

PREVENTION AND CONTROL OF HIGHWAY TUNNEL FIRES

Research, Development,
and Technology

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U.S. Department
of Transportation

**Federal Highway
Administration**

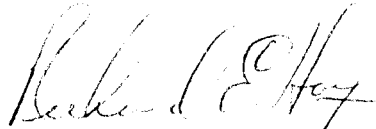
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MAY 1984



FOREWORD

This report presents methods of preventing, responding to, and controlling fires in existing and future highway tunnels. Means of evaluation of and reducing the risk for such fires and reducing damage, injuries, and fatalities are presented. The findings and recommendations of the report are based on evaluations of: (1) experimental tunnel fire tests; (2) significant highway tunnel fires; (3) observations of highway tunnels; (4) interviews with major highway tunnel operators; and (5) accident risks of unrestricted transit of hazardous materials. Effects of traffic, tunnel design, and operations on such risks are discussed. A ventilation system with a fire/emergency operating mode is recommended.



Richard E. Hay, Director
Office of Engineering
and Highway Operations
Research and Development

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U. S. DEPARTMENT OF TRANSPORTATION

FEDERAL HIGHWAY ADMINISTRATION

SUBJECT

FHWA/RD-83/032, "PREVENTION AND CONTROL
OF HIGHWAY TUNNEL FIRES"

FHWA BULLETIN

September 5, 1984

Distributed with this Bulletin is the subject report which discusses and presents recommendations to reduce risk, damage, and fatalities from fires in existing and future highway tunnels. These recommendations have received concurrence by expert reviewers.

The history of highway tunnel fires was examined for design and operating features affecting ignition, spread, detection, response, control, resulting damage, and survivability aspects. Investigation also included tunnel operator interviews and evaluation of literature.

Accident occurrence probability history for heavy duty vehicles on open highways and related fire frequency for trucks carrying hazardous materials on these roads were examined. Based on such records and the conditions for a reference highway tunnel (straight, flat, 1 mile long, 33 feet wide, and 16 feet high) a risk analysis for unrestricted transit of hazardous materials was performed. This was applied to 35 of the highway tunnels examined in this study. Qualitative assessments of the effects of traffic, tunnel design (length, horizontal and vertical alignments, and width) and operations (lighting and ventilation) on this risk were made. Comprehensive design and operating recommendations for prevention, detection, alarm, notification, control, extinguishment, suppression, and survival are developed.

Observations of selected highway tunnels in Italy, Switzerland, and France (at Italian border) particularly in reference to the past occurrence of fires are presented in Appendix D. Aspects of highway design, traffic operations, lighting, ventilation, and fire detection, and control for these highway tunnels are given.

Inquiries about the research may be made to the Construction, Maintenance and Environmental Design Division, HNR-30, or to the Bridge Division, HNG-32, Federal Highway Administration, Washington, D.C. 20590. Requests for additional copies of the report, for official use, will be honored while the limited supply lasts. Additional copies for the public are available for a fee from the National Technical Information Service (NTIS), U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161. Sufficient copies of the report are being distributed to

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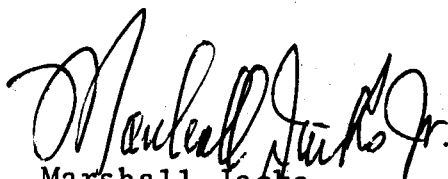
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16. Abstract This study investigates steps that can be taken to reduce the risk, damage, and fatalities from fires in existing and future highway tunnels and the effect of unrestricted transit of hazardous materials through them. The history of highway tunnel fires is examined to discover the design and operating features bearing on ignition, spread, detection, alarm transmission, response, control, resulting damage, and survivability aspects. Major domestic highway tunnel operators are interviewed concerning tunnel fires and their responses tabulated and compared. The procedures and results of several tunnel fire tests are 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 is performed and applied to 35 tunnels included in the study. Qualitative assessments of the effects of traffic, tunnel design, and operations on this risk are made. Comprehensive design and operating recommendations for prevention, detection, alarm, notification, control, extinguishment, suppression, and survival are developed. A ventilation system with a fire/emergency operating mode designed to provide motorists trapped in a tunnel fire with optimal escape potential is described and its inclusion in future vehicular tunnels recommended.					
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METRIC CONVERSION FACTORS

APPROXIMATE CONVERSIONS FROM METRIC MEASURES

<u>SYMBOL</u>	<u>WHEN YOU KNOW</u>	<u>MULTIPLY BY</u>	<u>TO FIND</u>	<u>SYMBOL</u>
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.6	square meters	m ²
mi ²	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons(2000lb)	0.9	tonnes	t
VOLUME				
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cupe	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft ³	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM METRIC MEASURES

<u>SYMBOL</u>	<u>WHEN YOU KNOW</u>	<u>MULTIPLY BY</u>	<u>TO FIND</u>	<u>SYMBOL</u>
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares(10,000m ²)	2.5	acres	
MASS (weight)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000kg)	1.1	short tons	
VOLUME				
ml	milliliters	8.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m ³	cubic meters	36	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

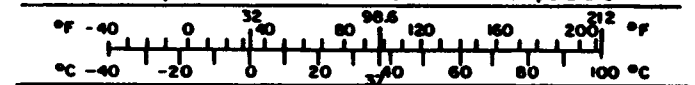
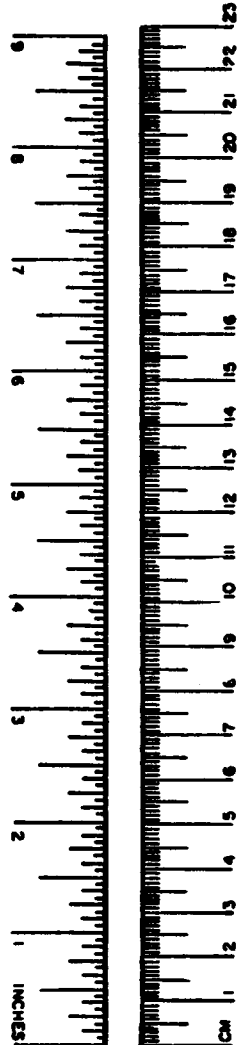


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INTRODUCTION

Broadly speaking, highway tunnel fires can involve either tunnel structure and systems or the vehicles that pass through it. 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 to the extent that 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 the open roads. There have apparently been only two major tunnel fires in the United States, only one of which involved fatalities, and two in the rest of the world. (Perhaps the worst such 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, points to several management attitudes, operating practices, and system design criteria found common to these tunnels being instrumental in maintaining this safety record, not simply good fortune.

The information and conclusions in this report have been organized in common pattern based on the chronological occurrence of events in a tunnel fire: prevention of conditions leading to ignition, detection/alarm/notification after ignition, response, control/extinguishment/suppression, and survival.

The tunnels investigated fall into three groups: subaqueous, dry urban, and dry remote, with the following characteristics:

- o Subaqueous: closely-watched, critical traffic links often congested with slow-moving commercial traffic. Usually one-way traffic in two-lane underwater tubes of sagging profile.
- o Dry urban: lightly-watched, arterial rush-hour routes frequented by habitual suburban drivers. Usually multi-lane with shoulders, cut-and-cover, with in-tunnel or near-portal interchanges and municipal services close at hand.
- o Dry remote: lightly-traveled interstate connections through geographic barriers without convenient alternate routes. Typically without local municipal services, i.e., fire protection or water.

The 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 assessing methods will result in different cost-effective fire prevention and control methods.

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 cross section. Trucks, on the other hand, cannot be turned or have sufficient frontal area to block a tunnel cross section, 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 includes poisonous, toxic, nuclear, or explosive materials, substances to which mere exposure can be life threatening or whose involvement 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, safely extinguished.

The second group includes flammable liquids, and certain hydrocarbon-based solids, that are normally expected to easily catch fire upon exposure to ignition sources. This study mainly concerns the tunnel fire safety ramifications of transporting these substances: fuels, organic chemicals, finely divided materials, and some foodstuffs. In this report, "hazardous material" refers to a substance that is or should be included in these first two groups.

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

These groups match the practical concerns of tunnel operators; assignment of thousands of substances to one or another group is beyond the present scope.

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. This study attempts 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.

TUNNEL FIRE SURVEY

Tunnel fires have been divided into three types based on their order-of-magnitude rate of energy output. They are 1) small automobile fires (1 MW or 950,000 Btu/min.), 2) medium fires (10 MW, 10 million Btu/min.), and major hazardous material fires (100 MW+, 100 million Btu/min.). Small automobile fires are routine incidents, occurring as frequently as weekly in congested urban tunnels. They have been universally extinguished without difficulty to date: no noteworthy examples were cited by tunnel operators interviewed during the study; none were featured in the literature reviewed.

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

Information concerning nine of these fires has been presented in summary form below. These summaries are followed by a discussion comparing and contrasting similar features of each as background for the evaluations of fire prevention and control options given later. Findings of several other studies that might shed light on the actions taken and results achieved follow this discussion. Finally, this section ends with a synopsis of existing tunnel operating practices bearing on fire prevention and control.

Fire Summaries

The factual information for nine significant vehicular tunnel fires has been summarized below in a standard format. The format gives the Location, Date, Type of Fire, Conditions at Ignition, Detection/Alarm/Notification Actions, Response, Control/Extinguishment/Suppression Actions, Survival/Damage, and Source of Information.

WALLACE

Location: Wallace Tunnel, I-10, Mobile, Alabama
Date: late 1970's
Type: Medium

Conditions at Ignition: 2 a.m. in very light traffic. Engine fire from broken fuel line in camper truck. Electric fuel pump fed fire after engine turned off. Owner abandoned vehicle.

Detection/Alarm/Notification: Operator noted fire on TV monitors, activated traffic-control red lights, summoned fire department.

Response: Fire equipment arrived within expected period. Very light traffic effectively stopped at portal. Ventilation system left inactive per fire department instructions. Tunnel filled with smoke; fire department unable to reach site of fire.

Control/Extinguishment/Suppression: None

Survival/Damage: Vehicle completely consumed; minor damage to tunnel; no injuries.

Source of Information: Study interview

CALDECOTT

Location: Caldecott Tunnel, US24, Oakland, California

Date: 7 April 1982

Type: Major hazardous material

Conditions at Ignition: Probably-inebriated westbound driver lost control of compact auto just past midnight in light traffic. Multiple glancing collisions with curbs and wall; stopped in left-hand lane just into straightaway from right-hand curve probably to inspect damage or effect minor repairs. At least two possibly three or more cars pass on right during next few minutes. Slightly-speeding empty bus unaware of obstacle tries to pass full gasoline truck/trailer combination as truck passes stopped auto, multiple collisions occur. Trailer tank ruptures; spilled gasoline ignites. Bus driver ejected by collision forces; bus continues, exits portal approximately 36 seconds after impact. Truck driver brings rig to stop, exits west portal on foot. As many as twenty cars enter east portal.

Detection/Alarm/Notification: Tunnel crew note noise and vibration from tunnel, see bus exit portal and come to rest against bridge pier (+0 minutes 40 seconds after tunnel accident). Operators dispatched to investigate, two go to east portal; one inspects bus then drives east up westbound tube (+1 minute 40 seconds). Console operator receives call from tunnel reporting "bunch of accidents"; connection lost before more information is exchanged (+1 minute 10 seconds). Console operator notes multiple simultaneous phone calls from tunnel seconds before entire system fails. Operator driving east up tunnel finds burning gasoline truck, must retreat to west portal to find operating emergency phone (+5 minutes minimum on operator's estimate). Console operator places first unambiguous call to Oakland Fire Department 7 minutes minimum after collision, as much as 10 minutes after original stoppage in left lane of tunnel. Alarm sounds at fire station 55 seconds after initiation of call.

Response: First pieces of fire equipment reach west portal 3 minutes 45 seconds after alarm (+10 minutes 45 seconds minimum after collision). First pieces of fire equipment reach east portal 7 minutes after alarm. Fire equipment from Orinda Fire Department reaches east portal +12 minutes after console operator's call. Oakland responds with seven engines (28 men), two chief's cars (four men), and three other units (eight men). Exhaust fans, which may have activated automatically during early stages of fire in response to high levels of CO sensed in tunnel, soon automatically shut down without having affected events or conditions in the tunnel.

Mother and grown son following bus in pickup witness collision between bus and gasoline truck, come to stop, notice small fire, back up but abandon pickup for fear of rearend collision. Mother calls on emergency phone (+1 minute after collision) until phone malfunctions; returns to pickup less than 50 feet from unmarked cross-adit to next tube. Son walks east in tunnel to warn motorists; approximately two minutes later enveloped by smoke; gropes way out last 200 feet to portal. Truck driver and passenger remain with beer truck less than 150 feet from unmarked cross-adit. Man in second pickup backs up when warned by son until enveloped by smoke near sedan with elderly couple, abandons vehicle and gropes remaining 80 feet to portal. All other vehicles clear tunnel backing out, either through impatience or prompted by sight of approaching smoke wall. Tunnel fills completely with smoke in excess of 300°F within 3 minutes of collision eastward from burning gasoline truck to portal.

Control/Extinguishment/Suppression: Natural draft eastward through tunnel blows all combustion products in that direction; firemen approach to within 75 feet of fire, make no attempt to suppress fire at that time. Fans left off through concern for maintaining natural draft. Firemen unable to operate corroded valves to direct water-gasoline mixture in tunnel drainage away from nearby lake; concentrate on explosion and pollution hazard at lake while waiting for fire to burn down. Extinguishment efforts started at 0129 a.m. (+75 minutes after initial collision); tunnel water pressure falls too low to support hose streams. Firemen near tanker observe water leaking from damaged hose connections. Residual gasoline fire extinguished using foam and dry powder. Fire under control at 0254.

Survival/Damage: Seven fatalities (auto driver, bus driver, mother, beer truck occupants, elderly couple), two hospitalized for smoke inhalation (son and pickup driver). Six vehicles totally destroyed in tunnel; one in collision with bridge pier. Tunnel suffered extensive superficial damage to walls, ceiling, and roadway. Most tunnel support systems

destroyed or severely damaged, including lighting, emergency phones, signs, alarms, wiring, commercial broadcast antenna, and firefighting water supply. Repair costs estimated in excess of three million dollars.

Source of Information: Oakland Fire Department report, information transmitted with R. E. Graham (Chief, Maintenance Branch South, Caltrans) letter of 21 May 82 to National Transportation Safety Board, and California Highway Patrol Accident Report.

BALTIMORE HARBOR

Location: Baltimore Harbor Freeway, Baltimore, Maryland

Date: 23 March 1978

Type: Major hazardous material

Conditions at Ignition: Soft drink delivery truck rams fuel oil tanker from behind in heavy traffic one quarter mile after exiting east portal of Baltimore Harbor Tunnel. Fuel spilled from soft drink truck ignites and spreads to tanker. Third truck carrying creosoted railroad ties also ignited.

Detection/Alarm/Notification: Unknown; tunnel personnel not involved.

Control/Extinguishment/Suppression: Fire department put out fire in unspecified short period.

Survival/Damage: Unknown; none to tunnel. Traffic congested around Baltimore metropolitan area throughout afternoon and evening.

Source of Information: Study interview.

HOLLAND

Location: Holland Tunnel, New York City, New York

Date: 13 May 1949

Type: Major hazardous material

Conditions at Ignition: Fully-enclosed trailer carrying 80 55-gallon drums of carbon disulfide enters New Jersey portal of tunnel, in violation of Port Authority regulations and allegedly unplacarded in violation of ICC regulations, in very heavy, slow traffic approximately 0830 a.m. Drum breaks free and ignites upon striking roadway approximately 2900 feet into tunnel. Truck rolls to stop in left lane. Four trucks catch fire or are abandoned adjacent to trailer in right lane. Five additional trucks stopped 350 feet to the rear grouped tightly in right lane also ignite. Approximately 125 automobiles, buses, and trucks fill both lanes back to New Jersey portal.

Detection/Alarm/Notification: Patrolling officer 100 feet from mishap transmits trouble signal to control room at 0848 a.m.; assists drivers escaping scene through cross-adit to north tube. First fire alarm transmitted by patrolling officers further east at 0856, who then run to assist. Tunnel personnel in tunnel west of fire promptly evacuate occupants on foot to New Jersey; start backing vehicles out of tunnel. Jersey City Fire Department receive telephone notice at 0905. New York Fire Department receive fire alarm at 0912.

Response: Three-man emergency crew drive west through eastbound tube on wrecker and jeep upon receiving 0856 fire alarm; commence fighting fire with 1½" hose and spray nozzle. Assist two tunnel patrolmen overcome by smoke. Knock down fires in two trucks of eastern group, tow one to New York portal. New York rescue company and battalion chief drive west through westbound tube; cross to scene at adit and relieve tunnel emergency crew. Some firemen in distress recover by breathing at the curb-level fresh air ports.

Second alarm transmitted at 0930 activates four engine companies, two ladder truck companies, and a water tower. Firemen not involved in firefighting search through burning trucks, help three trapped persons to safety. Additional NYC pumpers augment capacity of tunnel fire main; activate five 2½" hoses and a foam generator. New Jersey engine company, truck company, rescue company, and battalion chief transmit second alarm upon initial inspection at New Jersey portal. Oxygen masks ordered.

Fireman establish hose lines through half mile of abandoned vehicles; extinguish fires in second group of trucks. Tunnel ventilation accelerated to full capacity at fire site at approximately 0945; firemen discover they can work without masks. Two exhaust fans disabled by heat at 1000°F; third fan kept in service by water spray. Ceiling at fire collapses; fire boats monitor Hudson River above for signs of tube failure.

Remaining unburning vehicles removed by 1015; JCFD drives two pumpers east to fire site, joining forces with NYFD. Fire controlled by approximately 1300; overhauling operations continue until 0052 the next morning. Residual carbon disulfide and turpentine reflash at 1850 during cleanup; extinguished with 5-gallon foam extinguishers; area then covered with heavy foam.

Total equipment involved: one tow truck, several jeeps, seven chief units, five rescue companies, seven police emergency squads, 14 engine companies, six truck companies, one lighting truck, one water tower, one smoke ejector, one

foam truck, 40 additional firemen, at least 13 ambulances at the scene, and four Consolidated Edison emergency trucks with inhalators (total of 29 firefighting units, 20 medical units, seven supervisory units, at least three port authority vehicles, and four commercial vehicles with special apparatus on board. Unknown total of personnel in excess of 250).

Survival/Damage: Ten trucks and cargoes completely destroyed, 13 others damaged. 600 feet of tunnel wall and ceiling demolished; walls spalled in places to cast iron tube plates. 650 tons of debris removed from tunnel. Tube reopened to traffic 56 hours after fire started. All cable and wire connections through tube disrupted at fire. Total damage estimated at one million dollars (in 1949 dollars). Sixty-six injuries, 27 requiring hospitalization; no fatalities.

Source of Information: The Holland Tunnel Chemical Fire report by the National Board of Fire Underwriters

SQUIRREL HILL

Location: Squirrel Hill Tunnel, Pittsburgh, Pennsylvania

Date: Unknown

Type: Medium

Conditions at Ignition: Private auto abandoned and set afire in deserted, early morning tunnel.

