# FHWA Report: Prevention and Control of Highway Tunnel Fires

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ABSTRACT

This paper is comprised of some of the findings, conclusions, and recommendations of an FHWA report entitled "Prevention and Control of Highway Tunnel Fires." The study was conducted because FHWA personnel believed that although possibly many tunnel fires had occurred in the past, no record of these fires existed. Concern was expressed that if information on tunnel fires was not preserved, the experience gained during these fires could not be used to help prevent tunnel fires in the future. A consultant conducted the FHWA study, the scope of which did not include testing or physical investigations due to funding limitations. Investigated in the study were (a) steps that can be taken to reduce the risk, damage, and number of fatalities from fires in existing and future highway tunnels and (b) the effect of unrestricted transit of hazardous materials through tunnels. The history of highway tunnel fires was examined to determine the design and operating features that influenced ignition and spread of fire; detection, alarm transmission, and notification of appropriate authorities; response; control, extinguishment, and suppression; and resultant fatalities and damage. Operators in major domestic highway tunnels were interviewed about tunnel fires, and their responses were tabulated and compared. The procedures used in and results of several tunnel fire tests were examined and their recommendations evaluated in light of historical evidence and operating experience concerning tunnel fires. A risk analysis for unrestricted transit of hazardous materials through a reference tunnel was performed and applied to 35 tunnels included in the study. Qualitative assessments of the effects of traffic, tunnel design, and operations on this risk were made. Comprehensive design and operating recommendations for prevention, detection, alarm, notification, control, extinguishment, suppression, and survival were developed. A ventilation system with a fire and emergency operating mode designed to provide motorists trapped in a tunnel fire with optimal escape potential was described and its inclusion in future vehicular tunnels was recommended.

Highway tunnel fires can involve either the tunnel structure and systems or the vehicles that pass through it. However, no evidence of fires involving only tunnel structure or systems has been found. The nonflammable nature of the materials involved suggests that all highway tunnel fires will continue to originate in vehicles and their fuel, cargo, and furnishings. Tunnels will be damaged and lives lost because tunnel systems and operations cannot control the ignition hazard presented by these vehicles and the conditions brought about by a fire in a confined and often crowded tube.

Fire statistics indicate that highway tunnels are safer than open roads. There have apparently been only two major tunnel fires in the United States, only one of which involved fatalities, and two elsewhere. (What was perhaps the worst incident, that involving a Soviet military convoy in Afghanistan, has not been included in this study because of the lack of information and the special circumstances that apparently surround it.) Many operators of the older, more congested Eastern urban tunnels commented on their good luck for having escaped a fatal fire for so long. The evidence, however, suggests that it is not simply good fortune but, rather, management attitudes, operating practices, and system design criteria found common to these tunnels that have been instrumental in maintaining a good safety record.

The information and conclusions in this paper have been organized in a common pattern based on the chronological occurrence of events in a tunnel fire: conditions leading to ignition and spread of fire; detection, alarm, and notification of appropriate authorities after ignition; response; control, extinguishment, and suppression; and fatalities and damage.

The tunnels investigated fall into three groups: subaqueous, dry urban, and dry remote.

- Subaqueous: closely watched, critical traffic links that are often congested with slow-moving commercial traffic; usually one-way traffic in two-lane underwater tubes of sagging profile.
- Dry urban: lightly watched, arterial rush-hour routes frequented by habitual suburban drivers; usually multilane with shoulders, cut-and-cover, with in-tunnel or near-portal interchanges and municipal services nearby.
- Dry remote: lightly traveled Interstate connections through geographic barriers without convenient alternate routes; typically without local municipal services, that is, fire protection or water.

Cost, economic importance, traffic level, traffic mix, and operating environment differ for each of these groups, and so, consequently, do the risk and consequences of a fire. Application of risk-assessment methods will result in different cost-effective methods of fire prevention and control.

Vehicles have been classified into two groups, cars and trucks, based on maneuverability and frontal area. Cars can be turned around in the normally encountered two-lane tunnel and do not substantially fill its width. Trucks, however, cannot be turned or have sufficient frontal area to block a tunnel width, especially if two are side by side.

Cargoes have been divided into four groups without reference to formal classification schemes or published lists. The first group includes poisonous, toxic, nuclear, and explosive materials, substances to which mere exposure can be life threatening or involvement of which in a mishap could result in complete loss of a tunnel. Pressurized and liquefied gas containers should be included in this group because fires involving these materials can neither be allowed to burn in confined spaces nor, because of the threat of explosion from escaping gas, be safely extinguished.

The second group includes flammable liquids and certain hydrocarbon-based solids that are normally expected to easily catch fire when exposed to ignition sources. The FHWA study mainly concerned the tunnel fire safety ramifications of transporting the following substances: fuels, organic chemicals, finely divided materials, and some foodstuffs.

The third group includes combustible solids that will burn, such as paper and wood, but the normally transported forms of which, such as large rolls or lumber, do not easily catch fire. The fourth group includes nonflammable cargo.

The four groups described match the practical concerns of tunnel operators. However, assignment of thousands of substances to one or another group is beyond the scope of this study. In this paper, "hazardous material" refers to a substance that is or should be included in these first two groups.

Combinations of cargo and tunnel groups need to be subjected to quantitative risk assessments before the most cost-effective fire prevention and control strategy can be specified. The FHWA study attempted to list and evaluate the effectiveness of fire prevention and control systems, either in use, state of the art, or within reach of developing technology in the near future, to provide operators and designers a starting point for comprehensive risk analyses of the choices available.

## SURVEY OF TUNNEL FIRES

Tunnel fires were divided into three types based on the order-of-magnitude rate of their energy output. The three types are (a) small automobile fires (1 MW or 950,000 Btu/min); (b) medium fires (10 MW or 10 million Btu/min); and (c) major hazardous material fires (more than 100 MW or 100 million Btu/min).

Small automobile fires are routine incidents, occurring weekly in congested urban tunnels. They have been extinguished without difficulty to date: no noteworthy examples were cited by tunnel operators interviewed during the study and none were featured in the literature reviewed.

Four major hazardous material tunnel fires in the past 50 years were identified, two in the United States, one in Japan, and one in West Germany. Another, the Baltimore Harbor Tunnel fire, occurred just outside of a vehicular tunnel. Five medium-sized tunnel fires were identified, four in the United States and one in Vancouver, British Columbia.

Information concerning five of these fires has been summarized here. These summaries are followed by a discussion comparing and contrasting similar features of each fire as background for the evaluations of fire prevention and control options given later. Findings of several other studies that might highlight actions taken during a fire and results achieved follow this discussion. Finally, this section ends with a synopsis of existing tunnel operating practices for fire prevention and control.

### Summaries of Major Fires

Only two major fires have occurred during the history of tunnels in the United States: the 1949 Holland Tunnel fire (New York) and the 1982 Caldecott Tunnel fire (California). Summaries from the FHWA report about these two fires are given here.

### Holland Tunnel Fire

A major hazardous material fire occurred on May 13, 1949, in the Holland Tunnel in New York City.

#### *Conditions at Ignition*

A fully enclosed trailer carrying 80 55-gal drums of carbon disulfide entered the New Jersey portal of the tunnel, in violation of Port Authority regulations, and allegedly unplacarded, in violation of Interstate Commerce Commission regulations. Traffic was very heavy and slow; the time was approximately 8:30 a.m. The drum broke free and ignited upon striking the roadway approximately 2,900 ft into the tunnel. The truck rolled to a stop in the left lane. Four trucks caught fire or were abandoned next to the trailer in the right lane; also ignited were five trucks that stopped 350 ft behind the trailer and were grouped close together in the right lane. Approximately 125 automobiles, buses, and trucks filled both lanes, back to the New Jersey portal.

#### *Detection, Alarm, and Notification*

A patrolling officer 100 ft from the mishap transmitted a trouble signal to the control room at 8:48 a.m.; the officer assisted drivers escaping from the scene through a cross adit to the north tube. At 8:56 a.m. the first fire alarm was transmitted by patrolling officers farther east, who then ran to assist. Tunnel personnel in the tunnel west of the fire promptly evacuated occupants on foot to New Jersey; they started backing vehicles out of the tunnel. The Jersey City Fire Department received telephone notice at 9:05 a.m. The New York Fire Department received a fire alarm at 9:12 a.m.

#### *Response*

A three-man emergency crew drove west through the eastbound tube on a wrecker and jeep after receiving the 8:56 fire alarm; they commenced fighting the fire with a 1.5-in. hose and spray nozzle. They assisted two tunnel patrolmen overcome by smoke, knocked down fires in two trucks of the eastern group, and towed one to the New York portal. The New York rescue company and battalion chief drove west through the westbound tube, crossed to the scene at the adit, and relieved the tunnel emergency crew. Some firemen in distress recovered by breathing at the curb-level fresh air ports.

A second alarm transmitted at 9:30 a.m. activated four engine companies, two ladder truck companies, and a water tower. Firemen not involved in firefighting searched through burning trucks and helped three trapped persons to safety. Additional New York City pumpers augmented the capacity of the tunnel fire main; they activated five 2.5-in. hoses and a foam generator. The New Jersey engine company, truck company, rescue company, and battalion chief transmitted a second alarm after an initial inspection at the New Jersey portal. Oxygen masks were ordered.

