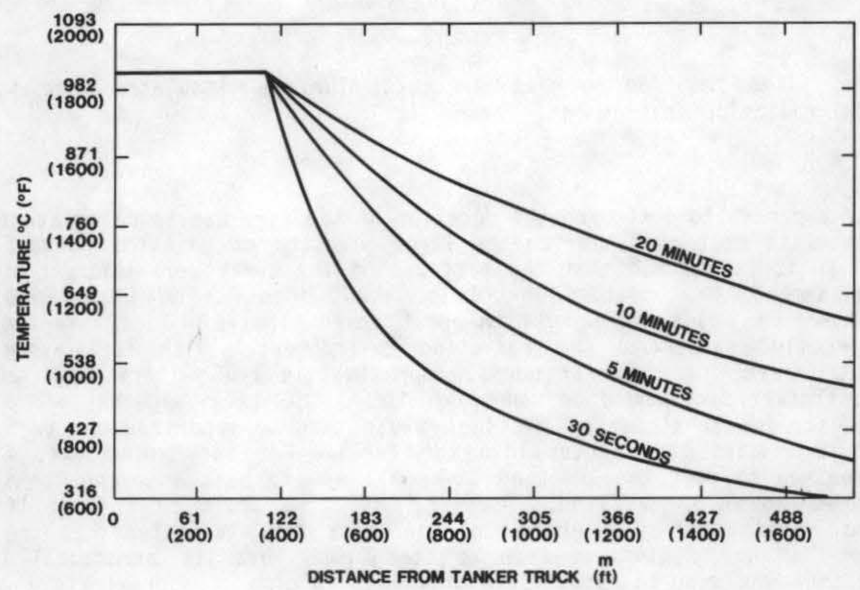

Fig. 4. Approximate gas temperature in tunnel.

CONCLUSIONS ABOUT THERMAL ENVIRONMENT

The various analyses and the physical evidence yield a consistent description of the thermal environment. The average temperature of the combustion products for more than a hundred meters upslope from the tanker was likely between 1000°C and 1050°C. The duration of the fire was between 28 and 40 minutes. Analyses indicate that vaporized fuel was provided from both the truck and trailer tanks for the first 28 minutes and from the truck tank only for approximately the following 12 minutes.

PPREDICTED RESPONSE OF TYPE B PACKAGE TO THE FIRE ENVIRONMENT

The response of a cask to a thermal environment is dependent upon the characteristics of the fire and properties of the cask, including its thermal mass, surface emissivity and absorptivity. These thermal properties are determined by the type of material used to construct the cask and the condition of its surface throughout a fire.

In order to estimate the thermal response of a thick-walled cask to the calculated environment for the Caldecott Tunnel Fire and to the regulatory tests, a simple one-dimensional model was developed and used to represent a cask wall. An 0.23-meter (9-inch) thick plate of stainless steel was modeled with an insulated boundary on one side and a fire environment on the other. In the model, the fire was represented by applying a radiation heat flux, which was determined by the temperature and emittance of the fire and the absorptivity of the stainless steel, to one surface of the plate. In turn, the plate was allowed to conduct the heat from this surface to its interior and also to radiate heat from its surface. Surface absorptivity and emissivity were assumed to be equal. Results obtained using this simple model, as shown in Table 1, indicate that the net thermal energy to the plate, when subjected to the Caldecott tunnel fire environment, is strongly dependent upon assumed surface properties and could be either less than or greater than the thermal input received when subjected to the regulatory test conditions. The model implicitly assumed that the material from which the plate was constructed does not degrade or melt at the increased temperatures. This assumption is valid for the stainless steel plate used in this analysis and is probably valid for the outside shell material of most Type B packages.

The response of a Type B package with a thin metal wall as the external surface was also examined. In this instance, the exterior wall quickly equilibrated to the fire temperature and the net energy input was significantly lower. Net thermal input to a thin walled package is a function of package design and the ability of the external skin to withstand the fire temperature.

Simple analytical models have limitations and calculated results may not always be representative of physical results obtained in experiments. For example, this model does not account for processes that are thought to occur such as quenching of the flame in regions very near a package wall (which would tend to reduce heat input) nor does it account for soot deposition which would change surface properties and might increase the heat input. Additionally, it does not account for physical characteristics of a specific Type B package design such as voided shielding areas and layers of different materials with different thermal properties.

As shown in the table, net energy input to the plate is quite sensitive to the absorptivity selected. Generally speaking, surfaces that are polished have lower absorptivities than oxidized surfaces. The actual absorptivity will be a function of the material, surface finish, and age. Typically, unpainted finished metals will have an absorptivity less than 0.2; however, in a fire environment, the absorptivity could change throughout the duration of a fire. As a result, conclusions about the thermal response of any specific Type B package should not be drawn from these statements about the severity of the Caldecott Tunnel fire environment unless cask-specific analyses and experiments are performed.