Detection/Alarm/Notification: Fire eventually discovered by unspecified means. Fire department summoned by unspecified means.

Response: Local fire department responded with unspecified resources.

Control/Extinguishment/Suppression: Fire extinguished without incident.

Survival/Damage: Vehicle destroyed. No damage to tunnel. No injuries.

Source of Information: Study interview

BLUE MOUNTAIN

Location: Blue Mountain Tunnel, Pennsylvania Turnpike,
Franklin County, Pennsylvania

Date: 1965-66

Type: Medium

Conditions at Ignition: Truck carrying fish oil (not considered hazardous material at the time) caught fire in tunnel.

Detection/Alarm/Notification: Unknown

Response: Fire department responded to unspecified degree.

Control/Extinguishment/Suppression: Fire extinguished without incident; combustion products left tunnel without mechanical assistance.

Survival/Damage: Unspecified damage to truck. Minor if any damage to tunnel. No injuries specified.

Source of Information: Study interview

CHESAPEAKE BAY

Location: Chesapeake Bay Bridge/Tunnel, Norfolk, Virginia

Date: 3 April 1974

Type: Medium

Conditions at Ignition: Six-wheel closed refrigeration truck blows left rear tire and careens out of control down grade in south tunnel, contacts curb and overturns, blocking both lanes. Full, 50-gallon, fiberglass fuel tank explodes in flames upon overturn.

Detection/Alarm/Notification: Mid-tunnel booth patrolman hears blowout, observes overturn and explosion, reports "accident with fire" to control booth at 1218 p.m.

Response: Booth patrolman moves to scene; assists driver and directs him to safety; halts oncoming traffic. Tunnel emergency trucks dispatched from two shoreward portal islands at 1219. Three other tunnel units in transit on bridge also converge. Chief of Police arrives at 1221, finds Virginia State Trooper unit already giving aid to injured driver and crew of north emergency truck already fighting fire with hose and foam. Additional alarm placed to Chesapeake Beach Fire Department, who respond with one engine, one rescue unit, and one ambulance. Flush truck and maintenance wrecker also summoned.

Control/Extinguishment/Suppression: Fuel fire brought under control within six or seven minutes; secondary fires extinguished soon after. Some dense smoke hung in area during fire, but breathing apparatus not required. Exhaust fans operated throughout fire. Internal telephone system required since fire destroyed overhead antenna. Driver conveyed to hospital by 1250.

Survival/Damage: Truck essentially destroyed; cargo undamaged. Tunnel ceiling tiles, hand rail, and antenna wire damaged by impact or fire, value unspecified. Tunnel reopened to traffic at 1650. One injury, driver hospitalized in shock with burns on arms and legs.

Source of Information: Memoranda of booth patrolman and Chief of Police sergeant of 5 April 74 concerning Economy Stores, Inc. truck accident/fire.

NIHONZAKA

Location: Nihonzaka Tunnel, Shizuoka Prefecture, near Yaizu City, Japan (100 miles southwest of Tokyo) correct Japanese pronunciation: Nee-hon-za-ka, without stress. "Nihon" is the Japanese name for their post-WWII nation.

Date: 11 July 79 (Wednesday)
Type: Major hazardous material

Conditions at Ignition: Four large trucks and two autos involved in collision three quarters through westbound tube; spilled fuel ignited at 1839 p.m. 231 vehicles are in tunnel behind fire or enter tunnel unheeding or in contravention to emergency warnings at east portal.

Detection/Alarm/Notification: Operators notice smoke in tube on TV monitors, display 'OFF LIMITS' sign at east portal, reverse ventilation system, and notify Shizuoka Fire Department, behind fire, at 1842. Yaizu City Fire Department, in front of fire and much closer to tunnel, summoned at 1918. Automatic spray heads interlocked with fire detector activate at accident site.

Response: Motorists at scene deploy hoses from hydrant boxes, but cannot activate water since valves require the pushing of an operating button in addition to traditional turning of handle. Shizuoka equipment at east portal at 1848 unable to reach accident site, assist 42 vehicles escape tunnel. Automatic spray system reportedly suppresses fire at initial site at 1850, but fire reignites at 1920.

208 occupants of vehicles trapped in tunnel escape on foot out east portal by 2030. Three Yaizu City engine companies arrive and augment fire main at FD connections at west portal.

Control/Extinguishment/Suppression: Initial efforts consume entire 40,800 gallon (155,000 liter) water supply by 2005 (one hour twenty-six minutes after automatic spray heads activate) without extinguishing fire. Unburned combustible vapors from accident site spread fire to two other groups of vehicles in tunnel when water supply is exhausted. Suppression resumed with water relayed from unspecified natural sources. Fire under control Friday afternoon but continued burning until 1000 18 July, nearly a week after initial incident. Semi-transverse ventilation system, with reversible supply fans only, operated in exhaust mode (maximum exhaust capacity one half rated supply capacity) throughout emergency but was unable to clear heat and smoke enough to allow breathing-apparatus-equipped firemen to work effectively in tunnel. Total equipment and personnel involved: 34 engines, two portable fire pumps, 30 (10 ton) tank trucks, three ambulances, 654 personnel.

Survival/Damage: Of 231 vehicles including 66 trucks in tunnel during course of incident, 58 are undamaged, 173 destroyed. Ceiling, walls, and tunnel systems almost completely destroyed for central 1145 meters. Seven fatalities, six in collision and one of injuries suffered in collision; two other unspecified injuries. "Police and sufferers will take matter into court," ends summary report.

Source of Information: Tokyo Fire Department letter to Hamburg, West Germany, Fire Department of 30 August 79; Summary of Automobile Fire in Nihonzaka Tunnel, of unknown source but written in English by a Japanese; and National Bureau of Standards Memorandum for the Files by D. Gross of 26 September 79 concerning visit to test facilities in Japan.

MOORFLEET

Location: Moorfleet Tunnel, Hamburg, West Germany
Date: 31 August, 1969
Type: Major hazardous material

Conditions at Ignition: Driver of truck trailer combination carrying 14 tons of polyethylene stopped in cut-and-cover tunnel at 0110 a.m. probably to inspect malfunction by tunnel illumination. Discovered burning tire on trailer, uncoupled and drove tractor out of tunnel.

Detection/Alarm/Notification: Unknown

Response: Unknown

Control/Extinguishment/Suppression: Fire was extinguished using foam; water used to cool wreckage. Other details unspecified.

Survival/Damage: Uncaptioned pictures reveal damage to ceiling and walls similar to Caldecott and Holland Tunnel fires; no other details available.

Discussion

In their totality, the Fire Summaries above indicate that fires will start in tunnels and, if flammable or hazardous materials are allowed transit, these will eventually be involved, even through improbable or even freakish circumstances. Witness the Caldecott accident wherein a stopped auto, 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 to their timing--a small vehicle instead of a bus, any cargo but flammable liquid, a shutdown in a different lane, etc.--could have prevented the conflagration.

Simple prohibition of hazardous materials, or a subset of them, 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 shown by the Holland Tunnel fire, where an extremely dangerous and prohibited chemical was out of sight in an enclosed trailer not normally used to carry it, to later break free and spontaneously ignite. The Squirrel Hill, Blue Mountain, and Moorfleet Tunnel fires 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 pre-inspection for mechanical faults and mandated intervals between vehicles in an otherwise deserted tunnel still only reduce the possibility of fire, not irradiate it.

It appears major hazardous material fires in tunnels, once started, can be controlled only by heroic efforts under lucky circumstances where effective support systems are also present. The decisive actions of those involved in the opening moments of the Holland Tunnel fire, where tunnel operators and fire-

fighters without protective equipment persisted in the face of noxious fumes from a fire of unknown nature, such that many were overcome, can only be described as heroic. They were aided by two factors not both present at the two other major hazardous material tunnel fires for which full details are known: trained personnel on the scene at the time of the accident and effective ventilation and fire suppression systems in the tunnel.

The fire summaries for both medium and major hazardous material fires show a consistent pattern: where trained officials are on hand from the start (Holland, Chesapeake Bay) the fire is controlled with minimum loss of life and property damage despite the seriousness of the fire, but where such officials are absent (Caldecott, Nihonzaka) 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 when ventilation and suppression systems are available and used. Where ventilation systems were large enough to remove significant quantities of smoke and heat from the area of a fire (Holland, Chesapeake Bay) and were operated at full capacity during the emergency, firefighters were able to approach the fire and remain long enough to control it. Where ventilation systems either had too little capacity or were not activated (Wallace, Caldecott, Nihonzaka), 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 data points, 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) seem to stand at opposite ends of a spectrum of fire prevention and control.

The apparent failure of the Caldecott Tunnel's fire main under the stress of heat and blast from the tanker fire, in contrast to the reported constant use of the Holland Tunnel's during its emergency, despite the more extensive local damage suffered by the latter, is also noteworthy. Tunnel communication systems purportedly installed to serve in emergencies were typically disabled soon after large fires ignited. Emergency phones and antenna wires seem particularly vulnerable, having failed in early stages of the Caldecott, Holland, and Chesapeake Bay fires.

The activation of the automatic spray system in the Nihonzaka tunnel is the only reported incidence 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 not supplied with water. Points of ignition and combustible vapors remained after an hour and twenty-six minutes to reignite after the water supply was exhausted. In this instance, then, sprinklers did not prove an effective fire control tool, although in combination with directed hose streams their effectiveness may have been much enhanced.

Although events seem to stress the importance of tunnel personnel in an emergency, the role played by motorists cannot be discounted. In four incidents (Wallace, Squirrel Hill, Chesapeake Bay, and Moorfleet) none were present, in two others (Baltimore Harbor Freeway and Holland) what actions they might have taken were superseded by officials' directions, and motorists' roles are not related in the Blue Mountain incident, so no conclusions can be drawn from them. But the actions of bystanders in two major hazardous material fires (Caldecott and Nihonzaka) were the only local responses before the fires became uncontrollable, and their actions are significant.

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

Findings of Other Studies

Four recent studies bear on the subject of fire prevention and control in vehicular tunnels: The Swiss Kommission for Sicherheitsmassnahmen in Strassentunneln (the Ofenegg report), the United Kingdom's Fire Research Station report Studies of Fire and Smoke Behavior Relevant to Tunnels (the Heselden study), the Ingenieurgemeinschaft Laesser-Feizlmayr Austrian Tunnel Fire Study (the Feizlmayr study), and Japan's Study on a New Ventilation System to Effectively Eliminate Fire Smoke in a Tunnel (the Nihon Doro Kodan report).

The Ofenegg report details a number of tests performed in an abandoned Swiss railway tunnel to investigate the CO concentration, temperature distribution, visibility, response to ventilation, response to sprinklers, effect on tunnel systems and structures, and effect on vehicles and people of several fire sizes as a function of time. Several animal carcasses and vehicles were exposed at various distances to deliberately-ignited pans of gasoline. Two types of ventilation systems, longitudinal and semi-transverse supply-only, were evaluated;

the tunnel had no exhaust provisions. Sprinklers were mounted over the fuel basin and their effectiveness evaluated. Eight tests were scheduled--plain, longitudinally ventilated, semi-transversely ventilated, and with sprinklers--for two sized fires, 500 liters and 1000 liters.

During the 500 liter gasoline burn tests, the semi-transverse supply had no mitigating effects, while the longitudinal ventilation "drove the flames torch-like" downwind. During the 500 liter sprinkler test, sprinkler droplets initially evaporated into a high-temperature steam cloud, causing more damage than the unsprinklered fires. The open fire was apparently soon extinguished, accompanied by a strong odor of gasoline at the portal, but the fire reignited after 17 minutes (status of sprinkler flow unstated) with a pronounced but non-explosive wave-front propagation. The ultimate minimum survival distance for an upright subject was judged closer than for the unsprinkled fires, however.

During the 1000 liter gasoline burn tests, calculated burning rates were lower than those observed for similarly-sized fires in the open. Started immediately after ignition this time, the sprinklers reduced the maximum arch temperature from 800°C to 450°C, but the steam apparently pushed burning gases and gasoline vapors into adjacent tunnel sections, where they continued to burn. The fire was apparently extinguished for 10 minutes, but the tunnel filled with gasoline vapors, which exploded in the 19th minute, causing extensive damage to the test setups and injuring three technicians.

Events during these sprinkler tests match those in the Nihonzaka fire summary. All three incidents cast doubt on the effectiveness of sprinklers in containing a fire or in limiting the range and severity of damage. A delay in activation produces huge volumes of high temperature steam as dangerous as the combustion products. If all ignition sources cannot be extinguished and the site uniformly cooled below a safe temperature the fire will reignite, perhaps explosively, when the sprinklers are shut off. Meanwhile, unburned vapors are propelled around the tunnel and ventilation ducts at great hazard to those safely away from the fire, even if the fire is extinguished.

The Heselden study draws upon the Ofenegg report, Fire Research Station tunnel fire experiments, and on the Holland and Moorfleet fires (the only hazardous material tunnel fires known at that time) to quantify the spread of smoke and fire and the resulting temperature profile in a hypothetical tunnel. These quantitative results are dealt with in the Risk Analysis below, but the study makes several qualitative points.

The report gives additional information on the Moorfleet fire in Hamburg:

- o A rear tire caught fire and, when the driver stopped at the centre of the tunnel, the flames spread upwards to the load. The driver tried to fight the fire with a fire extinguisher, but was unsuccessful. Uncoupling the trailer, he drove off for help, but in his excitement did not use one of the telephones provided along the motorway. When the fire brigade arrived, they found dense smoke pouring from both ends of the 250 m long tunnel, but a layer of clear air about 1 m high remained above the road surface, where the combustion air for the fire was being drawn in. The fire brigade had to look for water for some time, but when fire-fighting actually started with foam the fire was extinguished in a few minutes.

While Mr. Heselden believes this incident indicates "The behavior of untrained people as opposed to people trained to deal with a fire emergency... can be irrational and ill-judged", it may only reinforce observations in other incidents where the reactions, both physical and mental, of those involved in the mishap are impaired, but bystanders are able to take effective action, e.g. the Caldecott and Nihonzaka fires.

Other qualitative points made in the Heselden study include:

- o With the smallest fire, in a car, the problems [of control] should be manageable. Even with no ventilation or extraction it is doubtful if any able-bodied person could be endangered. It should be reasonably easy for firefighters to approach the fire.

This is supported by the lack of reported difficulty arising from frequently-occurring automobile fires, which are routinely extinguished without incident, often by bystanders before trained help arrives.

The report goes on to say, however, that:

- o The petrol spill fires represent a considerable hazard for escapers and, without control of smoke flow, create formidable, probably impossible difficulties for firefighting. Escapers would have to run, not walk.

This is supported by the Holland Tunnel fire, where difficulties were indeed formidable before the ventilation system was accelerated.

- o It is hard to see any way in which such fires could be dealt with except by halting smoke movement in one

direction, which would require an air velocity of up to some 7 m/sec (15.5 miles per hour). Failing this the fire would have to be allowed to burn itself out.

One-directional movement was achieved at the Caldecott fire with wind velocities near 10 miles per hour. Heselden, and several reported approaches to within 75 feet of Caldecott's fire, suggest it could have been attacked at once from the west, had there been reason to risk doing so. Concerning this strategy:

- o If the longitudinal air flow is successful in halting smoke and ceiling flame movement in one direction, then it must be remembered that longer flames would be produced on the downstream side and ignition would be possible over longer distances.

This was certainly the case at Caldecott, where autos were burned out all the way to the east portal.

The conditions in Caldecott's #3 bore at the time of the fire--a natural draft against traffic which neither artificial ventilation nor the traffic's piston effect can overcome--should be recognized as the most dangerous situation in the event of a fire.

The Heselden report places great stress on maintaining stratification of exhaust products and incoming fresh air during a tunnel fire:

- o From the fire point of view, any ventilation system which injects air into the tunnel at a high level is strongly to be avoided. In the event of a serious fire this air will not be able to dilute the smoke to a level acceptable to human life and will only increase the quantity of smoke that has to be disposed of, or that can cause a hazard. Furthermore, the air could bring an otherwise stable smoke layer down to a low level.

One recalls trapped firefighters breathing from the curb-level fresh air inlets in Holland Tunnel fire.

It is important to note that in no test or fire where transverse ventilation or exhaust was used did this serve to spread the fire or increase its burning rate. Only in the Nihonzaka fire literature was there any mention of this common concern actually occurring, and in truth any observed fanning or increase in burning rate must have been the results of large quantities of combustible gases being propelled through the tunnel by the sprinklers. The position of the exhaust fans at the western, upwind portal at Caldecott

probably rendered them ineffective in removing smoke from the far end of the tunnel and, had they been turned on, may indeed have served only to spread smoke and heat in both directions from the fire, thus endangering firefighters at its western edge as feared.

The Feizlmayr study, commissioned by the Austrian Ministry for Construction and Technical Affairs, summarizes a fire test program carried out in an abandoned rail tunnel equipped with a fully transverse ventilation system. The investigators attempted to answer the following questions:

- o How do conditions in the traffic space differ when applying different patterns of ventilation?
- o What improvements can be expected from selected changes to the design, construction, and operation of exhaust air openings?

The test program consisted of 23 tests of a "standard" fire of 200 liters of gasoline with a fire area of 6.8 m², three tests of 400 liters of gasoline with a fire area of 13.6 m², and four other tests of other fuels. These tests investigated the effect of varying five parameters:

- o Location of fresh air injection (high or low).
- o Quantity of smoke and fumes exhausted.
- o Quantity of fresh air injected.
- o Forced longitudinal ventilation in the traffic space.
- o Conditions in the traffic space (open or obstructed).

The investigators believe the size of the area affected by the fire and thus the possibilities of escape and rescue depend to a great extent on the pattern of ventilation, more so than on any other parameter. With longitudinal flows of at least 6.5 ft/sec (4.4 miles/hour), a "burner effect" was created on the exhaust air side of a fire. The smoke spread at approximately the same rate as the longitudinal flow (for the 200 liter fires), but even small fires filled long sections of the tunnel on the exhaust side of the fire point with smoke.

They suggest it is not possible to rescue people on the exhaust air side from the fresh air side. Contrary to the conditions on the exhaust air side, however, a longitudinal flow creates very favorable conditions on the fresh air side of the fire. If the longitudinal flow can be stopped, or if none exists from the start, the danger area and the smoke area will be symmetric to the fire point. The tests confirmed that full extraction in connection with throttled fresh air reduces the danger area as well as the smoke area.

Maximum exhaust air temperature reached during full extraction tests was only 85°C (185°F) and decreased as the fire point approached the fan location. With this dilution, the investigators believe 250°C (482°F) to be a sufficiently high temperature criteria for exhaust fans installed in a fully transverse system. This does not agree with actual conditions experienced in the Holland Tunnel and Caldecott fires.