Firemen established hose lines through one-half mile of abandoned vehicles and extinguished fires in the second group of trucks. Tunnel ventilation accelerated to full capacity at the fire site at approximately 9:45 a.m.; firemen discovered that they could work without masks. Two exhaust fans were disabled by heat at 1,000° F; a third fan was kept in service by a water spray. The ceiling over the fire collapsed; fire boats monitored the Hudson River above for signs of tube failure.

The remaining unburning vehicles were removed by 10:15 a.m.; the New Jersey Fire Department drove two pumpers east to the fire site, joining forces with the New York Fire Department. The fire was under control by approximately 1:00 p.m.; overhauling operations continued until 12:52 a.m. the next morning. Residual carbon disulfide and turpentine reflashed at 6:50 p.m. during cleanup; it was extinguished with 5-gal foam extinguishers. The area was then covered with heavy foam.

*Total Equipment Involved*

The following equipment and personnel were involved in fighting the fire: 1 tow truck, several jeeps, 7 chief units, 5 rescue companies, 7 police emergency squads, 14 engine companies, 6 truck companies, 1 lighting truck, 1 water tower, 1 smoke ejector, 1 foam truck, 40 additional firemen, at least 13 ambulances at the scene, and 4 Consolidated Edison emergency trucks with inhalators. (These numbers represent a total of 29 firefighting units, 20 medical units, 7 supervisory units, at least 3 port authority vehicles, and 4 commercial vehicles with special apparatus on board. The total number of personnel involved is unknown, but was more than 250 persons.)

*Survival and Damage*

Ten trucks and cargoes were completely destroyed and 13 others were damaged. Six-hundred ft of tunnel wall and ceiling were demolished; walls were spalled in places to cast iron tube plates. Debris removed from the tunnel totaled 650 tons. The tube was reopened to traffic 56 hr after the fire started. All cable and wire connections through the tube were disrupted during the fire. Total damage was estimated at $1 million (in 1949 dollars). There were 66 injuries, 27 of which required hospitalization; there were no fatalities.

The information in this summary is from the Holland Tunnel chemical fire report by the National Board of Fire Underwriters.

## Caldecott Tunnel Fire

A major hazardous material fire occurred on April 7, 1982, in the Caldecott Tunnel on US-24 in Oakland, California.

*Conditions at Ignition*

A westbound driver who was probably inebriated lost control of a compact automobile just after midnight in light traffic. There were multiple glancing collisions with curbs and the wall; the driver stopped in the left lane slightly into the straightaway from a right curve, probably to inspect damage or effect minor repairs. At least two, possibly three or more, cars passed on the right during the next few minutes. A slightly speeding empty bus that was unaware of the obstacle tried to pass a full gasoline truck-trailer combination. As the truck passed the stopped automobile, multiple collisions occurred. A trailer tank ruptured; spilled gasoline ignited. The bus driver was ejected by collision forces; the bus continued and exited from the portal approximately 36 sec after impact. The truck driver brought the rig to a stop and exited from the west portal on foot. As many as 20 cars entered the east portal.

*Detection, Alarm, and Notification*

The tunnel crew noted noise and vibration from the tunnel and saw the bus exit from the portal and come to rest against the bridge pier (40 sec after the tunnel accident). Operators were dispatched to investigate; two went to the east portal, and one inspected the bus and then drove east up the westbound tube (1 min 40 sec after the accident). The console operator received a call from the tunnel reporting a "bunch of accidents"; however, the telephone connection was lost before more information was exchanged (1 min 10 sec after the accident). The console operator noted multiple simultaneous phone calls from the tunnel seconds before the entire system failed. An operator driving east up the tunnel found a burning gasoline truck and had to retreat to the west portal to find an emergency phone that was operating (a minimum of 5 min after the accident, by the operator's estimate). A console operator placed the first unambiguous call to the Oakland Fire Department a minimum of 7 min after the collision, which was as much as 10 min after the original stoppage in the left lane of the tunnel. An alarm sounded at the fire station 55 sec after initiation of the call.

*Response*

The first pieces of fire equipment reached the west portal 3 min 45 sec after the alarm (a minimum of 10 min 45 sec after the collision). The first fire equipment reached the east portal 7 min after the alarm. Fire equipment from Orinda Fire Department reached the east portal 12 min after the console operator's call. Oakland responded with 7 engines (28 men), two chiefs' cars (4 men), and 3 other units (8 men). Exhaust fans, which may have activated automatically during early stages of the fire in response to high levels of carbon monoxide sensed in the tunnel, soon automatically shut down without having affected events or conditions in the tunnel.

A mother and son following the bus in a pickup truck witnessed the collision between the bus and the gasoline truck, came to a stop, noticed a small fire, and backed up, but abandoned the pickup truck in fear of having a rear-end collision. The woman made calls on an emergency phone (1 min after the collision) until the phone malfunctioned; she returned to the pickup truck less than 50 ft from the unmarked cross adit to the next tube. The son walked east in the tunnel to warn motorists; approximately 2 min later he was enveloped by smoke; he groped his way out of the last 200 ft to the portal. The truck driver and the passenger remained with the beer truck less than 150 ft from the unmarked cross adit. A man in a second pickup truck backed up when warned by the son until enveloped by smoke near a sedan with an elderly couple in it, abandoned the vehicle, and groped through the remaining 80 ft to the portal. All other vehicles cleared the tunnel by backing out, either because of impatience or sight of an approaching smoke wall. The tunnel filled completely with smoke hotter than 300° F eastward from the burning gasoline truck to the portal, within 3 min of the collision.

#### *Control, Extinguishment, and Suppression*

A natural draft eastward through the tunnel blew all combustion products in that direction; firemen approached to within 75 ft of the fire, but made no attempt to suppress the fire at that time. Fans were left off because of concern for maintaining a natural draft. Firemen were unable to operate corroded valves to direct a water-gasoline mixture in the tunnel drainage away from a nearby lake; they concentrated on the explosion and pollution hazard at the lake while waiting for the fire to burn down. Efforts to extinguish the fire began at 1:29 a.m. (75 min after the initial collision); however, the tunnel water pressure fell to a pressure too low to support the hose streams. Firemen near the tanker observed water leaking from damaged hose connections. The residual gasoline fire was extinguished by using foam and dry powder. The fire was under control at 2:54 p.m.

#### *Survival and Damage*

There were 7 fatalities (the automobile driver, bus driver, mother, beer truck occupants, and elderly couple), and two persons were hospitalized for smoke inhalation (the son and the driver of the pickup truck). Six vehicles were totally destroyed in the tunnel, one in a collision with a bridge pier. The tunnel sustained extensive superficial damage to the walls, ceiling, and roadway. Most tunnel support systems were destroyed or severely damaged, including the lighting, emergency phones, signs, alarms, wiring, commercial broadcast antenna, and firefighting water supply. Repair costs were estimated to be more than $3 million.

This summary was compiled from three sources: the Oakland Fire Department report, information transmitted in a letter by R.E. Graham (Chief, Maintenance Branch South, Caltrans) to the National Transportation Safety Board on May 21, 1982, and the California Highway Patrol accident report.

## Summaries of Less Severe Fires

Three other less severe fires occurred, each providing lessons because of the way in which fire fighting was handled, how the tunnel was designed, and so forth.

### Wallace Tunnel Fire

A medium-sized fire occurred in the late 1970s in the Wallace Tunnel on I-10 in Mobile, Alabama.

At 2:00 a.m. in very light traffic an engine fire began due to a broken fuel line in a camper truck. An electric fuel pump fed the fire after the engine was turned off. The owner abandoned the vehicle.

The tunnel operator noted the fire on the television monitors, activated the traffic-control red lights, and summoned the fire department. Fire equipment arrived within the expected time period. The very light traffic effectively stopped at the portal. The ventilation system was left inactive, in accordance with fire department instructions. The tunnel filled with smoke; fire department personnel were unable to reach the site of the fire. There were no attempts made to control, extinguish, or suppress the fire. The vehicle was completely consumed and there was minor damage to the tunnel. There were no injuries.

The source of information in this summary is a telephone interview with Gordon H. Prescott, then tunnel manager, on December 14, 1982.

### Baltimore Harbor Tunnel Fire

A major hazardous material fire occurred on March 23, 1978 on the Baltimore Harbor Freeway in Baltimore, Maryland. A soft drink delivery truck rammed into a fuel oil tanker from behind in heavy traffic one-quarter mile after exiting from the east portal of the Baltimore Harbor Tunnel. Fuel that spilled from the soft drink truck ignited and spread to the tanker. A third truck carrying creosoted railroad ties also ignited.

How the fire was detected and how the fire department was notified is unknown; tunnel personnel were not involved. The fire department put out the fire in an unspecified short period. There was no damage to the tunnel; however, traffic was congested around the Baltimore metropolitan area throughout the afternoon and evening.