TABLE 1
Net Heat into a 0.23-meter Thick Stainless-steel Plate with Insulated Backface

Q_{net} from Tunnel Fire Conditions

Plate Absorptivity, α	1000°C, ε = 0.9 for 28 min.	1050°C, ε = 0.9 for 40 min.
	MJ/m^2	MJ/m^2
0.8	168	193
0.6	133	154
0.4	93	108
0.2	48	57
0.1	25	29

Regulatory conditions (T = 802°C (1475°F); emissivity, ε = 0.9; absorptivity, α = 0.8; 30 minutes) Q_{net} = 94 MJ/m^2.

PROBABILITY CONSIDERATIONS

This accident and its relationship to the regulatory requirements for Type B packages is placed in some perspective by considering the probability of a similar tunnel fire occurring, coupled with the probability that the accident would occur while there was a Type B radioactive material shipment coincidentally in the tunnel.

To evaluate the probability of an accident at least as severe as the one that occurred, two factors were required: (1) the rate of occurrence for accidents that are at least as severe as this one and that involve large quantities of flammable material and (2) the number of trucks traveling through the tunnel annually. Table 2 contains values for parameters used in the analysis and the associated references. The resulting probability for the occurrence of an accident in the Caldecott tunnel, which is at least as severe as the one that occurred, is 1×10^{-3}/year.

In order to consider the additional condition that a radioactive material shipment might be in the tunnel at the same time as the severe accident, it is necessary to determine the fraction of time that Type B radioactive material shipments are in the tunnel. Using general commerce statistics, it was estimated that a radioactive material shipment would be found in the tunnel 0.002% of the time. Since the occurrence of a severe accident and the existence of a radioactive material shipment in the tunnel at any given time are independent events, the product of their likelihood is the probability of coincidental occurrence. As a result, the probability that both events would occur simultaneously is approximately 2×10^{-8}/year.

Several simplifying assumptions were used in deriving this value. The most important of which were: (1) the shipment of radioactive material would be subjected to the same environment anywhere in the tunnel; (2) the number of Type B radioactive material shipments traveling through the tunnel is characterized by the number of such shipments in the United States; and (3) accident rates in the tunnel are adequately represented by the accident rates of these shipments for all road types and types of terrain.

Extending the probabilities to all the tunnels on major U.S. highways is possible by assuming that the Caldecott Tunnel traffic is typical of all U.S. tunnel traffic. The resulting probability of a severe fire occurring in a tunnel in the contiguous United States is approximately 4.5×10^{-2} or about one accident every twenty-two years on the average. The coupled probability that a Type B package would also be present in a tunnel when a severe fire accident occurs is approximately 1×10^{-6}/year or on the average about one such accident every million years in the U.S.

The significance of the probability value, despite inherent limitations of any assumptions or uncertainties used in generating it, is found in its order-of-magnitude. With reasonable certainty, it can be said that the likelihood of having these simultaneous events is small.

Table 2
Values of Parameters Used in Probability Analysis

Parameters	Values	References
Truck traffic volume Caldecott Tunnel	1219 trucks/day	(2)
Fraction of truck traffic flow that is Type B radioactive material shipments.	3.1×10^{-5}	(3, 4)
Accident rate with severe fire resulting	2.4×10^{-9} accidents/km	(5)
Tunnels on major U.S. highways	268 lane-km	(6)

CONCLUSIONS

Observation and analyses yield a consistent description of the Caldecott Tunnel fire thermal environment of approximately 1000°C for 28 to 40 minutes. This environment was nearly uniform for a distance of 100 to 200 meters downwind (east) of the tank truck and trailer. Predictions of the response of a Type B package using simple analytical models indicate that the net thermal energy received by the package is a strong function of the surface and material properties and package design. The thermal input from the tunnel fire may be either greater or less than that from regulatory conditions. The likelihood of a tunnel-fire accident occurring when a Type B package is in the tunnel is small.

1. Title 10, Code of Federal Regulations, Part 71, Appendix B.

2. State of California, "1980 Annual Average Daily Truck Traffic on the California State Highway System," September, 1981.

3. U. S. Department of Transportation, "Accidents of Motor Carriers of Property 1980-1981," Federal Highway Administration Bureau of Motor Carrier Safety, August 27, 1982.

4. U. S. Nuclear Regulatory Commission, Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes, NUREG-0170, Volume 1, December, 1977.

5. R. K. Clarke, J. T. Foley, W. F. Hartman, and D. W. Larson, Severities of Transportation Accidents, Vol. III - Motor Carriers, SLA74-0001, Sandia National Laboratories, Albuquerque, NM, July, 1976.

6. Private Communication: James Washington, Federal Highway Administration, Dept. of Transportation, Washington, DC, May, 1983.