Because their test results so strongly supported the benefits of a fully transverse system running in a full extraction mode during a fire, the investigators made the following recommendations for the design and operation of tunnel ventilation systems:

- o The very rapid development of the investigated tunnel fires commands the conclusion that the first rescue operation for the people in the danger area should be to select a suitable pattern of ventilation for creating the best possible conditions in the traffic space under the given circumstances.
- o In order to fulfill this requirement it is necessary:
 - a) that the fire be quickly detected (alarm system) and transmitted to a tunnel control center where the operating pattern can be selected and;
 - b) that the appropriate technical and organizational measures be prepared, securing a fast and correct selection of the operating pattern of the ventilation system in case of fire (fire alarm program).
- o The tunnel therefore must be equipped with a quickly responding fire warning system. Signals should be transmitted with minimum possible delay into the control center.
- o The fans should be designed in such a way that orders from the control center can be executed within a very short time.
- o For each tunnel a fire alarm program should be established, specifying in detail the operating pattern of the ventilation system in relation to the location of the fire and other marginal conditions.
- o In cases where the control center is equipped with a computer the individual programs should be stored and available to be called off at any time.
- o The main goal of all measures must be to prevent the spreading of hot fumes and smoke in the traffic space.

- o This recommendation must be given without any restriction for all tunnels with two-way traffic.

Concerning the location of fresh air injection:

- o The overriding recommendation derived from the tests requires throttling of the fresh air supply (or change-over to extraction in case of a reversible semi-transverse system) in case of fire.
- o When the fresh air supply is throttled the injection "from below" shows no decisive advantage compared with the injection "from above".

And the question of enlarged exhaust openings:

- o The only conclusion gained during the tests is that the enlargement of the exhaust openings near the fire point has no effect as long as a considerable (6.5 ft/sec or 4.4 mile/hour) longitudinal flow passes over the fire point.
- o In fully transverse systems the immediate action must be to get longitudinal flows under control before trying to make further improvements by enlarged exhaust openings.

These last two points concerning enlarged exhaust openings were incorporated into a system investigated by the Nihon Doro Kodan, the Japan Highway Public Corporation, using scale model tests and a full-sized installation of large, damper-controlled ceiling ports in an in-service tunnel on the Chuo Expressway. This investigation is summarized in the Nihon Doro Kodan report.

During normal operations the ports were operated as a series of controlled supply outlets. Under fire emergency conditions two ports bracketing the fire were fully opened, the rest completely closed, and the supply fans reversed to exhaust smoke from the spot of the fire. The scale model tests of this modification to the standard Japanese semi-transverse ventilation proved successful enough to warrant a full-sized design. Based on this, such a system was designed and installed in the Amikake Tunnel, and in July 1975 full-scale experiments confirmed the effectiveness of this arrangement.

The Amikake Tunnel, built with a semi-transverse, reversible supply ventilation system and large, controllable, smoke vents based on the scale model tests, is a two-lane, two-way highway tunnel at the border of Nagano and Gifu Prefectures in the mountains 150 miles west of Tokyo. It is 6315 feet (1943 meters) long and slopes 1.7% upward to the west. Its

four axial flow supply fans were sized for 1700 vehicles per hour and deliver 206,000 cfm (100 cms) each in normal (supply) rotation and 144,000 cfm (70 cms) each in reverse (exhaust) rotation. Sets of three ports are installed 327 ft o.c. (100 m) with a total area of 170 ft² (16 m²) and include opposed multi-blade, motor-operated dampers to deliver fresh air at a uniform rate through every port during normal operation and to either fully open or fully close in the case of fire. In addition, the mid-tunnel supply duct bulkhead has a controllable smoke damper to allow all four fans to exhaust from a fire in either half-section. The dampers automatically open and close in response to signals from fire detectors, can be manually activated to respond to a fire, and can be individually opened and closed.

The important results of this investigation were related in the Nihon Doro Kodan report as follows:

- o Best smoke removal was achieved by operating both east and west fans for extraction regardless of the fire location, with the bulkhead damper fully open.
- o Under these conditions, air flowed towards the open damper or dampers by as much as 11 mph (5 meters per second).
- o The space between the fire point and the open damper or dampers is filled with smoke.
- o The inertial effects of longitudinal air flow is lost within three minutes after fire mode is activated.

The report concludes that:

- o smoke can be kept within the minimum space and can be extracted quickly if the kinetic energy of the smoke flow produced by the thermal energy of fire is less than the energy of ventilating air blowing along the driveway toward the smoke venting dampers when the fans are run in reverse direction. This is achieved by the relationship between the scale of fire and the capacity of the ventilation fans (i.e. if the fire is too big, the fans won't extract all the smoke).
- o ventilation fans are generally designed for the purposes of reducing concentration of exhaust gases from vehicles and extending the visible distance by taking into consideration estimated traffic volume, the tunnel length, natural ventilation, ventilation by movement of vehicles, and so on. Depending on these design conditions, there may be a small number of cases in which smoke can be reasonably extracted by existing ventilation systems.

- o for determining the capacity of ventilating fans in the future, the fire smoke venting capacity of the fans be designed to meet the scale of a real vehicle fire.

Synopsis of Study Interviews:

The principal investigator interviewed 18 agencies operating 35 vehicular tunnels gathering background information for this study. These tunnels and operators are listed in Appendix A. All interviews were taped; a tape log is included in Appendix B. A summary transcription of salient points made by the respondents has been included in Appendix C. These salient points have been tabulated below.

Care should be used in drawing conclusions from this tabulation alone. The numbers listed under each heading are not necessarily inclusive. Responses from single agencies operating more than one tunnel (the Pennsylvania Turnpike Commission, for instance, with five) carry more numerical weight than others who only operate one. In the end, the numbers only illustrate the range of opinions, practices, and systems encountered before any conclusions were formulated. In retrospect, some of these could be characterized as questionable or even unsafe. Nonetheless, they have been presented here and in Appendix C without prejudice.

Tunnel Classification

Subaqueous	16
Dry urban	10
Dry remote	9

Safety-related Configurations

One-way traffic in tube	27
Two-way traffic in tube	8
Cross-tube adits	9
No adits	15
Tunnel profile factor in fire	5
Accident rate analyses performed	1

Restrictions

Hazardous materials prohibited	31
Cargoes inspected at portals	13
No inspections	17
Liquid cargoes prohibited	10
Alternate route available	24
No alternate route available	4
Allow supervised transit	1
Would consider supervised transit	2
Oppose supervised transit	7
Hazardous materials restricted during heavy traffic	1

Motorists' Attitudes Characterized as

Normally cautious	10
Normally netural	3
Often incautious	1
Occasionally phobic	3

Traffic Regulations

Speed limits reduced	3
Lane changes prohibited	9
Trucks restricted to one lane	1
Identical with connecting roadways	17

Enforcement

Tunnel personnel empowered to cite violators	5
Violators referred to law enforcement agency	2
Violators seldom observed or cited	5

Monitoring Systems

TV cameras used	10
TV cameras installed but not used	1
TV cameras planned	2
Tunnel always manned	5
Tunnel usually manned	5
Tunnel sometimes manned	2
Tunnel never manned	15
Traffic flow detection loops	4
No monitoring system	10

Communication Systems

AM rebroadcast	5
AM rebroadcast planned	3
Signs ineffective in emergencies	12
Loudspeakers/bullhorns ineffective	4
Telephones	22
Systems degraded/inoperative in fire	3

Drainage Systems

Adequate for large spill	4
Often blocked by debris	6
Inadequate for large spill	4
Failed during major fire	2
Sump explosion-proof	2
Sump not explosion-proof	3
Spill management plan promulgated	1

Ventilation Systems

Transverse	14
Semi-transverse	1
Reversible longitudinal	2
Longitudinal	17
Piston effect ventilation effective	9
Designed to survive fire	5
Effective in fires to date	5
Advocate running during fire	15
Not activated during fire	2
Could not survive fire	7
Fans under automatic control	4
Fire department supervises during fire	3
Emergency ventilation plan promulgated	8
Smoke test used to develop plan	2

Fire Detection/Alarm/Notification Systems

Personnel on duty in tunnel	7
Smoke detectors at fan outlets	3
Fire alarms or buttons	5
Fire alarms abused to summon routine assistance	1
Telephones only	4
None	8

Normal Response to Fire

Motorists often extinguish without supervision	6
Tunnel crews usually extinguish	14
Fire department usually extinguishes	2
Fire department summoned as last resort	2

Fire Vehicles at Tunnel

Full-sized fire truck	6
Tunnel wrecker with firefighting equipment	10
None	8

Fire Department Liaison

Direct line	4
Dial phone	24
Radio link	5
Regular drills scheduled	8
Frequent responses serve as drills	1
FD within 5 miles	20
FD farther than 5 miles	13
Formal fire/emergency plan promulgated	10

Tunnel Fire Extinguishers

In niches	31
CO ₂ preferred	8
Dry chemical preferred	15
Both CO ₂ and powder provided	2
No fire extinguishers	3

Tunnel Fire Main

Either wet or dry main with hydrants	29
Water supply unlimited	19
Water stored at site	3
Fire main degraded during fire	1
No fire main	3
System not described	2

Tunnel Sprinkler System

Present in tunnel	3
Not present	10
System not described	11
Oppose sprinklers in tunnel	17
Deluge system in fan room	3

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 8,000,000 miles of hazardous material tank truck travel. The magnitude of such a fire within a highway tunnel is significant. A fire involving a 30-gallon spill or 20 gpm leak of a liquefied flammable gas or Class I flammable liquid, or involving a 160 gallon 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 gallon spill or 40 gpm leak of a liquefied flammable gas or Type I flammable liquid, or a fire involving a 500 gallon spill or 200 gallon leak of a Class II or Class III combustible liquid, will present a severe fire exposure to the tunnel structure, with ceiling temperatures approaching 2000°F for a duration of more than 1 hour.

A hazardous material cargo spill involving a liquefied flammable gas or Type I flammable liquid which does not involve an immediate fire can create a significant explosion potential within a tunnel. An explosion involving those vapors can create blast overpressures which 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 should an explosion 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 feet wide, 16 feet high and one mile long with a horizontal tunnel bore. This tunnel will be referred to as the Reference Tunnel in this analysis.

Fire Frequency Prediction

There have been few hazardous material tank truck fires occurring 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, a statistical basis for predicting the frequency of hazardous material tank truck accidents/fires in highway tunnels could not be developed. However, a statistical basis for predicting the open highway accident/fire frequency of hazardous material tank trucks was developed and used to predict the highway tunnel accident/fire frequency.

Several agencies were contacted to obtain information on the hazardous material tank truck open highway accident/fire frequency. The agencies contacted were:

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

The documents obtained from these sources which were used to predict the hazardous material tank truck accident/fire frequency include:

1. "ATA National Truck and Industrial Contest - 1982", American Trucking Association, Inc.

2. "Analysis of Accident Reports Involving Fire - January through June 1968", Bureau of Motor Carrier Safety.
3. "Summary of Motor Vehicle Accidents in the Petroleum Industry for 1981" - August 1982, American Petroleum Institute.
4. "Accidents of Motor Carriers of Property - 1979", Bureau of Motor Carrier Safety.
5. "New Drive for Truck Safety", Journal of American Insurance Association - May/June 1970.
6. "Motor Vehicle Standards for Hazardous Material Transportation" - January 1970, Factory Mutual Research Corporation.

These documents report that:

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

5. The cargo was involved in 87 percent of the fires involving hazardous material tank trucks.

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

- A. The average tank truck accident frequency was taken as 4.91 accidents per million miles.
- B. Assuming that 8.5 percent of the accidents result in a 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).
- C. 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).
- D. Assuming that 87 percent of the tank truck fires involve the cargo, the cargo fire frequency is estimated at 0.124 cargo fires per million miles (0.142 fires per million miles X 0.87 cargo fires per fire = 0.124 cargo fires per million miles).

The fire and hazardous cargo spill frequency for the Reference Tunnel are predicted, using these frequencies, as:

1. One cargo spill per 2,390,000 tunnel crossings.
2. 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 hazardous material fire and spill frequencies are predicted as:

1. One cargo spill occurring every 65 years.
2. One cargo fire occurring every 221 years.

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

Fire/Smoke Spread Potential

The flames from a hazardous material fire in a highway tunnel will spread along the tunnel ceiling and 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 mega-watt intensity will create air temperatures in excess of 120°F in the Reference Tunnel approximately 630 feet beyond the fire in the direction in which the smoke is moving. Similarly, the smoke from a 50 mega-watt fire will create air temperatures in excess of 120°F 1850 feet beyond the fire while the smoke from a 100 mega-watt fire will create such temperatures 3,100 feet beyond the fire. Exposure to temperatures above 120°F will quickly cause second degree burns and is considered life threatening according to Chapter 3 of the National Fire Protection Association Handbook - 15th Edition. In addition, the smoke will fill the tunnel, in the direction in which the fire ventilates, with toxic combustion products, making human survival doubtful beyond the point of fire origin. Theoretical calculations indicate that smoke will spread away from the fire at a rate of 238 feet per minute (2.7 miles per hour) for a fire with a 3 mega-watt intensity and 1225 feet per minute (14 miles per hour) for a fire with a 100 mega-watt 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 the estimated tunnel temperatures as a function of the fire intensity and the 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 the fire intensity for a fire occurring in the Reference Tunnel. Both Figures 1 and 2 assume 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 on 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

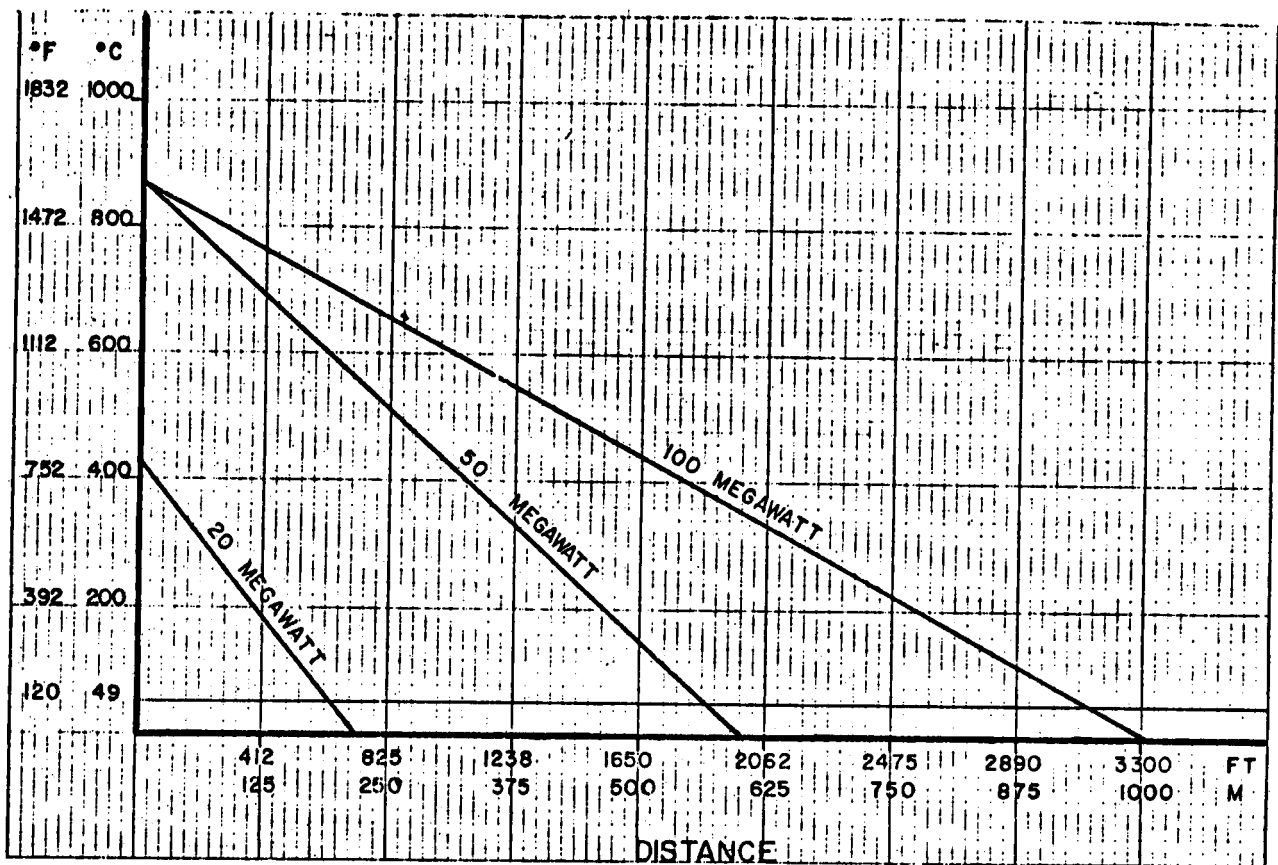


Fig. 1 Tunnel Temperature vs. Distance (without smoke extraction) (in still air)

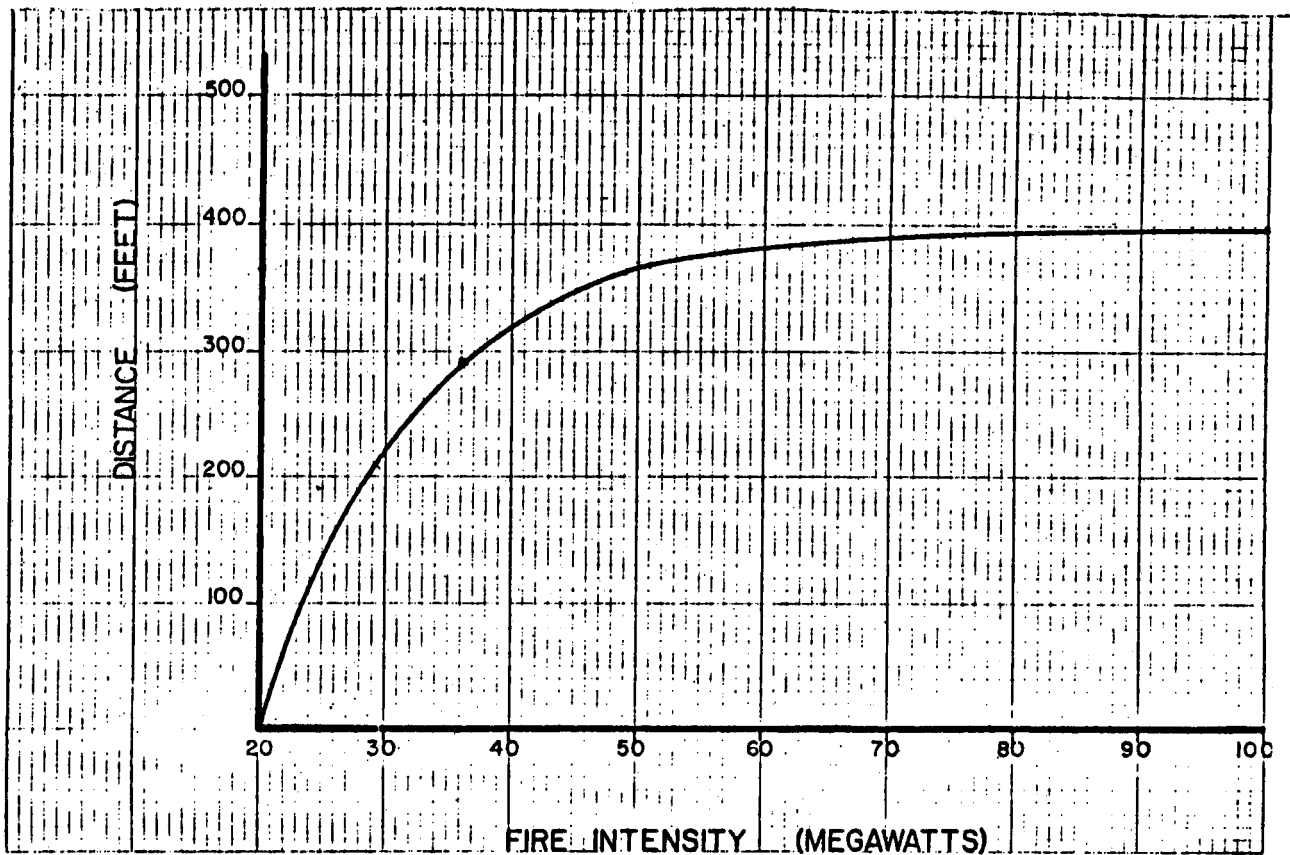


Fig. 2 Distance of Flame Along Ceiling vs. Fire Intensity

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 the Reference Tunnel, the ceiling flame projection will be longer, the smoke will move faster through the tunnel, and the distance at which the temperature exceeds 120°F will be further 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, 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 mega-watts can endanger the lives of all people who happen to be within 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 mega-watts will also endanger the lives of all people within the tunnel, and may cause structural damage to the tunnel because the ceiling temperatures within several hundred feet of the fire will approach 2000°F.