This summary was based on information obtained in a study interview with Bernard Jedrowicz, then tunnel manager, on December 6, 1982, in Baltimore, Maryland.

### Nihonzaka Tunnel Fire

A major hazardous material fire occurred on July 11, 1979, in the Nihonzaka Tunnel, Shizuoka Prefecture, near Yaizu City, Japan (100 miles southwest of Tokyo).

#### *Conditions at Ignition*

Four large trucks and two automobiles were involved in a collision three-quarters of the way through the westbound tube; spilled fuel ignited at 6:39 p.m. Two hundred and thirty-one vehicles were in the tunnel behind the fire or entered the tunnel unheeding or in contravention to emergency warnings at the east portal.

#### *Detection, Alarm, and Notification*

Tunnel operators noticed smoke in the tube on the television monitors, displayed an "OFF LIMITS" sign at the east portal, reversed the ventilation system, and notified the Shizuoka Fire Department, which was located behind the fire, at 6:42 p.m. The Yaizu City Fire Department, in front of the fire and much closer to the tunnel, was summoned at 7:18 p.m. Automatic spray heads interlocked with the fire detector that was activated at the accident site.

#### *Response*

Motorists at the scene deployed hoses from hydrant boxes but could not activate water because valves required the pushing of an operating button in addition to the traditional turning of the handle. Shizuoka equipment at the east portal at 6:48 p.m. was unable to reach the accident site; it assisted

42 vehicles to escape from the tunnel. The automatic spray system reportedly suppressed the fire at the initial site at 6:50 p.m., but the fire reignited at 7:20 p.m.. Two hundred and eight occupants of vehicles trapped in the tunnel escaped on foot out of the east portal by 8:30 p.m. Three Yaizu City engine companies arrived and augmented the fire main at fire department connections at the west portal.

### *Control, Extinguishment, and Suppression*

Initial efforts consumed the entire 40,800-gal (155,000-L) water supply by 8:05 p.m. (1 hr, 26 min after automatic spray heads activated) without extinguishing the fire. Unburned combustible vapors from the accident site spread the fire to two other groups of vehicles in the tunnel when the water supply was exhausted. Suppression resumed with water relayed from unspecified natural sources. The fire was under control by Friday afternoon, but continued burning until 10:00 a.m. on July 18, nearly one week after the initial incident. The semi-transverse ventilation system, with reversible supply fans only, operated in an exhaust mode (maximum exhaust capacity one-half rated supply capacity) throughout the emergency, but was unable to clear heat and smoke enough to allow firemen equipped with breathing apparatus to work effectively in the tunnel. Total equipment and personnel involved was 34 engines, 2 portable fire pumps, 30 (10-ton) tank trucks, 3 ambulances, and 654 personnel.

### *Survival and Damage*

Of 231 vehicles, including 66 trucks, in the tunnel during the course of the incident, 58 were undamaged and 173 were destroyed. The ceiling, walls, and tunnel systems were almost completely destroyed in the central 1145 meters. There were 7 fatalities, 6 in the collision and 1 due to injuries suffered in the collision; there were 2 other unspecified injuries. According to the summary report, police and sufferers will take the matter to court.

There were three sources of information used in preparing this summary: (a) a Tokyo Fire Department letter to the Hamburg, West Germany, Fire Department on August 30, 1979; (b) Summary of Automobile Fire in Nihonzaka Tunnel; and (c) Memorandum for the Files, D. Gross, National Bureau of Standards, September 26, 1979, concerning a visit to test facilities in Japan.

## Discussion

Together, these fire summaries indicate that fires will start in tunnels, and if flammable or hazardous materials are allowed to travel in tunnels, they will eventually be involved, even through improbable circumstances. Note the Caldecott accident in which a stopped automobile, a gasoline truck, and a large bus all arrived at one spot in a two-lane tunnel simultaneously in otherwise light traffic. Any number of minute changes in the participants or their timing--a small vehicle instead of a bus, any cargo but flammable liquid, a shutdown in a different lane, and so forth--could have prevented the conflagration.

Simple prohibition of hazardous materials in tunnels, or a subset of hazardous materials, is insufficient as a safety measure unless combined with an energetic program of inspection, including random spot checks and prosecution of violators. Even this is not foolproof, as demonstrated by the Holland Tunnel fire in which an extremely dangerous and prohibited chemical was out of sight in an enclosed trailer not normally used to carry it; the trailer later broke free and spontaneously ignited. Fires at Squirrel Hill, Blue Mountain, and Moorfleet Tunnel (which are discussed in more detail in the FHWA report) resulted from abnormal and unforeseeable circumstances at ignition: arson in Squirrel Hill, ignition of a flammable food product not normally considered dangerous at Blue Mountain, and deliberate use of tunnel illumination at night as an inspection aid in Moorfleet.

Programs of controlled, supervised transit with preinspection for mechanical faults and mandated intervals between vehicles in an otherwise deserted tunnel still only reduce the possibility of fire; they do not eradicate it.

It appears that major hazardous material fires in tunnels, once started, can be controlled only by heroic efforts under fortunate circumstances in which effective support systems are also present. The decisive actions of those involved in the beginning moments of the Holland Tunnel fire, in which tunnel operators and firefighters persisted without protective equipment in the face of noxious fumes from a fire of an unknown nature to the extent that many were overcome, can only be described as heroic. They were aided by two factors not present at the two other major hazardous material tunnel fires about which full details are known: (a) trained personnel were on the scene at the time of the accident, and (b) effective ventilation and fire suppression systems were present in the tunnel.

The fire summaries for both medium-sized and major hazardous material fires show a consistent pattern: when trained officials are present from the beginning [such as in the Holland Tunnel fire and Chesapeake Bay Bridge-Tunnel fire (Norfolk, Virginia, as discussed in the FHWA report)], the fire is controlled with minimum loss of life and property damage despite the seriousness of the fire. However, when officials are absent (such as in the Caldecott and Nihonzaka fires), the fire burns to completion regardless of the level of effort put forth by motorists at the scene.

The fire summaries also show a pattern of successful fire control in fires in which ventilation and suppression systems are available and used. When ventilation systems were large enough to remove significant quantities of smoke and heat from the area of a fire (such as in the Holland Tunnel and Chesapeake Bay fires) and were operated at full capacity during the emergency, firefighters were able to approach the fire and remain there long enough to control it. When ventilation systems either had too little capacity or were not activated (such as in the Wallace, Caldecott, and Nihonzaka fires), the tunnels filled with smoke and no suppression was possible for an extended period. Fortuitous events may have played a significant role in this small number of examples, but the circumstances and results of the Chesapeake Bay fire (tunnel operator on hand, prompt response by tunnel crew, effective ventilation at the scene, fire soon extinguished) and the Wallace Tunnel fire (no operator at the scene, fire department response only, ventilation system not activated, fire burned itself out) appear to represent opposite types of fire prevention and control efforts.

The Caldecott Tunnel's fire main apparently failed under the stress of heat and blast from the tanker fire; in contrast, the Holland Tunnel's fire main reportedly was constantly used during its emergency--yet more extensive local damage was suffered by the Holland Tunnel. Tunnel communication systems purportedly installed to serve during emergencies were typically disabled soon after large fires ignited. Emergency phones and antenna wires appear particularly vulnerable, having failed in early stages of the Caldecott, Holland, and Chesapeake Bay fires.

The activation of the automatic spray system during the Nihonzaka tunnel fire is the only reported incident of sprinklers or similar systems having responded to an accidentally ignited tunnel fire. It apparently suppressed the fire but was unable to completely extinguish it at any time, even at its most effective point, without the help of hoses, which were deployed but were not supplied with water. Points of ignition and combustible vapors remained after 1 hr, 26 min and reignited after the water supply was exhausted. In this instance, then, sprinklers did not prove to be an effective fire control tool, although in combination with directed hose streams their effectiveness may have been much enhanced.

Although events appear to stress the importance of tunnel personnel during an emergency, the role played by motorists cannot be discounted. In four incidents (Wallace, Squirrel Hill, Chesapeake Bay, and Moorfleet fires) no motorists were present; in two other accidents (Baltimore Harbor Tunnel and Holland Tunnel fires), actions they might have taken were superseded by officials' directions; and in the Blue Mountain incident motorists' roles were not recorded. Therefore, no conclusions can be drawn from these 7 fires. However, the actions of bystanders during two major hazardous material fires (Caldecott and Nihonzaka) were the only local responses before the fires became uncontrollable, and their actions were significant.

While those actually involved in the mishaps were dazed or injured, other motorists took positive actions: the mother and son at the Caldecott fire attempted to inform the control room and warn others; bystanders at the Nihonzaka fire apparently attempted to fight it on their own. Both of these groups were defeated by system failures or oversights: quickly disabled emergency phones, unmarked potential fire exits, esoteric fire hydrant valves, lack of instructions.

## RISK ANALYSIS

### Summary

The fire and explosion risk of a hazardous material tank truck in a highway tunnel is a function of the frequency with which an incident may occur and the magnitude of such an incident. The frequency with which an incident is expected to occur is remote, with one fire expected to occur for every 8 million miles of travel by a hazardous material tank truck. However, the magnitude of such a fire in a highway tunnel is significant. A fire involving a 30-gal spill or 20-gpm leak of a liquefied flammable gas or Class I flammable liquid, or involving a 160-gal spill or 100-gpm leak of a Class II or Class III combustible liquid, will endanger all people within the tunnel but will probably not cause structural damage. A fire involving a 100-gal spill or 40-gpm leak of a liquefied flammable gas or Type I flammable liquid, or a fire involving a 500-gal spill or 200-gal leak of a Class II or Class III combustible liquid, will present a severe fire exposure to the tunnel structure, with ceiling temperatures approaching 2,000° F for longer than 1 hr.

A hazardous material cargo spill involving a liquefied flammable gas or Type I flammable liquid that does not involve an immediate fire can create a significant explosion potential in a tunnel. An explosion involving those vapors can create blast overpressures that will cause structural damage to the tunnel. The explosion may be either a deflagration (subsonic flame speed) or a detonation (supersonic flame speed). Similarly, an explosion potential exists if a fire involving a liquefied flammable gas or a Class I flammable liquid is extinguished before all of the available fuel is consumed or contained. Attempts to suppress a fire involving this type of hazardous material may be counterproductive if an explosion should occur after the fire is extinguished. Class II and Class III combustible liquids do not present a significant explosion potential unless they are heated above their flash point by an exposing fire.

### Reference Tunnel

A reference tunnel has been established to assist in explaining the highway tunnel fire risk. The reference tunnel is 33 ft wide, 16 ft high, and 1 mile long, with a horizontal tunnel bore, and will be referred to as the "reference tunnel" during this analysis.

### Fire Frequency Prediction

Few hazardous material tank truck fires have occurred in highway tunnels in the United States, primarily because such trucks have been prohibited from using most highway tunnels since the 1949 Holland Tunnel fire. Because of this prohibition, a statistical basis for predicting the frequency of accidents and fires involving hazardous material tank trucks in highway tunnels could not be developed. However, a statistical basis for predicting the open highway accident and fire frequency involving hazardous material tank trucks was developed and used to predict the highway tunnel accident and fire frequency.

Several agencies were contacted to obtain information on the frequency of open highway accidents and fires of hazardous material tank trucks:

- American Trucking Associations
- National Tank Truck Carriers, Inc.
- American Petroleum Institute
- American Insurance Association
- National Transportation Safety Board
- National Safety Council
- Bureau of Motor Carrier Safety
- National Fire Protection Association
- Insurance Institute for Highway Safety
- University of Michigan Transportation Research Institute

The documents obtained from these agencies, which were used to predict the frequency of accidents and fires of hazardous material tank trucks, include:

1. "ATA National Truck and Industrial Contest--1982," American Trucking Associations, Inc., Alexandria, Va.
2. "Analysis of Accident Reports Involving Fire--January Through June 1968," Bureau of Motor Carrier Safety, Washington, D.C.
3. "Summary of Motor Vehicle Accidents in the Petroleum Industry for 1981," American Petroleum Institute, Washington, D.C., August 1982.
4. "Accidents of Motor Carriers of Property--1979," Bureau of Motor Carrier Safety, Washington, D.C.
5. "New Drive for Truck Safety," Journal of American Insurance Association, May/June 1970.

6. "Motor Vehicle Standards for Hazardous Material Transportation," Factory Mutual Research Corporation, Norwood, Mass., January 1970.

The following information is reported in these six sources.

1. Trucks, in general, have an accident frequency that varied from 6.89 to 7.50 accidents per million miles during the years 1976 to 1981. In comparison, tank trucks had an accident frequency that varied from 3.97 to 5.98 accidents per million miles for these same years. The average accident frequency of tank trucks during this time period was 4.91 accidents per million miles. This suggests that tank truck operators may have a more favorable accident history than do truck operators in general.
2. Few truck accidents resulted in fire (1.7 percent of all truck accidents). Hazardous material tank trucks had a fire-to-accident ratio that was 70 percent higher than that of the general trucking industry, in which 2.9 percent of all accidents resulted in fire during the period July 1966 to December 1968.
3. Approximately 50 percent of the reported fires were caused by collisions. The remaining 50 percent were caused by noncollision accidents such as overheated brakes or tires, defective exhaust systems, and defective electrical systems. Control of tunnel crossings for hazardous material tank trucks may reduce the probability of collision accidents and subsequent fires. However, inspection of hazardous material tank trucks before tunnel crossing also appears to be needed if the anticipated fire frequency is to be reduced significantly.
4. Hazardous material tank truck accidents resulted in cargo being spilled in 8.5 percent of the accidents.
5. Cargo was involved in 87 percent of the fires involving hazardous material tank trucks.

This information was used to calculate a fire frequency for hazardous material tank trucks traveling in highway tunnels:

1. Average tank truck accident frequency was taken as 4.91 accidents per million miles.
2. Assuming that 8.5 percent of the accidents result in spilled cargo, the number of cargo spills per million miles is estimated as 0.418 (4.91 accidents per million miles x 0.085 cargo spills per accident = 0.418 cargo spills per million miles).
3. Assuming that 2.9 percent of the accidents involving tank trucks result in fire, the number of fires per million miles of tank truck travel is estimated as 0.142 fires per million miles (4.91 accidents per million miles x 0.029 fires per accident = 0.142 fires per million miles).
4. Assuming that 87 percent of the tank truck fires involve cargo, the cargo fire frequency is estimated at 0.124 cargo fires per million (0.142 fires per million miles x 0.87 cargo fires per fire = 0.124 cargo fires per million miles).

Using these frequencies, the spill frequency and the fire frequency for hazardous cargo for the reference tunnel are predicted as (a) one cargo spill per 2,390,000 tunnel crossings, and (b) one cargo fire per 8,064,000 tunnel crossings. Assuming that hazardous material tank truck crossings occur at the rate of 100 crossings per day (36,500 crossings per year), the fire and spill frequencies of hazardous materials are predicted as (a) one cargo spill occurring every 65 years, and (b) one cargo fire occurring every 221 years.

The incident frequencies for tunnels of other lengths or for a different number of hazardous material tank truck crossings may be calculated in a similar manner.

## Spread Potential of Fire and Smoke

The flames from a hazardous material fire in a highway tunnel will spread along the tunnel ceiling. The smoke (the combustion gases and particulate matter will be referred to collectively as smoke throughout this analysis) will move through the tunnel, spreading heat and toxic gases away from the fire location.

The smoke from a fire burning at a 20-MW intensity will create air temperatures higher than 120° F in the reference tunnel approximately 630 ft beyond the fire in the direction in which the smoke is moving. Similarly, the smoke from a 50-MW fire will create air temperatures higher than 120° F at a distance of 1,850 ft beyond the fire, while the smoke from a 100-MW fire will create these temperatures 3,100 ft beyond the fire.

Exposure to temperatures higher than 120° F will quickly cause second degree burns and is considered life threatening (1). In addition, smoke will fill the tunnel, in the direction in which the fire ventilates, with toxic combustion products, making human survival improbable beyond the point of fire origin. Theoretical calculations indicate that smoke will spread away from the fire at a rate of 238 ft/min (2.7 mph) for a fire with a 3-MW intensity and 1,225 ft/min (14 mph) for a fire with a 100-MW intensity. People may survive on the air inlet side of the fire where combustion air is entering the tunnel, but they will probably not be able to survive on the exhaust side of the fire.

Figure 1 shows estimated tunnel temperatures as a function of fire intensity and distance from the fire for a fire occurring in the reference tunnel. Figure 2 shows the estimated distance that flames will project along the tunnel ceiling as a function of fire intensity for a fire occurring in the reference tunnel. It is assumed in both Figures 1 and 2 that the fire will ventilate in one direction only. If the fire actually ventilates in both directions, the distances beyond the fire at which flames will project along the tunnel ceiling or at which temperatures will reach certain limits will be approximately one-half the distances shown in Figures 1 and 2.

The tunnel geometry and air flow in the tunnel (caused by the ventilation system or by a natural draft) can affect the tunnel temperature profile and smoke velocity. When a longitudinal air flow occurs, the smoke velocity will probably increase and the flames and heat will travel in the direction of the air flow. When the tunnel is sloped in an upward direction, the smoke velocity will increase in the upward direction due to the effects of natural ventilation. When the tunnel cross-sectional area is smaller than that of the reference tunnel, the ceiling flame projection will be longer, the smoke will move through the tunnel more quickly, and the distance at which the temperature exceeds 120° F will be farther away from the fire.

Conversely, a tunnel with a larger cross-sectional area than the reference tunnel will have a shorter flame projection along the ceiling and slower smoke movement through the tunnel, and the distance at which the tunnel temperature exceeds 120° F will be closer to the fire. Figure 3 shows the estimated speed of smoke movement as a function of the fire intensity for a fire occurring in the reference tunnel.