Fire/Smoke Spread Potential Reduction

A tunnel emergency ventilation system can reduce the temperatures within a tunnel during a fire. For example, the smoke from a 20 mega-watt fire will create air temperatures in excess of 120°F within approximately 290 feet of the fire in the Reference Tunnel if it is provided with emergency ventilation at a rate of 127 cubic feet per minute per foot of tunnel length. Similarly, the 50 mega-watt fire will create temperatures in excess of 120°F 370 feet beyond the fire while the 100 mega-watt will create those temperatures at 720 feet beyond the fire. Figure 4 shows the affect of the ventilation system on the temperatures in the Reference Tunnel.

Automatic fire suppression systems may be of benefit in preventing structural damage to a tunnel but will possibly not be effective in reducing loss of life in the event of a hazardous material tunnel fire. The fire will probably be fully involved

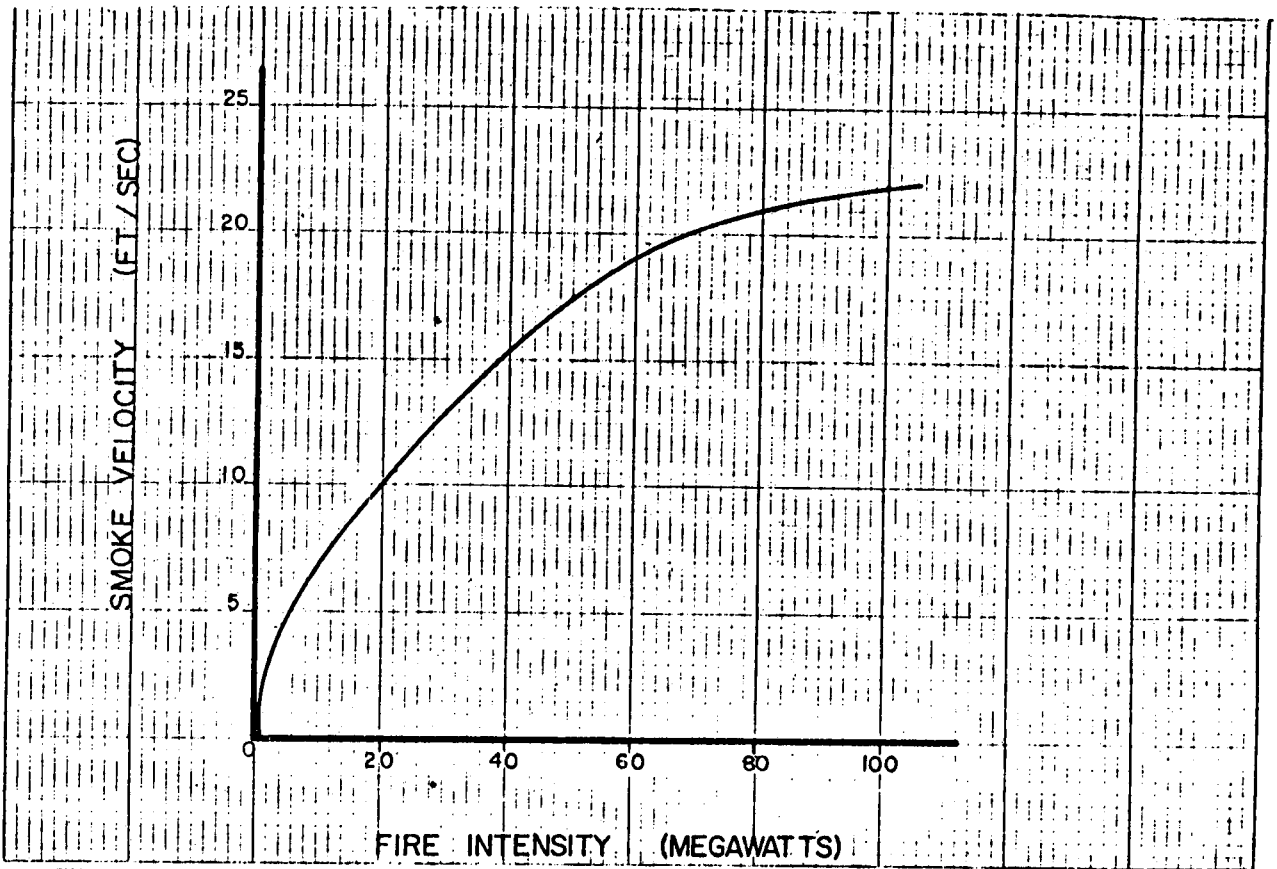


Fig. 3 Smoke Velocity vs. Fire Intensity

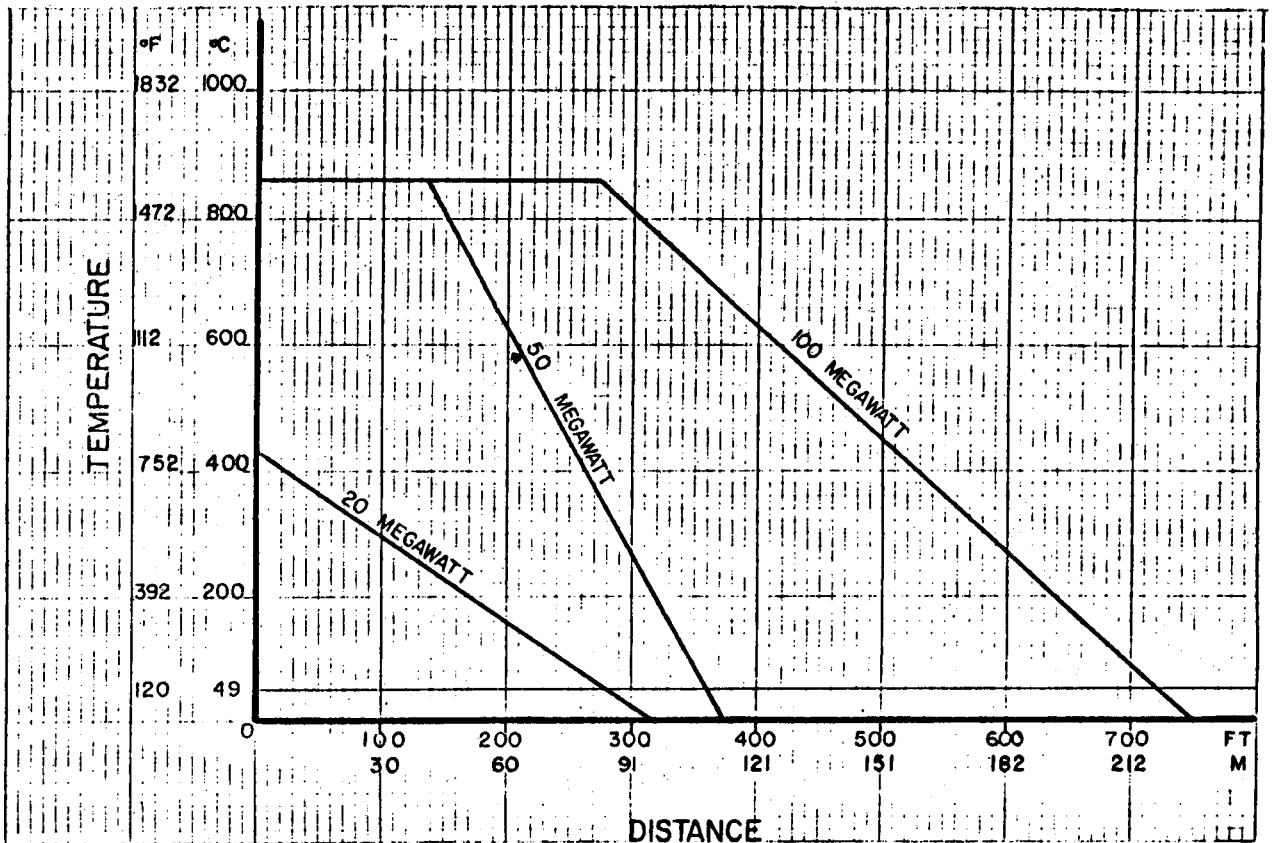


Fig. 4 Tunnel Temperature vs. Dist. (with smoke extraction of 127 cfm/ft)

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 the delivery system piping is filled with water. Discharging water onto a fully involved hazardous material fire within an enclosed tunnel may increase the danger to the tunnel occupants because of the steam generated when water contacts the fire.

Fire Intensity

The potential intensity of a highway tunnel fire involving a hazardous material tank truck was determined by reviewing the research studies and fire reports listed in Appendix A. These deal with:

1. Hazardous material tank truck accidents/fires, both on the open road and within highway tunnels.
2. Research and experimentation in fire development and smoke movement, both in tunnels and in buildings.
3. 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.

The initial critical factor in the fire development is the quantity of spilled liquid. A fire involving a total spill of more than 32 gallons or a continuous leak of more than 20 gallons per minute of a liquefied flammable gas or Class I flammable liquid (flash point less than 100°F) will result in a fire intensity exceeding 20 mega-watts. Similarly, a fire involving a total spill of more than 162 gallons or a continuous leak of more than 98 gpm will result in a fire intensity exceeding 100 mega-watts.

A fire involving a total spill of more than 104 gallons or a continuous leak of more than 42 gallons per minute 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 mega-watts. Similarly, a fire involving a total spill of more than 526 gallons or a continuous leak of more than 206 gpm will result in a fire intensity exceeding 100 mega-watts.

Figures 5 through 10 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 spilled material burning rate (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 on Figure 7.
4. Figure 8 shows the fire intensity as a function of the quantity of spilled material or the 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. Figure 9 shows the estimated flow rates from broken schedule 40 steel pipe. The flow rates are shown for various pipe sizes from 1/4 inch through 2 inch.
6. Figure 10 shows the fire intensity as a function of the flow rate from a tank leak. Figure 10 was developed using Figure 7 by equating the leak rate to the fuel burning rate. Figure 10 shows that a liquefied flammable gas or Class I flammable liquid leak from a broken 1/2 inch pipe can result in a 20 mega-watt fire while a leak from a broken 1-1/4-inch pipe can result in a 100 mega-watt fire. Similarly, a Class II or III combustible liquid leak from a broken 1-1/4-inch pipe can result in a 20 mega-watt fire while a leak from a broken 2 inch pipe can result in a 100 mega-watt fire.

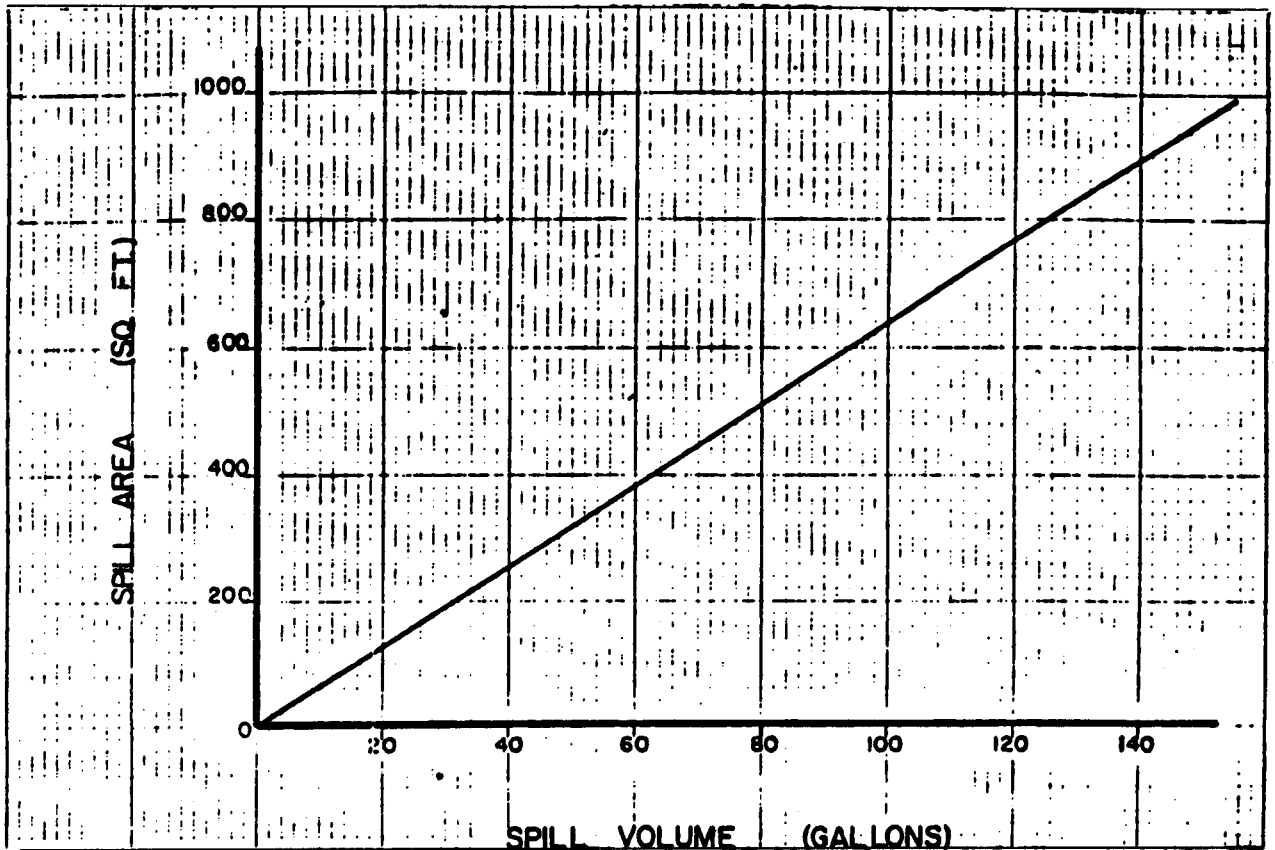


Fig. 5 Liquid Spill Area vs. Spill Quantity

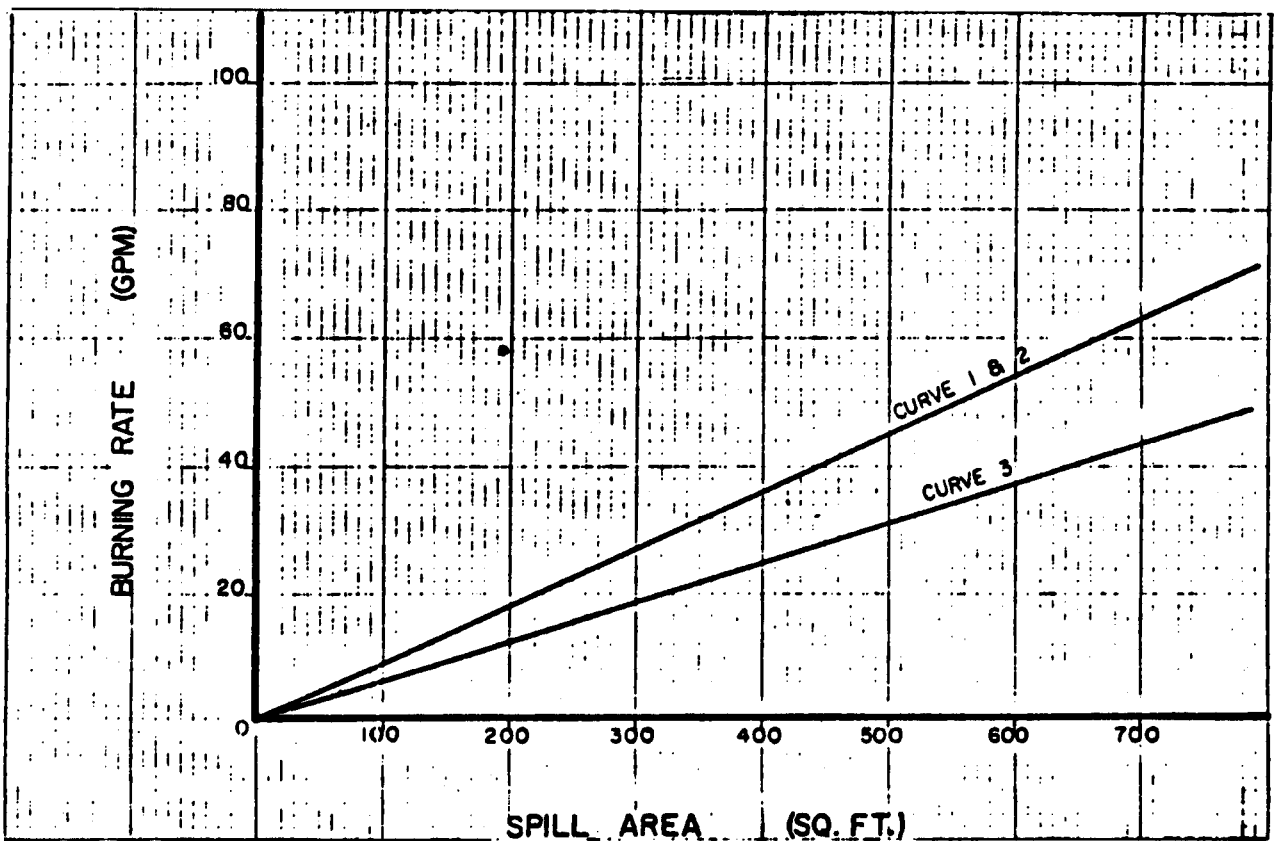


Fig. 6 Fuel Burning Rate vs. Liquid Spill Area

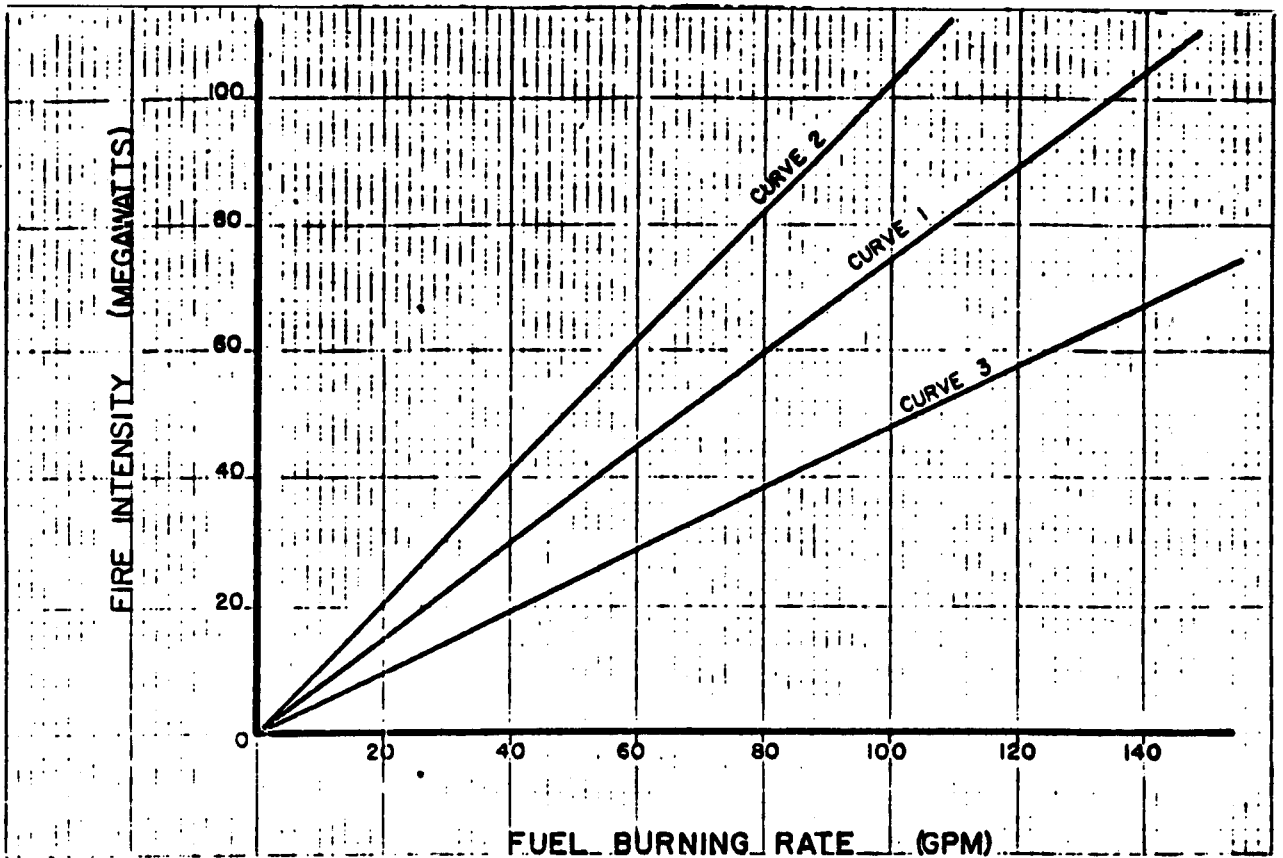


Fig. 7 Fire Intensity vs. Fuel Burning Rate

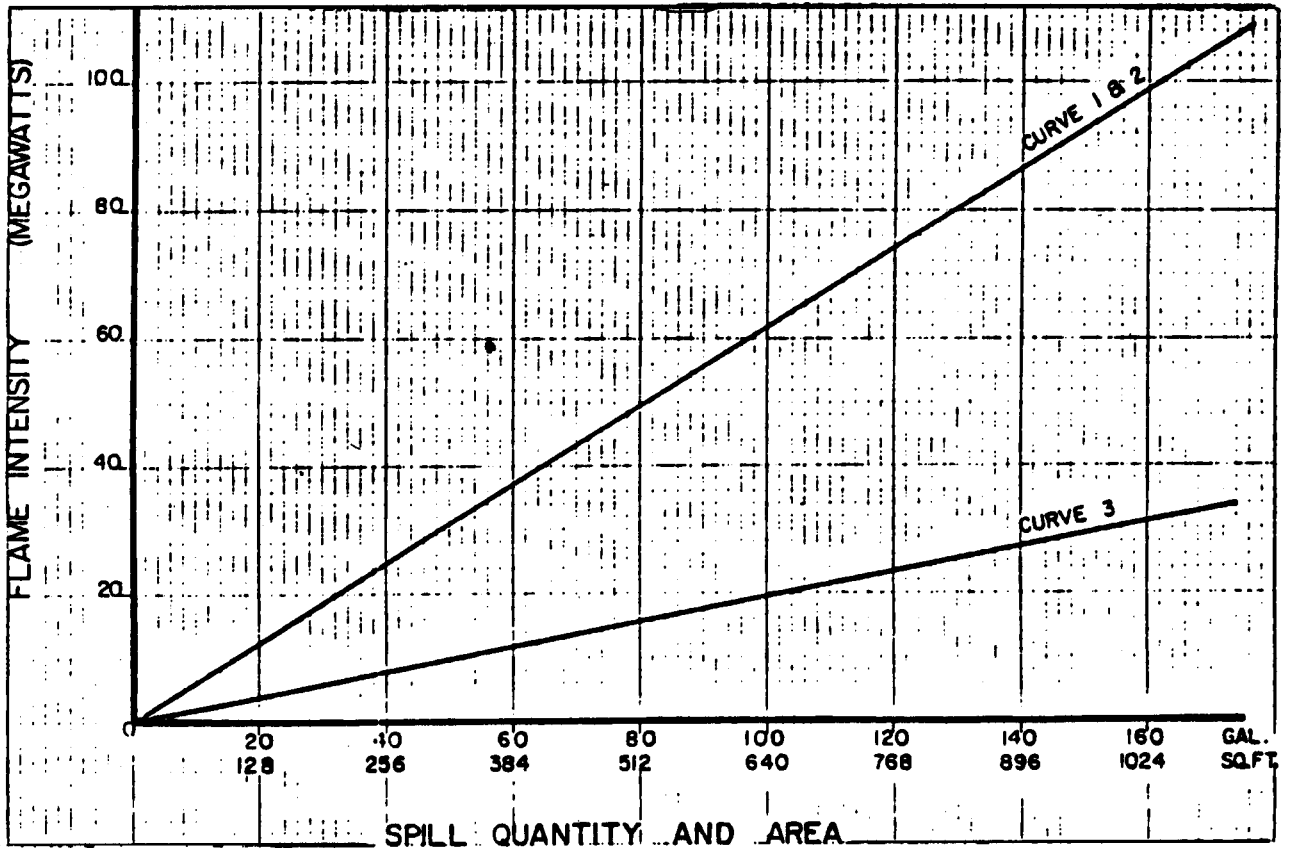


Fig. 8 Fire Intensity vs. Spill Quantity and Area

Nominal Schedule 40
Pipe Size

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

Fig. 9 Flow Rate vs. Sch. 40 Pipe Size

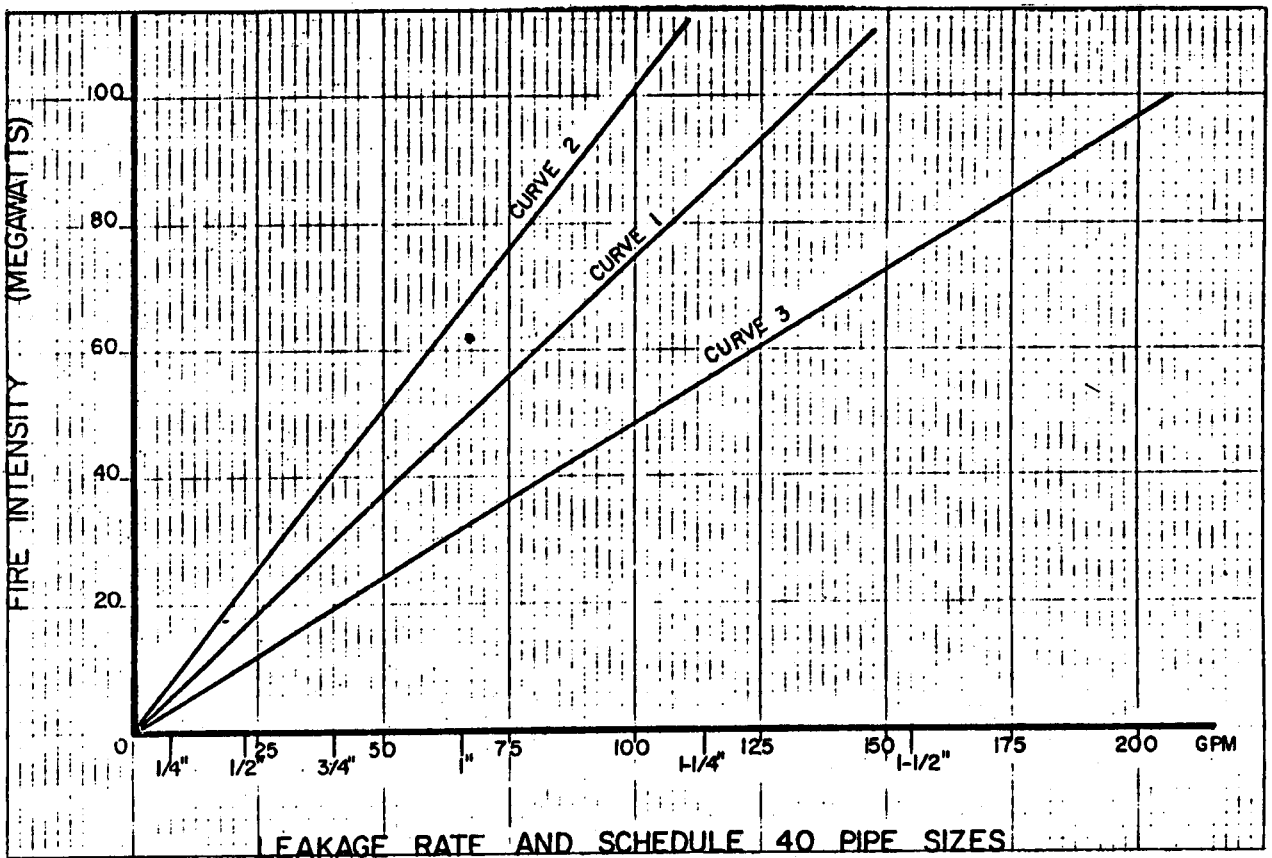


Fig. 10 Fire Intensity vs. Fuel Leakage Rate

The second critical factor in the fire development is the availability of combustion air. Approximately 1350 cubic feet 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 cubic feet per minute 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 feet per minute (5.8 miles per hour). It seems reasonable to expect that this amount of combustion air would be available to a fire within the Reference Tunnel. Consequently, combustion air does not appear to be a controlling factor in fires burning at a rate of 200 gallons per minute or lower.

The third critical factor in the fire development is the ability of the smoke to leave the tunnel. As the entering combustion air is heated by the fire, it will expand. Assuming an average smoke temperature of 500°C, the combustion gases will have expanded to approximately 2.62 times their initial volume. They will leave the tunnel at a faster rate than the entering combustion air. The volume of smoke produced by a 200 gallon per minute fire will be approximately 710,000 cubic feet per minute. This smoke will leave the Reference Tunnel through the end opposite the combustion air at an average speed of 1345 feet per minute (15.3 miles per hour). Again, it seems 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, 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 inches. A fire involving such a spill will usually last less than 5 minutes.

A continuing small, unconfined spill fire which is fed by a cargo tank leak (such as a small cargo tank puncture, melt down of an aluminum cargo tank, or a broken pipe or valve) will last as long as the leak persists. A 100 gpm leak in a 8000 gallon gasoline tank truck could result in a 100 mega-watt fire which will last for approximately 80 minutes.

A catastrophic spill (involving a ruptured cargo tank) in a tunnel will probably be confined by the tunnel walls or roadway and may pond to depths over 0.25 inches or enter the tunnel drainage system, spreading the spilled hazardous material and the fire beyond the area of the accident. The duration of such a fire cannot be predicted.

Fire Scenarios

Four fire scenarios are considered. They include:

1. Scenario No. 1 - 20 mega-watt fire in Reference Tunnel. (Tunnel bore is horizontal).
2. Scenario No. 2 - 100 mega-watt fire in Reference Tunnel. (Tunnel bore is horizontal).
3. Scenario No. 3 - 20 mega-watt fire in sub-aqueous tunnel with same dimensions as Reference Tunnel. (Tunnel bore is sloped).
4. Scenario No. 4 - 100 mega-watt fire in sub-aqueous tunnel with same dimensions as Reference Tunnel. (Tunnel bore is sloped).

Fire Scenario No. 1 - This scenario considers a fire involving an 8,000 gallon gasoline tank truck from which 30 gallons of gasoline have been spilled through a 20 gpm leak prior to ignition. The leak will continue during the course of the fire, resulting in a 20 mega-watt fire. The results of that fire will be:

1. Flames will probably not reach the tunnel ceiling. The maximum ceiling temperature will be less than 900°F.
2. The fire will burn for approximately 400 minutes provided the spill size or leakage rate didn't increase.
3. The velocity of the smoke layer will be approximately 600 feet per minute.
4. The temperature within the tunnel on each side of the accident will exceed 120°F within 320 feet of the fire.

Fire Scenario No. 2 - This scenario considers a fire involving an 8,000 gallon gasoline tank truck from which 160 gallons of gasoline have been spilled through a 100 gpm leak prior to ignition. The leak will continue during the course of the fire, resulting in a 100 mega-watt fire. The results of that fire will be:

1. Flames will reach the tunnel ceiling and extend approximately 200 feet beyond the accident in each direction. The maximum ceiling temperature will approach 2000°F.
2. The fire will burn for approximately 80 minutes.
3. The velocity of the smoke layer will be approximately 1225 feet per minute.
4. The temperature in the tunnel on each side of the accident within approximately 550 feet of the center of the fire will exceed 1000°F.
5. The temperature in the tunnel on each side of the accident will exceed 120°F within 1550 feet of the fire.

Fire Scenario No. 3 - This scenario considers a fire involving an 8,000 gallon gasoline tank truck from which 30 gallons of gasoline have been spilled through a 20 gpm leak prior to ignition. The leak will continue during the course of the fire, resulting in a 20 mega-watt fire. The results of that fire will be:

1. Flames will probably reach the tunnel ceiling. The maximum ceiling temperature will be less than 900°F.
2. The fire will burn for approximately 400 minutes provided the spill size or leakage rate didn't increase.
3. The velocity of the smoke layer will be approximately 600 feet per minute.
4. The temperature within the tunnel on the exhaust side of the fire will exceed 120°F within 630 feet of the fire.

Fire Scenario No. 4 - This scenario considers a fire involving an 8,000 gallon gasoline tank truck from which 160 gallons of gasoline have been spilled through a 100 gpm leak prior to ignition. The leak will continue during the course of the fire, resulting in a 100 mega-watt fire. The results of that fire will be:

1. Flames will reach the tunnel ceiling and extend approximately 400 feet beyond the accident in the direction of smoke ventilation. The maximum ceiling temperature will approach 2000°F.
2. The fire will burn for approximately 80 minutes
3. The velocity of the smoke layer will be approximately 1225 feet per minute.
4. The temperature in the tunnel on the exhaust side of the fire within approximately 1100 feet of the center of the fire will exceed 1000°F.
5. The temperature in the tunnel on the exhaust side of the fire will exceed 120°F within 3100 feet of the fire.

All people within the tunnel in these four scenarios will be in danger. People entering the tunnels and those in the tunnels behind the accidents 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. Those persons traveling through the tunnels ahead of the vehicles involved in the accidents may be able to continue driving to safety. Their vehicle speed will probably be greater than the speed of the advancing smoke layer.

Explosion Potential

The vapors from a spilled liquefied flammable gas or Class I flammable liquid present an explosion potential within a tunnel. This potential is present if the spill occurs without a subsequent fire to consume the vapors, allowing their accumulation within the tunnel. It may also occur after a fire is suppressed but before the available fuel is consumed or contained. The fuel remaining 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 using the methods presented in NFPA 68 - "Venting Guides" 1978 Edition. This pressure was found to be in excess of 15 psi for the Reference Tunnel. Appendix C of NFPA 68 also advises that flame speeds as high as 6000 feet per second and overpressures of several hundred psi could be expected should an explosion occur within a tunnel or similar contained space. Should flame speeds of this magnitude occur, the explosion would be a detonation because of the super-sonic flame speed.

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

EVALUATION: PREVENTION

Fire prevention and control has long dealt with the familiar fire triangle consisting of ignition, fuel, and oxygen, all three of which are required to support combustion. This triangle principle has been applied to this section on the prevention of tunnel fires.

Sources of Ignition

Highway tunnel fires invariably originate in the vehicles using the tunnel. Accidents, mechanical failure, and human error have all been sources of ignition in the past. Criminal or mischievous action and sabotage cannot be ruled out: the Squirrel Hill fire was reportedly a result of arson.

The number of accidents per vehicle-mile is apparently lower in tunnels than on the open road. Several reasons have been suggested for this:

- o Drivers are more cautious in tunnels.
- o Tunnels are generally straight or gently curved at most.
- o Tunnels are generally free of intersections and interchanges.
- o Tunnels are generally well-lit and often supervised.
- o Traffic is often slow and congested, reducing the opportunity for high-speed relative motion between vehicles.
- o Tunnel conditions and the points they normally connect are conducive to purposive transit and inhibit the casual driver.

Nonetheless, accidents do occur in tunnels, and when fuel or flammable cargo is exposed it often catches fire. The Nihonzaka and Caldecott fires were the result of multi-vehicle collisions and subsequent ignition of flammables. Isolated head-on collisions have been reported in tunnels in an abnormal two-way traffic mode, e.g. one tube closed for maintenance and all traffic diverted through the other. No notable fires resulted from these reported collisions. Rear-end collisions apparently do not involve sufficient energy exchange to cause damage resulting in a fire. The potential is there, however: the Queens-Midtown tunnel reports frequent rear-end collisions just outside the portal when traffic backs up through the tunnel.

A more common cause of vehicular fires is mechanical failure. Broken fuel lines and electrical faults ignite as often in tunnels as on open roads, as do brake and bearing failures. Breakdowns seem to be profile-sensitive: they occur more frequently in the uphill tubes at Eisenhower and Caldecott. The Massachusetts Turnpike Authority reports frequent carburetor malfunctions resulting in fires in slow-moving traffic on the uphill grades of their Boston Harbor tunnels. The Wallace, Chesapeake Bay, and Moorfleet fires were all definitely the result of mechanical failures; the Holland Tunnel fire could be considered the ultimate result of a mechanical failure in cargo tie-downs.

Human error or inattention have also contributed to both accidents and fires in tunnels. Passenger-compartment fires resulting from careless smoking or similar mishaps are a common occurrence. To a certain extent all accidents are the result of human error, but the opening incident of the Caldecott fire--the inebriated driver's collision with the tunnel wall and stopping in the left lane to inspect damage--must be attributed substantially to this driver's impaired reactions and judgement.

The evidence still indicates that sources of ignition only infrequently start fires in additional vehicles. The investigator elicited recollections of only seven significant fires in the history of vehicular tunnels in the United States. Such fires as do occur are usually confined to the passenger or engine compartment and are quickly extinguished without incident. Their occurrence is not random, however, and the pattern that has emerged, though faint, indicates certain actions can be taken to reduce the frequency and severity of these sources of ignition.