A hazardous material tunnel fire burning at an intensity of 20 MW can endanger the lives of all

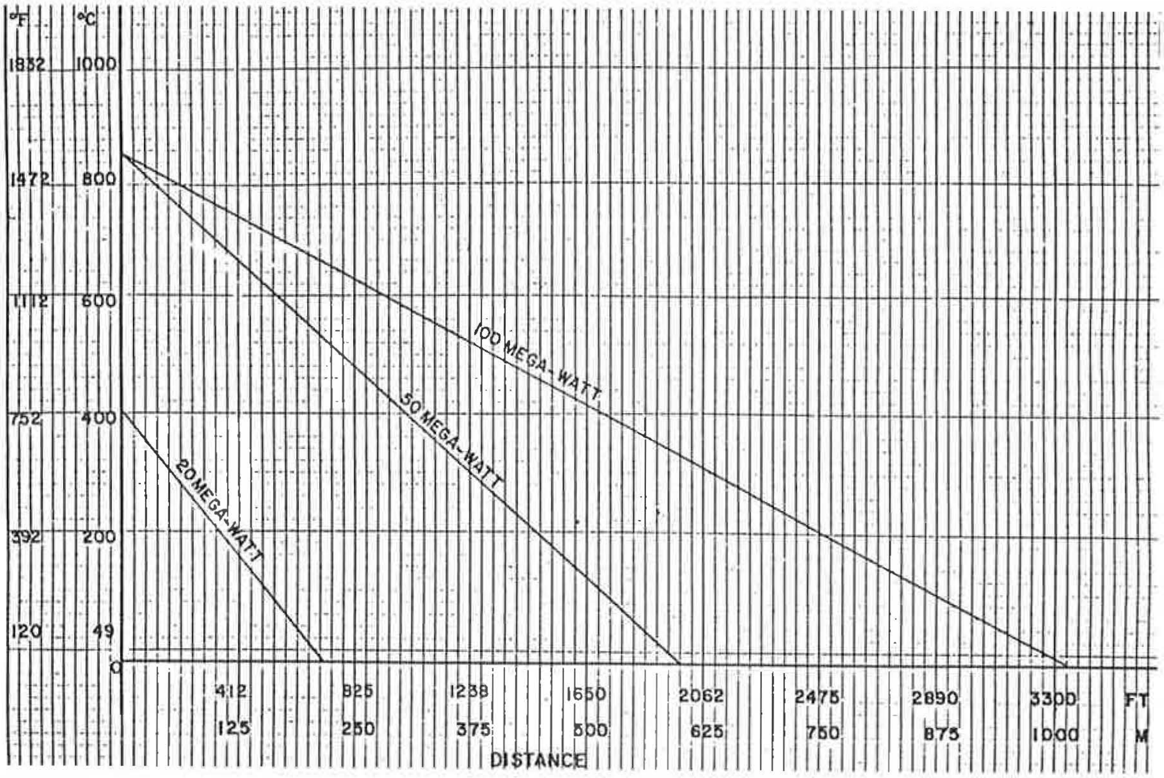


**FIGURE 1** Estimated tunnel temperature as a function of fire intensity and distance from fire (without smoke extraction).

people who are in the tunnel, but it will probably not cause serious structural damage to the tunnel because the ceiling temperature is not expected to exceed 900° F. A fire burning at an intensity of 100 MW will also endanger the lives of all people in the tunnel, and may cause structural damage to the tunnel because the ceiling temperatures within several hundred feet of the fire will approach 2,000° F.

Reduction of Spread Potential of Fire and Smoke

A tunnel emergency ventilation system can reduce the temperatures in a tunnel during a fire. For example, the smoke from a 20-MW fire will create air temperatures higher than 120° F within approximately 290 ft of the fire in the reference tunnel if it is provided with emergency ventilation at a rate of 127

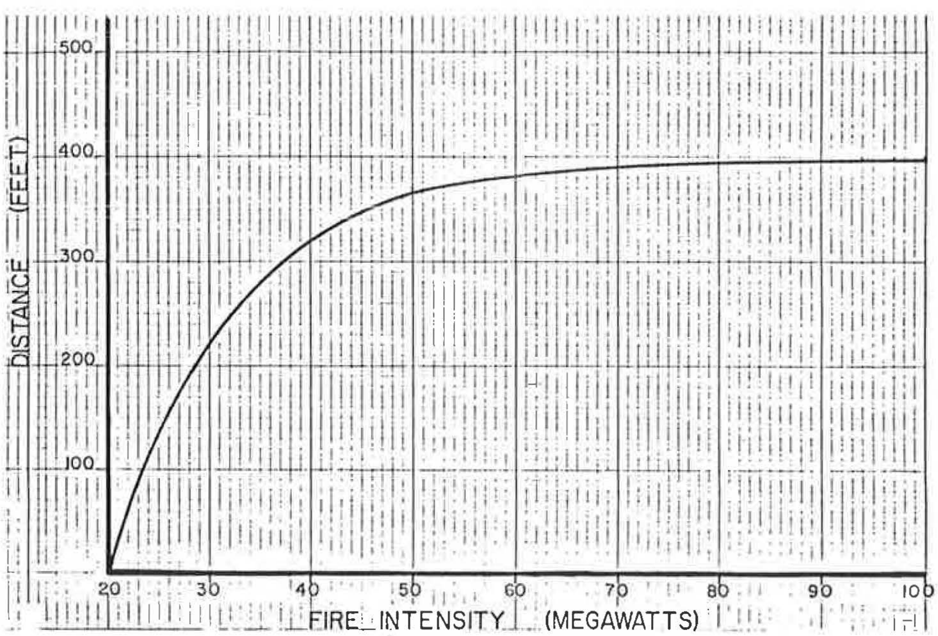


**FIGURE 2** Estimated distance of flame along tunnel ceiling as a function of fire intensity.

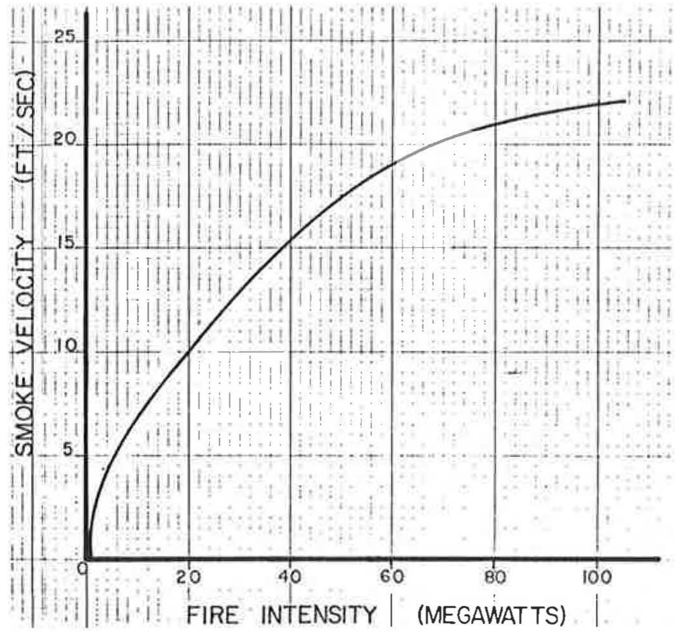


FIGURE 3 Estimated speed of smoke movement as a function of fire intensity.

ft³/min per foot of tunnel length. Similarly, the 50-MW fire will create temperatures higher than 120° F at a distance of 370 ft beyond the fire, while the 100-MW fire will create the same temperatures 720 ft beyond the fire. Figure 4 shows the effect of the ventilation system on the temperatures in the reference tunnel.

Automatic fire suppression systems may help prevent structural damage to a tunnel, but will possibly not be effective in reducing loss of life during a hazardous material tunnel fire. The fire will probably be fully involved before the suppression systems are able to activate. There will be a time lag between fire ignition and fire detection, and another time lag while the suppression system pumps are started, valves are opened, and delivery-system piping is filled with water. Discharging water onto a fully involved hazardous material fire in an enclosed tunnel may increase the danger to the tunnel occupants because of the steam generated when water comes in contact with the fire.