Sources of Fuel

Vehicles are fueled and lubricated by flammable liquids and will be for the foreseeable future. These fuels and lubricants and their residues will always be a source of combustibles in tunnels. Rubber tires are similarly both flammable and irreplaceable.

Cargoes and furnishings--upholstery, suitcases, personal effects, etc.--can also be flammable. As a result of the Holland tunnel fire in 1949, the Port of New York Authority (now called the Port Authority of New York and New Jersey) prepared a list of hazardous materials which should not be allowed in tunnels. The Port Authority was instrumental in having laws passed prohibiting transit of these hazardous materials through tunnels in States along the Eastern seaboard. They are the recognized leader in this effort to this day and periodically add hundreds of new materials to their list of proscribed materials.

Some substances explode, poison, toxify, or irradiate when spilled or disturbed, whether a fire is started or not. This first group of substances is not properly a subject of this study, but it may be said in passing that such materials should be denied passage if any alternate route or mode of travel is available.

A second group of substances herein called flammable liquids, but which also include certain solids, readily ignite from a momentary source, mild heating, or even spontaneously, and continue to burn thereafter. Such substances present an order-of-magnitude greater danger than a third group herein called combustible solids. Care should be taken: solid polyethylene pellets and creosoted railroad ties burned like flammable liquids at Moorfleet, Baltimore Harbor Freeway, and Nihonzaka.

Sources of Oxygen

Since fresh air is essential for the health and comfort of people in the tunnel, curtailing this supply as a preventive measure is clearly infeasible. Several actions concerning the fuel and ignition legs of the fire triangle are feasible, however, as discussed below.

Restrictions on Hazardous Materials

These restrictions serve to reduce the fuel available for a major tunnel fire. Several levels were identified.

- o Restricting flammable liquids and gases has been effective in preventing significant fires in the heavily-traveled eastern tunnels. Had the driver of the chemical truck complied with at least the present law, the Holland Tunnel fire would not have happened. The Moorfleet and Caldecott incidents would have been insignificant had flammable materials not been involved. The Nihonzaka facts are equivocal on this point, but the presence of flammable materials there no doubt contributed to the severity and burn time of that fire. The economic impact of a prohibition on the entire community should be soundly established through risk assessment studies of possible alternate routes before prohibition is implemented, especially if transit of such materials is now allowed.
- o Some tunnels prohibit combustible solids also. This adds only a marginal level of safety to a prohibition of flammable liquids and gases and of solid petrochemicals; it may be an uneconomical burden on the community if safe and convenient alternate routes are

unavailable. A load of newsprint which merely smoldered after four hours' exposure to the Holland Tunnel fire indicates many such substances present a small fire risk.

- o One tunnel has an established program of supervised transit of hazardous materials when the alternate route is blocked. Trucks are marshalled at the portals for inspection and periodically the tubes are cleared and the trucks sent through at safe intervals.
- o One tunnel prohibits hazardous materials during peak traffic periods. This has the obvious advantage of excluding them during a possibly high-accident period when damage and fatalities from a hazardous material fire could be high. Such periodic prohibitions should be based on statistical accident-rate studies and not on conjecture to assure that the prohibition spans the most dangerous intervals.
- o Some tunnels prohibit large quantities of liquid of any kind. Originally to prevent inconvenient spills, this policy has the subsidiary advantage of reducing the possibility of saturating the drainage and sump storage systems at a time when they might be needed to remove spilled flammable liquids.

Controls on Drivers' Actions

These controls serve to reduce the frequency of accidents and the resulting ignitions and of possible impediments to firefighting and life support systems.

- o Reduced speed limits bring more vehicles into the range where drivers have complete command of them, reduce the speed--and consequently the energy level--at which accidents may occur, and reinforce drivers' awareness that they are operating in a dangerous environment requiring greater care.
- o Prohibiting lane changing reduces the frequency of accidents.
- o Requiring trucks to drive in the right lane may reduce the anxiety of automobile drivers in a crowded tunnel and so reduce the number of accidents. It may reduce the number of car/truck accidents. It reportedly eases clearing of the tunnel. It is instituted primarily to prevent disruption of ventilation by large trucks stopping side-by-side in a tube, effectively blocking the flow of air.

Enforcement of Regulations

Restricting hazardous materials and placing controls on drivers' actions will be ineffective unless accompanied by vigorous enforcement. In general, the trucking industry and responsible drivers accept these restrictions and controls and do not knowingly violate them, but the occasional irresponsible or inattentive trucker or driver needs to be reminded or removed. Enforcement actions include the following.

- o Portal inspections to identify placarded vehicles carrying restricted materials or unplacarded vehicles suspected of doing so. Inspections also serve to glean vehicles with visible mechanical or other difficulties that might lead to stoppages or mishaps in the tunnel.
- o Random manifest and cargo checks are a necessary adjunct to visual inspections if portal checks are to be effective. Neither of these steps can totally prevent entry by misfeasant or criminal agents, however.
- o Overheight indicators prior to the portals serve to identify vehicles which will damage systems or structures within the tube.
- o Stationing tunnel personnel to observe and identify violators and either issuing citations at the scene or notifying cognizant authority for their follow-up is essential if either restrictions or controls are to be complied with. If physically in a position to do so, tunnel personnel should be empowered to issue citations for infractions they observe.
- o Operating agencies should pursue violators through the courts and prosecute to the fullest for similar reasons.
- o Operators should periodically update and revise regulations to assure fair and cost-effective management of the facility so that public confidence and cooperation can be maintained.

These enforcement steps cannot guarantee compliance, however. The Baltimore Harbor Tunnel issues over 100 citations per month to drivers violating the no-lane-changing rule, an apparent irreducible minimum of infractions, even if a small fraction of the tunnel's 66,000 ADT.

Designing with Safe Configurations

Several roadway features and profiles seem to enhance traffic safety and thus reduce the frequency of accidents and ignition sources. These include:

- o Avoiding sharp curves in the tunnel and its approaches. The Caldecott fire started in a collision on a blind corner.
- o Avoiding transition points such as exits or interchanges in the tunnel or near its portals. The Queens-Midtown Tunnel and the Deas Island Tunnel report frequent accidents caused by sharp curves and interchanges near a portal.
- o Providing effective lighting at the portals and within the tunnel. The Colorado Department of Highways reports a reduction in accidents in several shorter tunnels near Idaho Springs after additional lights were installed.
- o Providing interstate-standard lanes and overhead clearances for better visibility and emergency access.
- o Providing sufficient advisory messages for drivers to transition to tunnel conditions prior to entering the portals. Responses from operators of tunnels where roadway alignment or grades do not allow such an interval indicate a higher incidence of accidents at the tunnel portal, where drivers often imperceptibly slow.

Several other roadway features have been suggested which may or may not be advantageous in preventing fires. These include:

- o Adding shoulders to the roadway. While expensive, especially for subaqueous tubes, they provide space for disabled vehicles or for emergency access and an area for evasive action. They may also encourage pilfering or tampering with communication and fire suppression systems in the tunnel. Unless frequently cleaned, dirt and debris will cover them. Unless made a full lane wide they will not accommodate large vehicles, but if made a full lane wide they may someday carry traffic permanently, increasing the traffic flow by half but now without a shoulder whatever. In addition, tunnel shoulders may be used as a haven for sleeping drivers or as impromptu repair shops, thereby producing a more hazardous condition than a shoulderless roadway would present.

- o Exploiting driver phobia by reducing lane widths and imposing greater controls on drivers' freedom of movement. While brought forth primarily in response to the Caldecott fire because that tunnel operates under normal interstate highway regulations i.e., 55 mph and no hazardous material restrictions, an artificial policy such as this would not have prevented the mishap which led to that fire in any way. Some drivers are phobic in tunnels and their excessive caution presents a danger to unsuspecting motorists expecting a normal traffic flow. It is hard to construct a scenario where exploiting driver phobia would be an effective safety ploy.

EVALUATION: DETECTION/ALARM/NOTIFICATION

Paragraph 1-4.3 of NFPA 502-1981 states, "the primary need is a means for prompt and rapid notification to the authorities of the existence and location of an emergency and the development of effective means of traffic control." This need has been divided here into three subtasks: detecting a fire or potential fire, transmitting alarms to proper authorities, and notifying motorists of the situation and directing them to safety.

Detection

Once prevention has failed and a fire has started, early detection is the first step towards control. Several detection means were identified.

- o Personnel stationed in the tubes to monitor traffic have detected numerous fires. Tunnel monitors can also observe and assist at accidents to prevent their expanding.

The historical trend is away from manned tunnels. Originally police officers were assigned to tunnels and typically alternated two hours in the tube with two hours at some other duty such as toll collection. As uniformed policemen became unionized, demands for better working conditions were met by installing heated and air conditioned booths for monitors. In some cases, higher ventilation rates for the entire tunnel were demanded as a condition for stationing personnel in a tube. At least one operating agent, the Port Authority of New York and New Jersey, has substituted trained civilians for police officers. Manning has become increasingly expensive, however, so the manned intervals have been reduced to rush hours only, with TV camera monitoring from the control rooms sufficing at other times.

- o TV cameras are an effective substitution for personnel stationed in the tube. They must cover the entire tunnel, in sequence, at least.
- o Frequent transit by official vehicles, either police cruiser or tunnel service vehicle.
- o And finally, while not the best, drivers in transit can be made part of an effective detection system if supporting equipment is made available.

The effectiveness of TV monitoring systems is enhanced if traffic flow is also automatically monitored and attention drawn to the TV screens when an abnormal situation develops.

- o Magnetic loops connected to a computer have been used for such a task, but to be effective a traffic flow monitor must be sensitive enough to detect the stoppage of a single vehicle alone in the tunnel like that at Caldecott.
- o Doppler radar systems may serve such a role.
- o Discriminating audio pickups able to identify a change in the level or frequency distribution of tunnel noise identified as abnormal may be possible in the future.
- o Discriminating visual pickups able to recognize abnormal rates of change in the size of objects as evidence of stoppages may also be possible.
- o High technology systems such as these will no doubt require computers; computer-based control of all tunnel systems will eventually become the norm.

Automatic fire detection seems to have been universally rejected. Several systems were mentioned during the investigation.

- o Combustion product (smoke) detectors and flame (UV) detectors are unreliable in a tunnel environment and subject to too many false positive activations, from vertically-discharged, hot truck exhausts, for example.
- o High temperature sensors either lack sensitivity or are similarly prone to false positive activations.
- o Fan discharge smoke detectors were reported in three instances.

- o Detectors activated the sprinklers at Nihonzaka, but the effectiveness of this total system is called into question elsewhere in this report under Sprinklers.

Several urban interstate tunnels, merely covered portions of freeways, are essentially unmonitored and without effective fire detection systems. The risk of a major hazardous material fire in these tunnels is correspondingly high.

Alarm

Rapid transmission of alarms from the fire scene to the proper authorities is the second step in effective control. Some of the systems covered below under Communication are especially effective alarms.

- o Emergency telephones should be clearly marked, accompanied by simple operating instructions, and location-coded so the control room can identify the caller's position. Volume and sensitivity should be adjusted so the caller can understand messages in a noisy tunnel.
- o Fire alarm pullboxes, either buttons to push or levers to pull, should be located beside each telephone. Where these alarms were connected directly to the fire department, they have typically been removed because of patrons using them to summon routine assistance. If possible, then, these should connect to a control room and augment a surveillance system. In such a case, labeling the device "HELP" and its proximity to the emergency phone should encourage direct communication between driver and operator.
- o CB radio pickup antennas in the tube and signs prior to entry noting their presence could exploit this common vehicle system. Multiple antennas and fire-safe cable installation may be more effective in an emergency than a single wire, which is often burned away in the opening moments of a fire.
- o A direct link between tunnel control room and fire department dispatcher, either radio or land line, is faster and more failsafe than a dial phone. False alarms and trouble calls are eliminated; confirming call-backs will not be required.

Notification

Motorists in the tunnel must be notified of an emergency and directed in the interests of their safety. Appropriate systems for this task are listed below.

- o AM radio rebroadcast, on selected or popular stations can reach those whose AM radios are ON. FM radios cannot be reached with current technology and full radio-spectrum broadcast seems to attenuate signals below reasonable transmission power levels. FM rebroadcast will no doubt be possible in the future. Some systems rebroadcast pre-recorded messages on the three or four most popular local AM stations. The fidelity of, and the immediate credibility given to, a voice on a commercial radio broadcast should be kept in mind when evaluating an AM system vis a vis other possible choices. There are firms which will install a broad-band rebroadcast system if given rights to broadcast commercial announcements to the tunnel-driving audience.
- o CB radio broadcasts reach a limited but potentially important segment of tunnel occupants.
- o Traffic lights in the tunnel and at the portals in accordance with NFPA 502 are widespread. Red lights stop traffic approaching a mishap; yellow lights or arrows caution drivers already past it or direct them into a single lane to allow access for emergency vehicles.
- o Variable-message signs are common but also widely disparaged by operators as liable to be ignored by drivers. They certainly lack the content and credibility of AM rebroadcast.
- o Personnel in tunnel, as before, are the best but most expensive source of instructions to motorists.
- o Personnel at portals have been consistently noted as necessary for positive halting of traffic. At Nihonzaka vehicles entered the tunnel despite portal warnings on variable message signs.
- o Psychologically effective but physically soft barriers such as inflatable traffic bumps, inflatable plastic tubes everted from the roadway, ribbons dangled from an overhead sign, or a smoke generator above the portal to give the illusion of danger but not induce panic stops, obscure vision, or cause damage if contacted may be more effective than signs and less expensive than portal monitors not already present for inspections.
- o Warning signs should be placed in several locations well prior to the portal to help prepare motorists for a stop.

- o Loudspeakers have been installed with some success, but many operators report low reliability and low fidelity because of poor acoustics in noisy, confined tunnels with no sound-absorbing surfaces.

EVALUATION: RESPONSE

Having detected a fire and transmitted necessary alarms, a quick response in bringing limited control and extinguishment systems available into action is essential if minor fires are to be contained and if rescue efforts are to be successful. Appropriate responses at the time of an emergency demand prior planning and training and should include a Fire/Emergency Plan, close liaison with local fire departments, and appropriate tunnel-owned equipment.

Fire/Emergency Plan

Tunnel authorities should prepare and distribute a Fire/Emergency Plan in concert with local law enforcement, fire protection, and emergency preparedness organizations.

- o The nature and capabilities of tunnel systems should be described.
- o Tunnel organization and staffing should be described, along with names and numbers to call in case of mishaps.
- o Normal and emergency operating procedures should be described.
- o Dutiful, comprehensive lists of credible mishaps e.g., "disabled auto, no fire," or "ruptured gasoline tanker in rush-hour traffic," should be prepared.
- o The most effective response should be developed for each mishap.
- o The plan should specify a recommended direction of response either with-traffic, against-traffic, or through cross adits, for each mishap.
- o Primary and secondary approach routes should be mapped from each firehouse to each portal. Transit times should be determined for several traffic conditions and noted.

This plan should reference or include:

- o a Drainage Plan.
- o a Ventilation Plan.
- o a Traffic Control Plan.
- o a Rescue Plan.

It should include provisions for dissemination among those who may be called upon to respond professionally to emergencies. Finally, it should include provisions for its own periodic review and update.

Fire Department Liaison

A Fire/Emergency Plan is but the first step in establishing and maintaining an effective relationship with local fire departments. Effective liaison also requires

- o Familiarization tours for new employees of both organizations.
- o Frequent practice sessions if responses to actual emergencies are not routine occurrences. All tunnel systems, both primary and emergency, should be exercised during these sessions to promote familiarization and proper maintenance.

Both parties must be familiar enough and in agreement with the Fire/ Emergency Plan so that the nature of a mishap can be succinctly described and appropriate apparatus and manpower dispatched to the scene.

Fire department vehicle access to a tunnel's approaches separate from the normal roadway, such as special ramps and segments of knock-down fencing, should be provided so that congested traffic cannot impede an otherwise rapid response.

Tunnel Personnel and Vehicles

If alarms are to be effective they must convey accurate and sufficient information to those who will respond. This places great emphasis on adequate surveillance, detection, and communications systems so that inaccurate or counterproductive information is not transmitted. It also emphasizes a need for an operating staff organized and trained to take charge during an emergency and direct the actions of both the public and responding professionals. Groups which may respond and whose strengths and weaknesses need to be understood and accommodated include:

- o Non-professional drivers, especially if they live in the community and frequently use the tunnel, often extinguish fires before professional assistance can arrive. This is reported more from large urban

centers--Boston, New York, Pittsburgh, Oakland--than in remote areas where the patron is more likely to be a traveler. These drivers are often willing and able but unfamiliar with systems and so require instructions, as was the case in the Nihonzaka fire.

- o Professional drivers--truckdrivers and the like--are reportedly more knowledgeable, better equipped, i.e. with their own fire extinguishers, and quicker to respond than private motorists.
- o A tunnel monitor may be solo, so his ability to enlist and organize bystanders to help or to escape may be crucial.
- o Tunnel maintenance personnel trained in fire control with properly-equipped emergency vehicles have been nearly as effective as professional fire companies, and reach the scene much more quickly at remote locations.
- o The presence and assistance of state or local law enforcement officers responding to an emergency, as happened at the Chesapeake fire, cannot be discounted and reiterates the need for wide dissemination of the fire/emergency plan.
- o The services of professional fire fighters are indispensable at more serious fires.

NFPA 502 definitively describes a recommended tunnel vehicle in paragraph 3.2.1: "Apparatus should be designed for double-end lifting operation and equipped with 'dollies' for towing disabled vehicles from the tunnel. The apparatus should carry a potassium bicarbonate base dry chemical/AFFF (foam) or a similar self-contained fire fighting system and/or means to obtain water from a standpipe system. It should also carry portable extinguishers, complete self-contained breathing apparatus, cutting torches, forcible entry tools, hose, chains, coffin hoists, tarpaulins, and other appropriate hand tools." Since delicate tunnel lighting systems often fail in a fire, vehicles designed to respond to one must have directable spot and floodlights.

The synopses of study interviews show that six (remote) tunnels meet the fire protection requirements of this paragraph with full-sized fire trucks. Ten others report "Holland Tunnel standard" short-wheel-base emergency vehicles. At least eight have no fire-protection-equipped vehicle at the tunnel at all.

Some tunnel fire-protection vehicles carry provisions for foam. While not mentioned in NFPA 502, if the first response by tunnel personnel and vehicles is to have any chance at all of controlling fires as large as Holland and Caldecott, dry powder and/or provisions to obtain water from a standpipe system will by all indications not suffice. AFFF (foam) would have a chance of knocking down such a fire and controlling it until the fire department arrived.

If possible, at least one tunnel employee, the supervisor for each shift or the senior official during the day, should be qualified and empowered to direct the efforts of firefighters, or at least act as a technical consultant to the chief in charge at the scene. Many interviews reveal a willingness to abdicate control of all tunnel system operation and of rescue efforts to the arriving fire department, who may be unfamiliar with the systems and their capabilities, need time to appraise the situation, and be fixated on building firefighting techniques inappropriate to tunnel fires.

EVALUATION: CONTROL/EXTINGUISHMENT/SUPPRESSION

Several tunnel systems were suggested or in fact serve to control fires. These are fire extinguishers, stand pipes, and sprinklers, with their ancillary systems of water supply and drainage.

Fire Extinguishers

Quick response and maximum reliance on drivers in the tunnel continue to be important principles of tunnel fire control. Fire extinguishers placed in niches along a wall have proved to be an effective way to apply these two principles. No less than 31 of the tunnels studied provide them; only three do not, and because of pilferage not ineffectiveness. NFPA 502 recommends 20 pound dry powder extinguishers 300 feet on center. This may or may not be the optimal solution to the following criteria.

- o Type. Because rekindling is always a possibility with CO₂ extinguishment after the gas has dissipated and oxygen balance is restored, its coating effect makes dry powder the professionally recommended filler for the fires normally encountered, but some operators avoid it in favor of CO₂ because the latter requires no cleanup, does not damage vehicle components when applied, and, they believe, will involve them in less litigation. This aversion seems to be regional and may date from some isolated incident.

- o Weight. The capacity of the fire extinguisher should be balanced against its need to be carried some distance by perhaps sedentary private citizens. Two smaller ones may be more desirable.
- o Spacing and positioning. Spacing should be determined by the stamina expected in the most likely user. The elapsed time to travel some extra distance may be a minor consideration when compared with the exhaustion of that sedentary motorist after having run the extra distance, half of it carrying 25 pounds. Niches should be accessible from road level if possible to relieve the need to clamber up on a catwalk to retrieve an extinguisher. In multi-lane cut-and-cover tunnels where traffic flow may continue past a minor fire, extinguishers should be placed along both walls.
- o Familiarity. Fire extinguisher niches should be conspicuous. Simple instructions should be displayed at the niche and on the extinguisher. Keeping in mind the non-professional user, extinguishers should be as close to "point and shoot" as possible.
- o Security. Pilferage is a possibility. Premeditated theft-for-profit is probably beyond prevention but should seldom occur; malicious mischief may be diminished by niche doors marked with the standard "Alarm sounds when door is opened." Such alarms may indeed be a useful adjunct to other alarm systems. Any effective monitoring system will enable tunnel operators to observe and apprehend the miscreants if an alarm is actually installed. "Black Ebony" plastic doors have served effectively to protect fire extinguishers from the tunnel atmosphere and cleaning solutions.

As with all these systems, a cost/benefit analysis using expected accident/fire rate, expected traffic level, expected efficacy of niche extinguishers, expected availability of privately-owned extinguishers on vehicles in the tunnel, expected pilferage rate, and the expected repair and actuarial costs of either providing, maintaining, and replacing or not providing niche fire extinguishers should be carried out before a decision is made.

Stand Pipes

Fire lines and hydrants or hoses are also a common fire control system in tunnels. They are not often so used, however; only three respondents report having used a fire line for fire control: Holland, Caldecott, and Nihonzaka. These were, of course, the major hazardous material fires. Smaller fires are universally extinguished by other systems.

Only at the Holland Tunnel fire was the fire line particularly effective. At Caldecott the line or its hydrants suffered too much damage from the fire for it to deliver usable quantities at appropriate pressures. Because the hose lines at Nihonzaka were not activated early in that emergency, their early effect remains untested. Apparently the line was used in the later stages of the control effort, but the fire never was effectively controlled.

NFPA 502 recommends a capacity of 1000 gallons per minute (3800 L/Min) at 20 psi (140 kPa) minimum with conspicuous hose connections 300 feet (90 meters) on center maximum. Again, this may not be the optimal solution to the following criteria:

- o Capacity. 1000 gpm will allow four 2½" hose streams from a single fire main. Four such streams may be superfluous, especially if foam is available. 500 gpm for two 2½" hose streams per fire line may be cost effective, especially if cross-adits allow hoses to be led from other fire lines in the facility. A residual of 75 psig at the hose valve is required to guarantee the minimum of 65 psig nozzle pressure needed to develop cooling spray from combination nozzles.
- o Hoses. Several operators report dissatisfaction with the lifetime of linen hoses and have installed polyethylene. The 2½" hoses effective in the hands of professional firefighters may be ineffective or dangerous in the hands of private citizens. For this reason the more common practice is to remove hoses from the tunnel and carry them on vehicles.
- o Compatibility. Hydrants should be compatible with local fire department equipment.
- o Survivability. Fire lines and hose connections should be protected from the heat and blast of the most serious credible fire considered controllable. The line itself should be supplied from both ends and sectionalized with shutoff valves to facilitate repairs while maintaining service and to allow isolation of damaged portions where leaks may degrade the capacity of undamaged sections.
- o Freeze protection is required in colder climates, since ventilation will hold the tunnel temperature always near ambient. Dry lines are acceptable, since this system is not required for immediate response. One tunnel has set the supply connection for its dry line convenient to a city fire hydrant. Dry stand pipes can require as much as 5 minutes or more to fill, and this delay should be accommodated in the fire/emergency plan.

Although seldom used to control a fire, stand pipe water is frequently used to wash down accident sites and for normal cleaning.

Sprinklers

Sprinkler systems are highly regarded by fire protection professionals and fire departments because of their long successful history: it has been claimed that no life has ever been lost in a sprinklered building. Nonetheless, it does not appear that sprinklers are an effective fire control system in vehicular tunnels. To understand the reasons for this, the advantages of building sprinklers must be outlined.

Building sprinklers are automatic and relatively fast-acting for unoccupied spaces. They are failsafe both positively and negatively: the fusible links cannot survive above their set temperature but seldom open at room temperatures. Water flow can activate an alarm. A limited water spray is often effective in suppressing Class A fires in offices and warehouses until firefighters arrive. Freezing is seldom a problem, neither is the time delay required for activation of a pressurized dry pipe system. Occupants of sprinklered buildings are seldom taken aback by the spray when a fire is present. Their safety is not impaired, but is enhanced. Reduced insurance premiums usually finance a building's sprinklers.

Vehicular tunnel conditions cannot exploit sprinkler system strengths and turn most of them to a disadvantage. Tunnels are very long and narrow, often sloped laterally and longitudinally, vigorously ventilated, and never subdivided, so heat will normally not be localized over a fire. A dangerously-large, hazardous material fire will grow and spread hot combustion products far from its origin before sprinkler heads open, especially in colder regions where the system is by necessity a dry one. An inordinately large flow of water would be required to deliver an effective spray through all the possibly-open heads to assure application on the fire itself.

Automatic activation of the sprinklers by active detectors would of necessity have to be delayed until all traffic could be halted, since even light spray would catch drivers unaware, would be more than wipers could clear even were they ON, and would dangerously slicken the roadway. Water squirting from the ceiling of a subaqueous tunnel would suggest tunnel failure and induce panic in motorists. Inadvertent activation is clearly unacceptable.

Small fires are usually under vehicles, or inside passenger or engine compartments designed to be waterproof from above; overhead sprinklers would have no extinguishing effect. Unless quickly and completely extinguished at their source,

flammable liquid fires would continue to burn atop the sprinkler outwash. Drains, sumps, and sump-emptying pumps would have to be designed and sized to safely dispose of huge quantities of this burning mixture.

Logic dictates, and the Nihonzaka fire experience and Ofenegg study results support, that a thin spray on a very hot fire, if any delay at all between ignition and activation is interjected, will produce large quantities of superheated steam without materially suppressing the fire. The Ofenegg project found this steam to be more damaging than the comparatively well-behaved smoke. Spray away from the fire is not only wasted water but will tend to disturb any stratification of smoke and lifesaving fresh air that may have been established. The Nihonzaka narrative and the Ofenegg sprinkler tests suggest that sprinklers can only partially suppress a hazardous material tunnel fire without human intervention at the site, which means that firefighters must be active at the scene before the sprinklers consume all the water or are shut off. Otherwise, explosive fumes propelled through the tunnel and ventilation system may be reignited by unextinguished ignition sources or hot surfaces.

A sprinkler system that will not exacerbate a minor emergency nor impair fire control and rescue must meet the following design criteria.

- o It must be a deluge system zoned into optimally-sized networks so that the water supply available can produce an effective spray from all heads in two adjacent zones (in case a fire starts at the interface). It must be dry pipe where freezing could occur.
- o It must be manually activated, either at the site or preferably from the tunnel control room.
- o If centrally controlled it requires an effective surveillance system so that the attendant can locate the fire, ascertain that sprinklers are appropriate, and assure that traffic has stopped before activating a zone.
- o It requires a drainage and sump system adequate to dispose of expected volumes of outwash.
- o It requires an adequate water supply to maintain flow until firefighters can reach the scene and deploy directed hose streams at remaining ignition sources and hot surfaces.
- o It should apply AFFF solution for at least the initial five minutes of operation to seal flammable liquids until they can be flushed away.

Water Supply

Where possible, tunnel stand pipes should be connected to or, in the case of dry pipes, be connectable to municipal water systems. If no municipal system is available, sufficient water must be stored at the site or be obtained from dependable natural sources. NFPA 502 recommends a supply sufficient for 30 minutes flow at a recommended minimum flow rate of 1000 gal per min (3800 L/min), i.e., a minimum of 30,000 gallons (114,000 liters).

This may be excessive or insufficient. At Nihonzaka 86 minutes of sprinkler application consumed all 40,800 gallons (155,000 liters) without controlling the fire. On the other hand, water that will never be required to control a credible fire is unwarranted. Since water supply is an integral part of a complete fire prevention and control system, an adequate volume for the worst credible fire should be calculated as part of new tunnel design and the cost of providing this volume be used in the optimization of the complete fire protection design. An automatic foam system with its smaller water requirement may be safer and less expensive than a complex sprinkler system or stand pipes alone with their larger requirements.

Drainage

Adequate drainage is important to fire prevention and control in three ways: it helps maintain a safe roadway for traffic, thus reducing accidents and ignition sources; it safely and rapidly removes flammable or burning liquids washed from the roadway after an accident or during a fire; and it safely stores or disposes of hazardous liquids without catching fire itself. An adequate tunnel drainage system should meet the following criteria:

- o Wherever possible, the roadway should be crowned, not sloped in a single direction so that wash water or spent cleaning solution does not have to flow across traffic to find its way to a drain.
- o This necessarily requires drains on both sides of the roadway.
- o Rainwater entering downslope should be intercepted by cross-lane gratings inside the portal. Similar gratings should be placed at intervals on any long slopes to prevent liquids from running long distances downhill.
- o Access for cleaning is required for both scupper or catch basin systems.

- o Openings should be screened to prevent clogging. Several operators report chronic stoppages from beer and beverage cans and from styrofoam cups.
- o Scuppers or drain lines must be adequately sized to carry away the largest credible normal flow, from tunnel cleaning for instance. A gravity-induced flow of the possible 1000 gpm flow from sprinklers or hose streams is probably unattainable over useful lengths, since a 10" line is required on a 1% slope to remove this quantity.
- o The outlet may be required to comply with environmental guidelines on both new construction and existing tunnels.
- o Consequently, holding tank and diversion valves may be required. Their flow and volumetric capacity should accommodate the largest credible hazardous liquid spill, that is, the largest volume normally allowed transit.
- o The same volumetric requirements apply to low-point sumps.
- o Pumps handling any potentially flammable liquids must be explosion-proof (NEMA 7D); sump rooms should be gas-tight if escaping vapors can reach nonexplosion-proof electrical components.
- o Mid-point sumps should have discharge lines to the portals to eliminate truck transfer in mid-tunnel.

EVALUATION: SURVIVAL

Since fires of some kind are to some extent inevitable, vehicular tunnels and their systems must be designed and operated to maximize the life safety of tunnel patrons when a fire occurs and of firefighters who may be called upon to enter either for extinguishment or rescue. The systems covered here, communication, ventilation, lighting, and escape, primarily support the comfort and well-being of persons in a tunnel during normal operations, but their functions during emergencies are critical.

Communication

Important features of this system have been covered under Alarm, Notification, and Fire/Emergency Plan. It is given a more comprehensive treatment here. Several parties have a stake in this matter of communication: the operating agency, the control room staff, maintenance, monitoring, and inspec-

tion personnel, legislative bodies, governmental agencies, transportation industry associations, the general public, motorists approaching the tunnel and those in transit within it, motorists who have left their vehicles in an emergency, tunnel-affiliated or local emergency vehicles responding to an emergency, law enforcement agencies, emergency preparedness agencies, fire departments, and emergency personnel on foot at an accident or fire.

The tunnel operating agency, as a recipient of public funds and a holder of a public trust, should establish and maintain communications with the following:

- o the general public to gain their confidence and cooperation and to disseminate general procedures useful to them in an emergency. News releases, public affairs broadcasts, and magazines are appropriate media.
- o transportation industry associations to elicit their input to regulations and operating policies and to gain their cooperation in enforcement efforts.
- o government agencies, both federal and local, such as state highway departments and the Federal Highway Administration to provide practical operating experience as input and to take part in ongoing professional efforts to enhance tunnel safety.
- o legislative bodies to inform them of existing problems and to lobby for effective legislation where required.
- o law enforcement, emergency preparedness, and fire prevention agencies to prepare and disseminate an effective fire/emergency plan.
- o the tunnel operating staff to foster and maintain morale and a proper state of preparedness and training.

The tunnel control room staff needs communications channels of a more immediate nature with the following:

- o motorists approaching the tunnel to apprise them of conditions and any abnormalities for which they should prepare.
- o motorists in transit within the tunnel, again to apprise them of conditions and relay appropriate instructions or admonitions.
- o maintenance, monitoring, and inspection personnel to receive information, issue instructions, and coordinate efforts when required.

- o law enforcement agencies to report infractions and request assistance.
- o fire department dispatchers to summon apparatus and manpower in case of fire.
- o tunnel-affiliated or local emergency vehicles responding to an emergency, also to receive information, issue instructions, and coordinate efforts.
- o motorists who have left their vehicles in an emergency, to receive requests for help or information concerning events or conditions which they observe and to relay information or instructions to them.
- o fire department and emergency personnel on foot at an accident or fire, again to receive information, issue instructions, and coordinate efforts.

The fire/emergency plan should establish, and equipment should be available to facilitate, a radio communications network operable within the tunnel and from there to at least the control room to establish a link with the outside world. The complete communications system should also include as a minimum:

- o emergency telephones in the tunnel.
- o variable message signs both within the tunnel and prior to the portal.
- o an effective surveillance method.

Other presently-effective subsystems previously mentioned include:

- o fixed-message signs.
- o CB radio pickup antennas.
- o AM radio rebroadcast with pre-recording and supervisor override capabilities.
- o traffic lights.
- o personnel in the tunnel.
- o posted operating instructions for tunnel systems likely be used by private citizens.

The survivability of all systems during a fire should be the prime consideration in their design, selection, and installation.

Ventilation

Ventilation is normally provided to dilute noxious fumes and to maintain a clear atmosphere within a tunnel. The types of controls, fans, and other components, the most effective arrangements, and the tolerable levels of pollutants for normal operation are well documented in existing standards and in accepted practices. On the other hand, criteria for effective operation during a fire are not defined in any document. The recommended minimum installed capacity of 100 CFM per foot of lane of emergency capacity put forward by ASHRAE's Technical Committee TC5.9 on "Environmental Control of Enclosed Vehicular Facilities" in Chapter 13 of the 1982 Applications Handbook now serves as the sole emergency criterion.

There are no criteria regarding components, arrangements, or modes of operation to guide tunnel designers towards a ventilation system that could enhance life safety, reduce damage, and facilitate control efforts during a fire emergency. Consequently, only those modes inherent in a ventilation system designed solely to dilute vehicle emissions to tolerable levels and maintain a clear atmosphere have been available during emergencies. Depending on tunnel geometry and other factors not taken into account during ventilation system design, an otherwise adequate system will most likely provide less-than-satisfactory service during a fire.

The Ofenegg, Heselden, Feizlmayr, and Nihon Doro Kodan studies all indicate that a ventilation system can be an asset during a fire if appropriate capabilities have been incorporated in its design and if it is operated to exploit these capabilities. The Holland Tunnel and Chesapeake Bay fire summaries confirm this, as do the Wallace and Caldecott fire summaries in an obverse sense. These sources, especially Heselden's theoretical work and Nihon Doro Kodan's scale model and full-sized tunnel tests, indicate that the following features constitute appropriate criteria for a ventilation system fire/emergency design and operating mode.

- o It must be possible to stop longitudinal airflow as soon as possible after a fire is detected. Traffic normally induces a piston-effect longitudinal flow which can persist even after traffic has halted.
- o A vigorous exhaust must be extracted from a point as close to the fire as possible in sufficient quantity to induce a flow of at least 1000 feet per minute over the roadway cross sectional area from both directions.

- o Maintaining stratification of smoke and fresh air is imperative for the survival of any persons trapped below the smoke. Supply from other than curb-level ports will induce turbulence in the traffic space and impede any tendency towards stratification, while supply air introduced at the curb will exploit the thermal energy of a fire to encourage a smoke-free layer at the road level.
- o Exhaust path components must continue to operate in the presence of combustion products above 1000°F for substantial periods.
- o Controls and actuators must have sufficient flexibility, reliability, and responsiveness to enable a controller to establish the above conditions.
- o Fire detection systems must have sufficient sensitivity to allow a controller to recognize and locate a fire and to initiate an appropriate response to it.

A ventilation system designed in accordance with these criteria will confine the heat and smoke from a fire, and thereby limit the danger area, to the area between the fire and the extraction point or points. This area will be filled with smoke, however, but proper selection of extraction point should allow motorists to escape and firefighters to approach and control a fire.

The reversible, semi-transverse, supply-only ventilation system installed in the Amikake tunnel in Japan was specifically designed to incorporate these criteria. Opposed-blade dampers control the normal flow of air through large ceiling ports approximately 300 feet on center to produce a uniform supply along the tunnel. Four supply fans, two at each end, supply a duct divided at its midpoint by a bulkhead with a normally-closed damper. Detectors only 12 feet on center throughout the tunnel automatically switch the system to its emergency mode in case of a fire. The ceiling port closest to the fire is fully opened and all others are closed. The bulkhead damper is opened and the supply fans reversed to extract smoke through the one open port. This same situation was unintentionally produced during the Holland tunnel fire after the ceiling collapsed at the fire site and the exhaust fans were accelerated to maximum capacity.

The design of future ventilation systems for highway tunnels should include provisions for a smoke-extracting fire/emergency mode employing motorized dampers in large ceiling exhaust ports approximately 300 feet on center. While providing satisfactory normal air extraction for removal of vehicle exhaust emissions with all dampers held at their balanced

position, during a fire the full capacity of the exhaust fans would be drawn through the port nearest the fire, or through two ports bracketing the fire, all others being driven closed. If fans, ducts, and dampers are properly sized to induce a flow of at least 1000 feet per minute across the full roadway from both directions towards the fire, the smoke will be effectively removed.