## Fire Intensity

The potential intensity of a highway tunnel fire involving a hazardous material tank truck was determined by reviewing research studies and fire reports

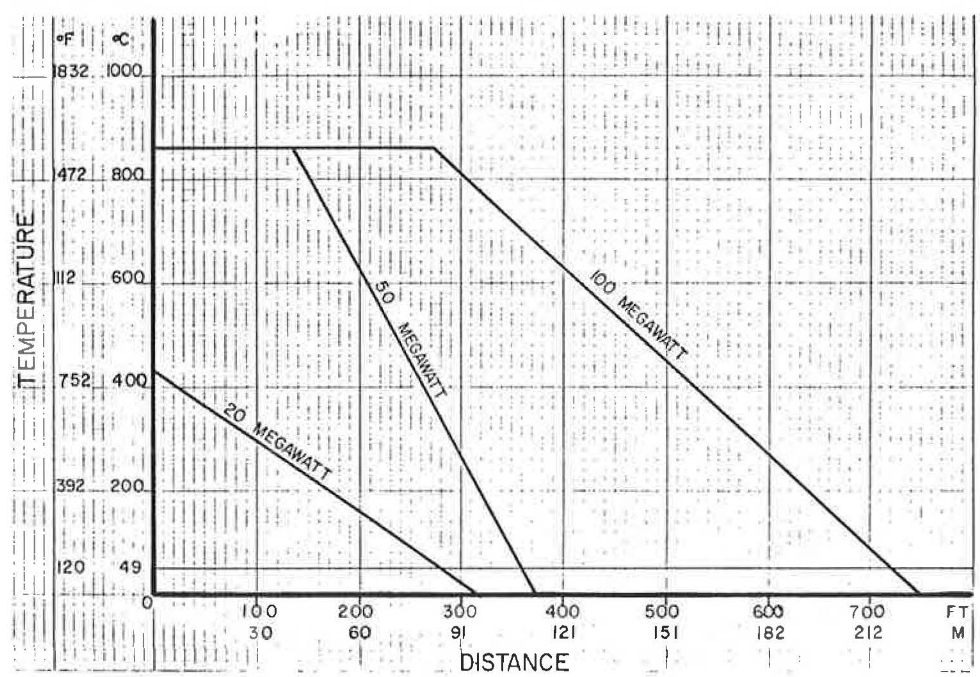


FIGURE 4 Effect of ventilation system on temperatures (with smoke extraction of 127 ft³/min per foot).

dealing with (a) accidents and fires of hazardous material tank trucks, both on the open road and in highway tunnels; (b) research and experimentation in fire development and smoke movement, both in tunnels and in buildings; and (c) actual tunnel fire tests.

The intensity of a highway tunnel fire involving a spilled hazardous material depends on the area of the spilled liquid, the availability of combustion air, and the ability of the smoke to escape from the tunnel. Each of these factors will be discussed further.

## Area of Spilled Liquid

Initially, the critical factor in fire development is the quantity of spilled liquid. A fire involving a total spill of more than 32 gal or a continuous leak of more than 20 gal/min of a liquefied flammable gas or Class I flammable liquid (flashpoint less than 100° F) will result in a fire intensity exceeding 20 MW. Similarly, a fire involving a total spill of more than 162 gal or a continuous leak of more than 98 gpm will result in a fire intensity exceeding 100 MW.

A fire involving a total spill of more than 104 gal or a continuous leak of more than 42 gal/min of a Class II or Class III combustible liquid (flash point equal to or greater than 100° F) will result in a fire intensity exceeding 20 MW. Similarly, a fire involving a total spill of more than 526 gal or a continuous leak of more than 206 gpm will result in a fire intensity exceeding 100 MW.

Figures 5-9 and Table 1 show the relationships between the total quantity or flow rate of spilled hazardous material and the resulting fire intensity.

1. Figure 5 shows the relationship between the quantity of spilled liquid and the area of an unconfined spill.

2. Figure 6 shows the burning rate of the spilled material (fuel burning rate) as a function of the spill area. Three curves are shown on Figure 6; Curve 1 represents a liquefied flammable gas, Curve 2 represents a Class I flammable liquid, and Curve 3 represents a Class II or a Class III combustible liquid.

3. Figure 7 shows the fire intensity as a function of the fuel burning rate. Three curves are shown on Figure 7: Curve 1 represents a liquefied flammable gas, Curve 2 represents a Class I flammable liquid, and Curve 3 represents a Class II or a Class III combustible liquid. The curves were developed using the theoretical heats of combustion of propane for Curve 1, gasoline for Curve 2, and acetic acid for Curve 3. Those theoretical heats of combustion were arbitrarily reduced by 50 percent to allow for incomplete combustion. This allowance is reflected in the fire intensities shown in Figure 7.

4. Figure 8 shows the fire intensity as a function of the quantity of spilled material, or spill area. Three curves are shown on Figure 8: Curve 1 represents a liquefied flammable gas, Curve 2 represents a Class I flammable liquid, and Curve 3 represents a Class II or a Class III combustible liquid.

5. Table 1 shows the estimated flow rates from broken schedule 40 steel pipe. The flow rates are shown for various pipe sizes from 1/4 in. to 2 in.

6. Figure 9 shows fire intensity as a function of flow rate from a tank leak. Figure 9 was developed by using Figure 7 and equating leak rate to fuel burning rate. Figure 9 demonstrates that a liquefied flammable gas or Class I flammable liquid leak from a broken 1/2-in. pipe can result in a 20-MW fire while a leak from a broken 1-1/4-in. pipe can result in a 100-MW fire. Similarly, a Class II or III combustible liquid leak from a broken 1-1/4-in. pipe can result in a 20-MW fire while a leak from a broken 2-in. pipe can result in a 100-MW fire.

## Availability of Combustion Air

The second critical factor in fire development is availability of combustion air. Approximately 1,350 $ft^3$ of combustion air is required to burn each gallon of spilled hazardous material. A spill fire burning at a rate of 200 gpm will require approximately 270,000 $ft^3$/min of combustion air. If all the combustion air entered at one end of the reference tunnel, it would need to travel at an average rate of 510 ft/min (5.8 mph). It appears reasonable to expect that this amount of combustion air would

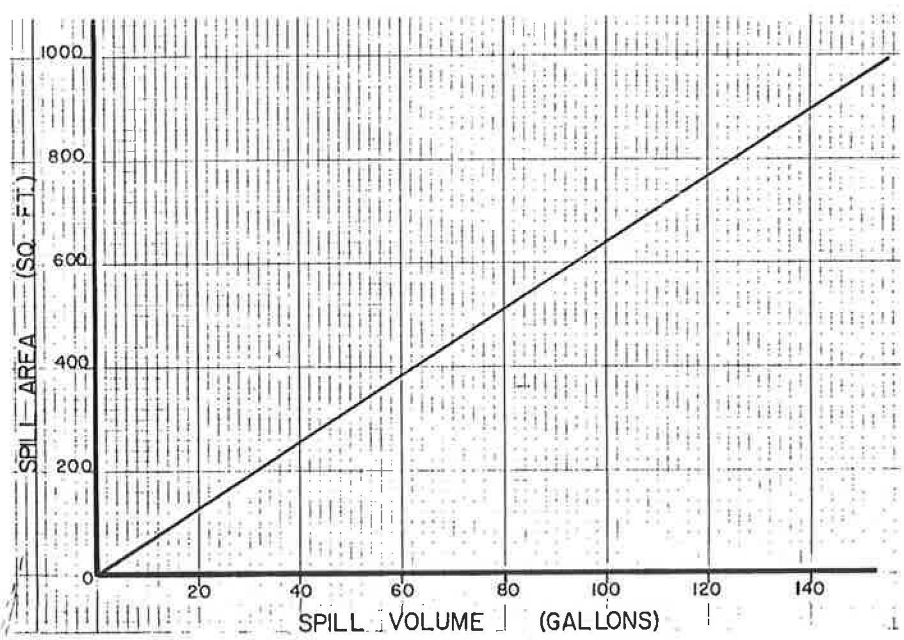


FIGURE 5 Relationship between quantity of spilled liquid and area of unconfined spill.

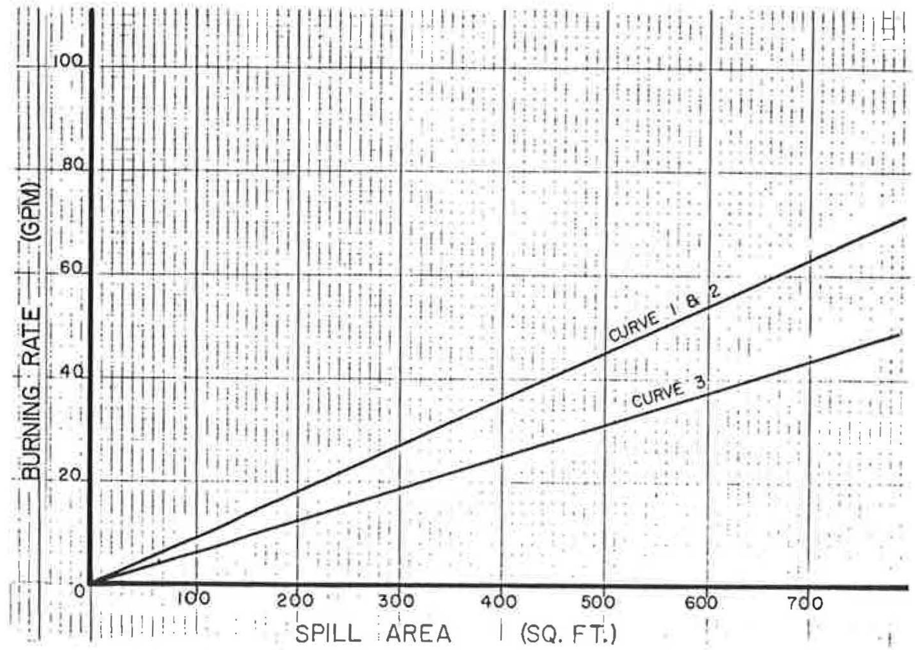


**FIGURE 6** Burning rate of spilled material (fuel burning rate) as a function of the spill area.

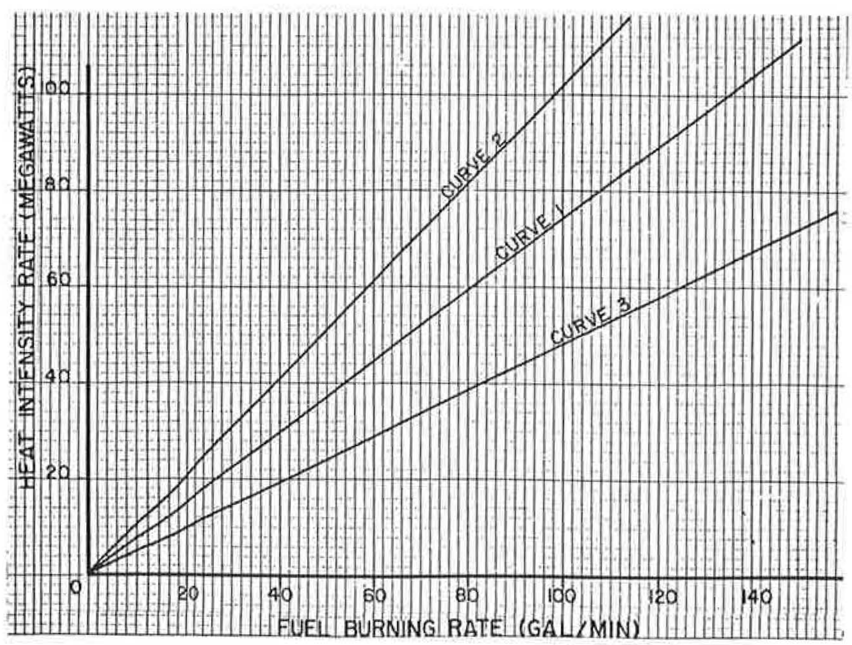


**FIGURE 7** Fire intensity as a function of fuel burning rate.

be available to a fire in the reference tunnel. Consequently, combustion air does not appear to be a controlling factor in fires burning at a rate of 200 gal per minute or lower.

Ability of Smoke to Escape From Tunnel

The third critical factor in fire development is the ability of the smoke to leave the tunnel. As the combustion air entering the tunnel is heated by the fire, it will expand. Assuming an average smoke temperature of 500° F, the combustion gases will expand to approximately 2.62 times their initial volume. They will leave the tunnel at a faster rate than combustion air will enter the tunnel. The volume of smoke produced by a 200-gal/min fire will be approximately 710,000 $ft^3$/min. This smoke will leave the reference tunnel through the end opposite from the combustion air at an average speed of 1,345 ft/min (15.3 mph). Again, it appears reasonable to expect that this volume of smoke can ventilate from the reference tunnel. The ability of the smoke to leave the tunnel does not appear to be a controlling factor in fires burning at a rate of 200 gpm or lower.

Fire Duration

The duration of a hazardous material highway tunnel fire will depend on the volume of available fuel and

**TABLE 1 Estimated Flow Rates from Broken Schedule 40 Steel Pipe**

| Nominal Schedule 40 Pipe Size (in.) | Flow Rate (gpm) |
|---|---|
| 1/4 | 7.9 |
| 1/2 | 23.0 |
| 3/4 | 40.5 |
| 1 | 65.6 |
| 1 1/4 | 113.0 |
| 1 1/2 | 155.0 |
| 2 | 255.0 |

the depth of the spilled fuel, or the fuel spill flow rate.

A small, unconfined spill will spread to an average depth of 0.25 in. A fire involving such a spill will usually last less than 5 min.

A continuing small, unconfined spill fire that is fed by a cargo tank leak (such as a small cargo tank puncture, meltdown of an aluminum cargo tank, or a broken pipe or valve) will last as long as the leak persists. A 100-gpm leak in an 8,000-gal gasoline tank truck could result in a 100-MW fire that will last for approximately 80 min.

A catastrophic spill (involving a ruptured cargo

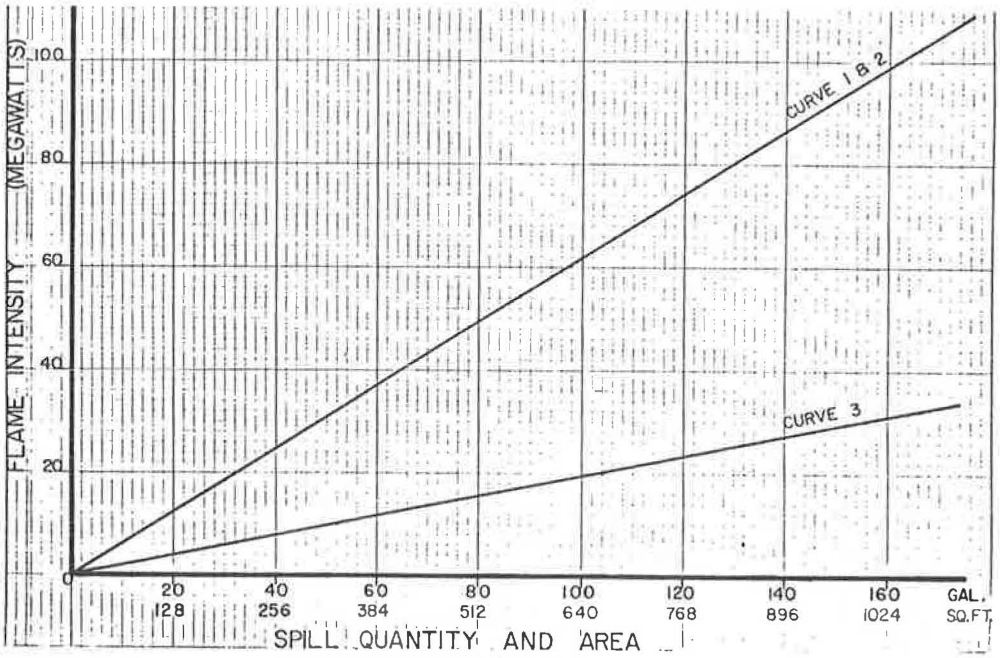


FIGURE 8 Fire intensity as a function of quantity of spilled material (spill area).

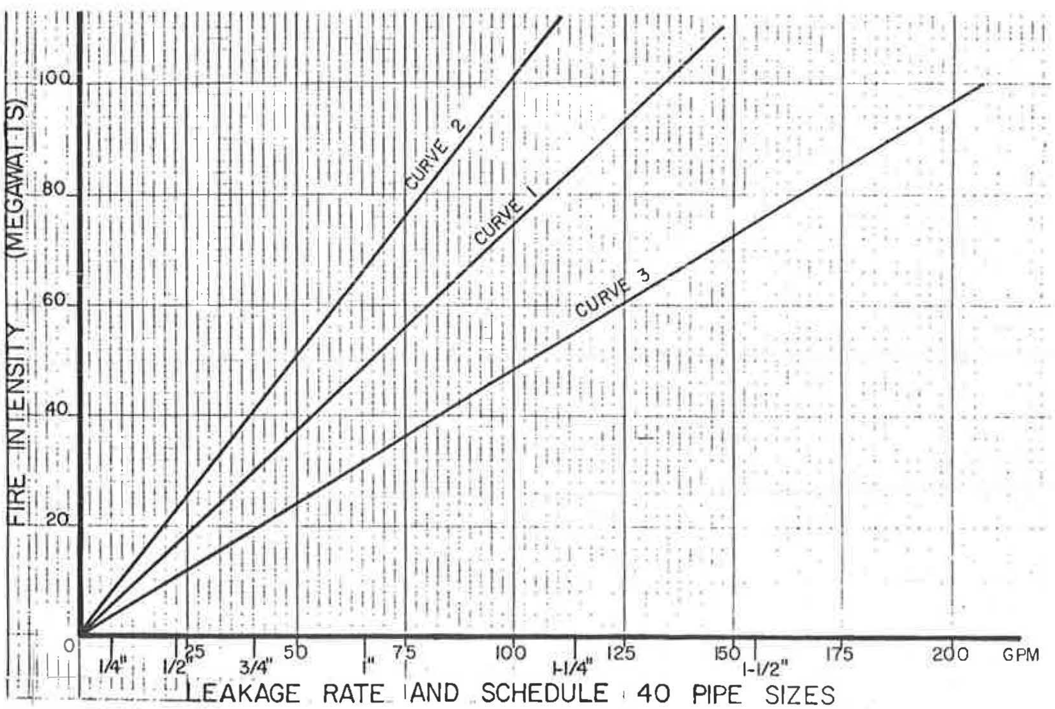


FIGURE 9 Fire intensity as a function of flow rate from a tank leak.

tank) in a tunnel will probably be confined by the tunnel walls or roadway and may pond to depths greater than 0.25 in. or enter the tunnel drainage system, spreading the spilled hazardous material and the fire beyond the area of the accident. The duration of this type of fire cannot be predicted.

## Fire Scenarios

Four fire scenarios are considered here. They include:

1. Scenario No. 1: 20-MW fire in reference tunnel (tunnel bore is horizontal).
2. Scenario No. 2: 100-MW fire in reference tunnel (tunnel bore is horizontal).
3. Scenario No. 3: 20-MW fire in subaqueous tunnel with same dimensions as reference tunnel (tunnel bore is sloped).
4. Scenario No. 4: 100-MW fire in subaqueous tunnel with same dimensions as reference tunnel (tunnel bore is sloped).

Each of these scenarios will be discussed further.

### Fire Scenario No. 1

This scenario considers a fire involving an 8,000-gal gasoline tank truck from which 30 gal of gasoline have been spilled through a 20-gpm leak before ignition. The leak will continue during the course of the fire, leading to a 20-MW fire. The results of that fire will be:

1. Flames will probably not reach the tunnel ceiling; the maximum ceiling temperature will be lower than 900° F.
2. The fire will burn for approximately 400 min, if the spill size or leakage rate does not increase.
3. The velocity of the smoke layer will be approximately 600 ft/min.
4. The temperature in the tunnel on each side of the accident will be higher than 120° F within 320 ft of the fire.

### Fire Scenario No. 2

This scenario considers a fire involving an 8,000-gal gasoline tank truck from which 160 gal of gasoline have been spilled through a 100-gpm leak before ignition. The leak will continue during the course of the fire, leading to a 100-MW fire. The results of that fire will be:

1. Flames will reach the tunnel ceiling and extend approximately 200 ft beyond the accident in each direction; maximum ceiling temperature will approach 2,000° F.
2. The fire will burn for approximately 80 min.
3. The velocity of the smoke layer will be approximately 1,225 ft/min.
4. The temperature in the tunnel on each side of the accident within approximately 550 ft of the center of the fire will be higher than 1,000° F.
5. The temperature in the tunnel on each side of the accident will be higher than 120° F within 1,550 ft of the fire.

### Fire Scenario No. 3

This scenario considers a fire involving an 8,000-gal gasoline tank truck from which 30 gal of gasoline have been spilled through a 20-gpm leak before ignition. The leak will continue during the course of the fire, leading to a 20-MW fire. The results of that fire will be:

1. Flames will probably reach the tunnel ceiling; maximum ceiling temperature will be lower than 900° F;
2. The fire will burn for approximately 400 min, if the spill size or leakage rate does not increase;
3. The velocity of the smoke layer will be approximately 600 ft/min; and
4. The temperature within the tunnel on the exhaust side of the fire will be higher than 120° F within 630 ft of the fire.

### Fire Scenario No. 4

This scenario considers a fire involving an 8,000-gal gasoline tank truck from which 160 gal of gasoline have been spilled through a 100-gpm leak before ignition. The leak will continue during the course of the fire, leading to a 100-MW fire. The results of that fire will be:

1. Flames will reach the tunnel ceiling and extend approximately 400 ft beyond the accident in the direction of smoke ventilation; maximum ceiling temperature will approach 2,000° F.
2. The fire will burn for approximately 80 min.
3. The velocity of the smoke layer will be approximately 1,225 ft/min.
4. The temperature in the tunnel on the exhaust side of the fire within approximately 1,100 ft of the center of the fire will be higher than 1,000° F.
5. The temperature in the tunnel on the exhaust side of the fire will be higher than 120° F within 3,100 ft of the fire.

### People in the Tunnel

All people in the tunnel in these four scenarios will be in danger. People entering the tunnel and those in the tunnel behind the accident will have little time to realize the danger ahead and react. The rapidly traveling smoke layer would overtake them as they attempted to escape, causing death by inhalation of toxic combustion products or by exposure to the hot gases. Persons traveling through the tunnels ahead of the vehicles involved in the accidents may be able to continue driving to safety. The speed of their vehicles will probably be faster than that of the speed of the advancing smoke layer.

## Explosion Potential

Vapors from a spilled liquefied flammable gas or Class I flammable liquid present an explosion potential in a tunnel. This potential is present if the spill occurs without a subsequent fire to consume the vapors, allowing their accumulation in the tunnel. Accumulation may also occur after a fire is suppressed but before the available fuel is consumed or contained. The fuel that remains after the fire is suppressed may vaporize and explode while firefighters are working at the scene.

The potential blast overpressure caused by a deflagration of a spilled liquefied flammable gas or vaporized Class I flammable liquid was calculated by using the methods presented in National Fire Protection Association (NFPA) standard 68, Venting Guides (1978 edition). This pressure was found to be in excess of 15 psi for the reference tunnel. It is advised in Appendix C of NFPA standard 68 that flame speeds as high as 6,000 ft/sec and overpressures of several hundred psi could be expected if an explosion should occur in a tunnel or similar contained space. If flame speeds of this magnitude should occur, the explosion would be a detonation because of the supersonic flame speed.

The explosion potential of a Class II or Class III combustible liquid (those liquids with a flash point equal to or higher than 100° F) is negligible unless there is an exposing fire that heats the hazardous material to a temperature higher than its flash point.

## CONCLUSIONS

Tunnel administrators have measurably contributed to the historically low rate of fires in highway tunnels by

1. Prohibiting hazardous cargoes,
2. Controlling drivers' actions, and
3. Enforcing both of the above.

Tunnel designers can contribute to the low rate of fires in highway tunnels by applying design criteria conducive to traffic safety.

Tunnel fires will occur with some nonzero frequency. If hazardous materials are allowed free passage, one fire will occur approximately every 4 years in the United States. Each fire will have an average of 60 fatalities.

Tunnel fires can be controlled by a combination of

- Detection systems;
- Alarm systems;
- Effective notification of tunnel patrons;
- Fire extinguishers in the tunnel per NFPA standard 502 (the 1981 Fire Protection for Limited Access Highways/Tunnels/Bridges/Elevated Roadways/Air Right Structures);
- Fire hydrants and water supply systems per NFPA standard 502;
- Planned responses by tunnel crew, fire department, and local emergency personnel;
- Properly trained and equipped personnel and vehicles; and
- Properly designed drainage and ventilation systems.

Damage and number of fatalities due to tunnel fires can be limited by (a) effective communication systems; (b) appropriate emergency ventilation modes; and (c) clearly indicated, accessible escape routes. Fire control systems of questionable value include (a) automatic fire and smoke detectors, (b) automatic sprinklers, and (c) highway shoulders.

## RECOMMENDATIONS

1. Explosive or potentially explosive materials should not, under any circumstances, be allowed to be transported through highway tunnels.
2. Hazardous materials should be allowed to be transported through highway tunnels only when demonstrably in the best economic interests of the community, and then only under controlled conditions.
3. Prohibition of hazardous materials should include effective inspection and enforcement procedures.
4. Effective regulation of drivers' actions in the tunnel should be imposed and enforced.
5. All tunnels should be monitored at all times, preferably by personnel in an on-site control room.
6. Tunnels should be designed to minimize traffic accident potential.
7. Detection systems should involve cost-effective surveillance, including personnel stationed in the tunnel, or TV cameras with traffic monitoring.
8. Alarm systems should include (a) telephones or manual alarms in tunnels; they should be connected to the control room, not to a fire station; (b) direct line to a fire station from the control room; and (c) two-way radio communication net inside of and outside of the tunnel.
9. Notification systems should include traffic lights, signs, AM radio rebroadcast, citizens band radio capability, personnel at portal, and personnel in tunnel, if possible.
10. Every operating agency should prepare a fire and emergency plan for each tunnel under its control.
11. Cooperation should be established and maintained with the local fire department, law enforcement, and emergency preparedness organizations.
12. Periodic practices and system exercises should be conducted.
13. Tunnel vehicles complying with NFPA standard 502 should be provided if adequate municipal fire service is not available.
14. ABC rated, 20-lb maximum, dry powder fire extinguishers should be provided in well-marked wall niches a maximum of 300 ft on center and safeguarded from damage, deterioration, and pilferage.
15. Hydrants compatible with local fire department equipment should be provided a maximum of 300 ft on center with sufficient supply or storage, and piping to provide 500 gpm per tunnel bore at 75-psig residual pressure, 1,000-gpm total facility flow, for a minimum of 2 hr (120,000 gal).
16. Fire hoses should be carried on vehicles, not installed in tunnels.
17. Fire protection systems should be protected from freezing and from the heat and blast of a credible fire.
18. Sprinklers are not recommended for highway tunnels.
19. Drainage systems should be designed and maintained to safely clear the roadway of, collect, and dispose of hazardous material spills and maximum fire-protection water flows.
20. For maximum life protection, systems and operations should be developed to save time when a hazardous material fire occurs.
21. If permitted by tunnel geometry and construction sequence, well-marked, accessible, ventilated, and lighted exits to safe locations should be provided a maximum of 300 ft on center in every bore.
22. Ventilation systems should include an emergency and fire operating mode that extracts air from sizeable, controllable, ceiling-level exhaust dampers a maximum of 300 ft on center; ventilation systems should be selected from the control room and should be large enough to induce a roadway area flow of 1,000 ft/min from both directions toward the damper. The entire system, including structural components and hangers, should be capable of continuing operation when exhaust gas temperatures reach 1,000° F.

## REFERENCE

1. Fire Protection Handbook, 15th ed. National Fire Protection Association, Batterymarch Park, Quincy, Mass., 1981, Ch. 3.