Operating in the smoke-extracting, fire/emergency mode in the 528 ft² reference tunnel requires 1,056,000 CFM of ambient air. This volume will increase fourfold in a fire, to over 4 million CFM of combustion products at 1500°F. If installing fourfold fan capacity is to be avoided, combustion products must be cooled. A water spray upstream of the exhaust fans cools the flow and reduces its volume, but at the same time increases the volume with added water vapor. 440 gallons per minutes of 50°F water will cool the exhaust from 1500°F to 600°F while reducing its volume to 2,200,000 CFM. The water will add 156,000 CFM of steam to the exhaust for a total flow of about 2,400,000 CFM.

Additional water can reduce temperature and total volume further to 212°F and 2,000,000 CFM, but water requirements are increased nearly sixfold to 2,760 gpm. Two hours of deluge would vaporize 53,000 gallons of water, which, at a remote site, would require that much additional storage.

All active and passive components should be capable of withstanding temperatures of 1000°F. Fan motors, drives, and bearings should be placed outside a potential exhaust pathway. Exhaust gases should be positively vented to the outside of any buildings and in a safe direction.

This recommended system would impose extra construction and maintenance costs and is more complex than typical existing systems. Regular maintenance and testing would be required to maintain the system in an acceptable operating condition; training and practice would be required to keep tunnel operators ready to employ the system in an effective manner during a fire. Although more complex than other similar dampered systems featuring flaps, springs, and fusible links, the recommended system is preferred because it can be periodically tested and exercised, has a quicker response, and allows the tunnel operator more positive control in the event of a fire. Cost benefit analyses should be performed to determine if these extra costs are less than the expected costs of damage, liability, and loss of a vital transportation link resulting from a major hazardous material fire which, as has been demonstrated above, cannot be absolutely prevented.

Several systems, either installed or contemplated--aside from their effectiveness during normal operations--show little capability of satisfactory operation during a fire/emergency. Ductless longitudinal systems with ceiling-suspended booster fans to augment traffic-induced flow can make no effective response to a fire. They have no extraction capability. Hot combustion products would no doubt completely fill the tunnel downwind of a fire. Fans enveloped by these products would be destroyed. Conditions and damage downwind of the fire would be similar to that in the Caldecott tunnel.

Supply-only longitudinal systems with reversible fans have two shortcomings: overall longitudinal flow cannot be stopped as long as fans are running in either direction, and exhaust capacity is typically 70% of supply capacity when axial fans are reversed. Such systems cannot contain the smoke and fumes of a fire in any area and indeed may draw it toward trapped motorists. Incorporating an oversized exhaust fan to which flow can be shunted during an emergency does not solve the problem of longitudinal flow, since combustion products are extracted through supply ports balanced for uniform flow.

Semi-transverse systems with air uniformly supplied from a duct parallel to the roadway can be converted to the recommended smoke extracting system if air is supplied at the ceiling. Reversible axial fans or shunted centrifugal fans can extract the smoke in the fire/emergency mode and properly sized and spaced dampers can be installed in the ceiling, along with appropriate detectors, controls, and actuators. If this system introduces air at a low level, conversion to an extraction mode should not be attempted, since low level extraction will draw smoke and heat to the roadway in an ineffective and unsafe manner.

Existing fully-transverse systems with low-level supply and ceiling-level exhaust ports, operation at full exhaust capacity during a fire can approach the effectiveness of the recommended system if sufficient exhaust capacity is available, although combustion products will be gradually extracted and thus will extend great distances along the tunnel from the fire. Conversion to the recommended smoke extraction system may not be justified in this case. Regardless of the position of the supply duct, either above the ceiling, behind a side wall, or under the roadway, if air is delivered low into the traffic space then supply at a reduced rate will help maintain stratification and provide a supply of fresh air at the roadway level. If supply air is introduced anywhere but at curb level, then supply fans should not be operated during a fire, since the supply air will blow heat and smoke to the roadway level, endangering any persons seeking refuge there.

In all these systems, either new or modified, it is imperative that gross longitudinal flow be halted in favor of positive flow towards a fire from both directions. A longitudinal flow as low as 5 mph will carry smoke past an exhaust duct to contaminate other areas of a tunnel. Systems which continue to produce such a flow are better shut down during a fire than left on to prevent the creation of conditions similar to those downwind of the Caldecott fire.

An analysis was made of an extraction system where large operable dampers or burnout panels are installed 300 ft. on center in addition to the normal exhaust system having uniformly spaced ports balanced for even extraction rates. Only the dampers or panels nearest a fire would open wide; all other dampers would remain closed with normal ports remaining open. Volume extracted through the open damper or panel is dependent upon its distance from the exhaust fan and never far exceeds 50% of total exhaust volume. It would be as little as 25% of total exhaust volume if the opened damper or panel was the farthest from the fan. This would be an inefficient use of the available fan capacity, since significant exhaust is drawn through the normal ports where no exhaust is desired in a fire/emergency. In cases where the fire is near the portal, this will produce a residual longitudinal flow, the very thing to be avoided. Consequently, a new design should include positive and selectable opening and closing.

Lighting

Sufficient and well-designed lighting systems incorporating proper entry and exit intensity transitions, subdivided circuitry, and assured supply sources reduce accidents and ignition sources and in this manner contribute to fire safety. Once a major hazardous material fire has started, however, normal lighting has little effect. Ceiling-level lamps will be obscured by smoke, so any effort or expense to make them heat-resistant has no life-preserving value.

The same is true for lighted emergency markers for fire extinguishers and stand pipes; if this equipment isn't found in cool, fresh air, the time for its use has passed.

If fire-resistant emergency lighting is to be installed it should be at curb level and in some manner--arrow-shaped lenses perhaps--indicate the direction to the nearest escape.

Escape

Emergency exits, either cross-tube adits or access to ventilation shafts, should be provided at reasonable intervals. Doors should be fireproof and reasonably gas-tight. The entry/exit areas should provide a safe haven in the opposite tube for persons escaping a hazard, that is, a walkway or recess out of the traffic. If not, the adit itself should be lighted and ventilated to provide life support until rescue arrives. Use of the adits should be encouraged in any case, since opposite-tube traffic may be light and will soon be stopped during a major emergency.

Doors should be marked "FIRE or EMERGENCY EXIT," and frequent arrows should point the direction and distance to the nearest such door. The doors should be at normal sidewalk level if possible to afford easy access for a large portion of possible patrons. Such adits served well in the Holland Tunnel Fire. They were also present in the Caldecott fire, one within 100 feet of several victims, but went unnoticed.

Estimated Fatalities with Unrestricted Hazardous Materials

As derived above in RISK ANALYSIS, a reference tunnel two lanes wide and one mile long will suffer one hazardous material fire every 220 years. The evidence presented there indicates a symmetrical danger zone, in which temperatures exceed 120°F, will extend 1550 feet on each side of the fire. To estimate fatalities a vehicle spacing of 100 feet on center and an occupancy of 2 persons per vehicle has been assumed, with no significant escape potential.

Per accident and study-wide fatality rates can then be calculated as follows:

$$(2 \text{ lanes}) \times (1550 \text{ feet/lane}) / (100 \text{ feet/vehicle}) = 31 \text{ vehicles}$$

$$(31 \text{ vehicles/accident}) \times (2 \text{ victims/vehicle}) = 62 \text{ victims/accident}$$

$$(62 \text{ victims/accident}) / (220 \text{ years/accident}) = .28 \text{ victims/year}$$

Each reference tunnel--each one mile length of two-lane tube--will suffer one hazardous material fire every 220 years; approximately 62 persons will be killed, a fatality rate of .28 fatalities/year, if hazardous materials are allowed transit and no actions to reduce the open-road accident rate or fire response time are implemented.

The 35 tunnels included in Appendix A have a total of 296,614 feet of two-lane tube, or 56.2 reference tunnels. The best estimate of their aggregate fatality rate for unrestricted hazardous material transit is

$$(220 \text{ years/accident}) / (56.2 \text{ tunnels study-wide}) = 3.9 \text{ years/accident}$$

$$(.28 \text{ victims/year-tunnel}) \times (56.2 \text{ tunnels}) = 15.7 \text{ victims/year.}$$

For the reference tunnel the probabilities of actual fatalities in a year can be calculated using the Poisson Distribution

$$P = \frac{e^{-m} m^r}{r!},$$

Where P is the probability of exactly r fatalities.
m is the mean annual fatality rate, and
r is an integer number of fatalities per year.

The results are shown below.

TABLE 1
Probability of Fatalities
 Unrestricted Hazardous Materials in Reference Tunnel
 $M = .28$

Actual Fatalities per Year (r)	0	1	2	3	4
Probability of Occurrence (P)	.756	.212	.030	.002	--

Similar calculations for a study-wide analysis based on the 35 tunnels included in Appendix A span scores of digits, each with a small probability, and give little useful information. An analysis based on a Normal approximation to a Poisson Distribution, whose variance equals its mean, allows the calculation of probabilities for ranges of fatalities and conveys much more information. Since the mean time between major hazardous material fires is longer than one year, a per-decade assessment is more meaningful than a per-year one. The distribution of expected fatalities per decade study-wide is given by a normal curve with $\mu = 157$ and $\sigma = 12.53$. The results are shown below.

TABLE 2
Probability of Fatalities
 Unrestricted Hazardous Materials in all Study Tunnels
 $\mu = 157$ fatalities/decade; $\sigma = 12.53$

Fatalities:	0/	121/	141/	151/	161/	171/	+190
	120	140	150	160	170	190	
Probability:	.0016	.0853	.2008	.3071	.2560	.1449	.0043

These figures are for the reference tunnel only, and assume that open-highway conditions, except for the confined space and lack of escape routes, prevail inside it. As a practical matter, several modifications are justified, since many tunnels differ from the reference tunnel and open highway conditions in general do not prevail.

The fire site in a sagging-profiled, sub-aqueous tunnel has a marked effect on survivability: a fire on the exit upslope will be relatively innocuous, since vehicles will drive away from rising smoke and fumes while those behind will remain in a draft of fresh air. A fire on the entry downslope, on the other hand, may trap all motorists between it and the entry portal in rising smoke and fumes. The same is true of tunnels with sloping profiles: the downhill drivers are at greater risk (not from accidents or stoppages, just from escaping smoke of a major fire.) Dry remote tunnels can expect far lighter traffic than the one vehicle per 100 feet of lane assumed in the reference tunnel calculations.

As pointed out earlier in this report, open highway conditions do not prevail in tunnels. Not only do statistics indicate them to be more accident-free, but the systems and procedures discussed herein decrease the risk once a fire has started. For instance, by the fire-site criterion given in the paragraph above, the Holland tunnel fire should have killed all motorists trapped between the burning carbon disulfide and the Jersey City portal. That it didn't is a testimonial to the mitigation possible from proper preparation, response, and action during a fire.

No attempt has been made to quantify these mitigating factors: it can only be said that the fatality rates given, .28 victims/year per mile-long tunnel and 15.7 victims/year for the 35 tunnels included in the study, represent upper bounds if hazardous materials are allowed free transit and surveillance and response remain at open highway levels. The yearly rate of .28 fatalities is suitable for economic tradeoff studies, if a per-fatality cost can be ascertained. The probabilities in Table 2 give an indication of the political costs of removing restrictions on hazardous material transit.

Future Tests

There is a need to perform full scale fire tests in a highway tunnel to learn more about the behavior of heat and smoke plus the effectiveness of some of the ventilation systems recommended in this report and their costs. The European and Japanese have done testing; the parameters of these tests, however, particularly the ventilation capacity, are well below that encountered in this country.

ASHRAE Committee TC59 is considering testing in a West Virginia Turnpike tunnel which will be abandoned in about four years. Several abandoned tunnels on the Pennsylvania Turnpike could also be used for full-scale tests although the fans have been removed. The West Virginia tunnel is ideal because it is equipped with fully transverse ventilation having ceiling exhaust and curb level supply. ASHRAE Committee TC5-9 is currently developing a program for these tests and investigating availability of funds.

CONCLUSIONS

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

- o prohibiting hazardous cargoes.
- o controlling drivers' actions.
- o enforcing both the above.

Tunnel designers can contribute to this low rate by applying design criteria conducive to traffic safety.

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

Tunnel fires can be controlled by a combination of

- o detection systems.
- o alarm systems.
- o effective notification of tunnel patrons.
- o fire extinguishers in the tunnel per NFPA 502.
- o fire hydrants and water supply systems per NFPA 502.
- o pre-planned responses by tunnel crew, fire department, and local emergency personnel.
- o properly trained and equipped personnel and vehicles.
- o properly designed drainage and ventilation systems.

Damage and fatalities from tunnel fires can be limited by

- o effective communication systems.
- o appropriate emergency ventilation modes.
- o clearly indicated, accessible escape routes.

Fire control systems of questionable value include

- o automatic fire and smoke detectors.

- o automatic sprinklers.

- o highway shoulders.

RECOMMENDATIONS

1. Explosive or potentially explosive materials should not under any circumstances be allowed transit through highway tunnels.
2. Hazardous materials should be allowed transit 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.
4. Effective regulation of drivers' actions in the tunnel should be imposed and enforced.
5. All tunnels should be monitored round the clock, preferably by personnel in an on-site control room.
6. Tunnels should be designed to minimize the traffic accident potential.
7. Detection systems should involve cost-effective surveillance, including
 - o personnel stationed in the tunnel, or
 - o TV cameras with traffic monitoring.
8. Alarm systems should include
 - o telephones or manual alarms in tunnels connected to the control room not a fire station.
 - o direct line to fire station from control room.
 - o two-way radio communication net inside and outside tunnel.
9. Notification systems should include
 - o traffic lights
 - o signs
 - o AM radio rebroadcast
 - o CB radio capability
 - o Personnel at portal
 - o Personnel in tunnel if possible.

10. Every operating agency should prepare a fire/emergency plan for each tunnel under its control.
11. Cooperation should be established and maintained with local fire department, law enforcement, and emergency preparedness organizations.
12. Periodic practices and system exercises should be conducted.
13. Tunnel vehicles complying with NFPA 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 300 feet on center and safeguarded from damage, deterioration, and pilferage.
15. Hydrants compatible with local fire department equipment should be provided a maximum 300 feet on center with sufficient supply, or storage, and piping to provide 500 gpm per tunnel bore @ 75 psig residual pressure, 1000 gpm total facility flow, for a minimum of two hours (120,000 gallons).
16. Fire hoses should be vehicle equipment and not installed in the tunnel.
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 in the event of a hazardous material fire.
21. If tunnel geometry and construction sequence permit, well-marked, accessible, ventilated, and lighted exits to safe havens should be provided a maximum of 300 feet on center in every bore.
22. Ventilation systems should include an emergency/fire operating mode which extracts air from sizeable, controllable, ceiling-level exhaust dampers a maximum of 300 feet on center, selectable from the control room, and

large enough to induce a roadway area flow of 1000 ft/min from both directions towards the damper. The entire system, including structural components and hangers, should be capable of continued operation when exhaust gas temperatures reach 1000°F.

APPENDIX A
TUNNELS IN STUDY

<u>NAME</u>	<u>OPERATOR/CONTACT</u>	<u>LENGTH (FT)</u>	<u>TUBE</u>	<u>LANES</u>	<u>TRAFFIC 10³/day</u>
Wallace (Mobile)	Alabama Highway Dept. 1701 Beltline Hwy. North Mobile, Alabama 36618 Gordon Prescott (205) 470-8280	3109	1 1	2 2	10
Caldecott (Oakland)	Cal. Division of Highways P.O. Box 559 Orinda, California 94563 E. R. Mayo (415) 848-3482	3610 3610 3371	1 1 1	2 2 2	100
Posey/Webster (Oakland)	same as above	3545 3350	1 1	2 2	24.5
Eisenhower (Loveland Pass)	Colo. Dept. of Highways 4201 East Arkansas Denver, Colorado 80222 Phillip McOllough (303) 623-4678	8941	1 1	2 2	20
I-95 Mall (Wash. D.C.)	D.C. Dept. of Transportation Division of Bridge Const. & Maintenance 4701 Shephard Parkway SW Washington, D.C. 20032 Daniel O'Donnell (202) 767-8528	3400	1 1	4 4	58
9th Street (Wash. D.C.)	same as above	1610	1	3	14
12th Street (Wash. D.C.)	same as above	729	1	3	22
Baltimore Hbr. (Baltimore)	Md. Transportations Authority Toll Facilities Administration P.O. Box 3432 Baltimore, Maryland 21225 B. W. Jedrowicz (301) 355-3500	7650	1 1	2 2	65.5
Dewey Square (Boston)	Mass. Dept. of Public Works 100 Nashua St. Boston, Massachusetts 02114 Louis DeFranzo (617) 727-5010	2400	1 1	3 2	125

<u>NAME</u>	<u>OPERATOR/CONTACT</u>	<u>LENGTH (FT)</u>	<u>TUBE</u>	<u>LANES</u>	<u>TRAFFIC 10³/day</u>
Callahan	Mass. Turnpike Authority 145 Havre Street Boston, Massachusetts 02128 William Crowther (617) 569-2106	5070	1	2	65
Summer (Boston)	same as above	5657	1	2	65
Prudential Center (Boston)	same as above	604	1 1	4 4	
Detroit-Windsor (Detroit)	Detroit-Canada Corp. 100 East Jefferson Detroit, Michigan 48226 Ronald Delaney (313) 567-4222	5130	1	2	18
Lowry Hill (Minneapolis)	Minn. Dept. of Highways 2055 North Lilac Dr. Minneapolis, Minnesota 55422 Edward Schanus (612) 545-3741	1496	1 1	3 3	32
Brooklyn- Battery (NYC)	Triborough Bridge & Tunnel Authority P.O. Box 35 New York, New York 10035 Robert Martin (212) 360-3000	9117	1 1	2 2	40
Queens-Midtown (NYC)	same as above	6272 6414	1 1	2 2	60
Holland (NYC)	Port Authority of NY & NJ Holland Tunnel 13th & Provost Jersey City, New York 07302 Frank Smyth (201) 963-5511	8558 8371	1 1	2 2	60
Lincoln (NYC)	Lincoln Tunnel 500 JFK Boulevard, East Weehawken, New Jersey 07087 Edward Bennet (201) 867-9095	8216 7482 8006	1 1 1	2 2 2	95

<u>NAME</u>	<u>OPERATOR/CONTACT</u>	<u>LENGTH (FT)</u>	<u>TUBE</u>	<u>LANES</u>	<u>TRAFFIC 10³/day</u>
Fort Pitt (Pittsburgh)	Pa. Dept. of Transportation Fort Pitt Tunnels District 11-3 Pittsburgh, Pennsylvania 15220 M. A. Schrauder (412) 381-1775	3600	1 1	2 2	78
Liberty (Pittsburgh)	same as above	5690	1 1	2 2	50
Squirrel Hill (Pittsburgh)	same as above	4225	1 1	2 2	83
Allegheny (Somerset Co.)	Pa. Turnpike Commission P.O. Box 8531 Harrisburg, Pennsylvania Kenneth Krotz (717) 939-9551	6070	1 1	2 2	20
Blue Mountain (Franklin Co.)	same as above	4339	1 1	2 2	12
Lehigh (Lehigh Co.)	same as above	4380	1	2	12
Kittatinny (Franklin Co.)	same as above	4727	1 1	2 2	12
Tuscarora (Franklin Co.)	same as above	5326	1 1	2 2	12
Big Walker (Wytheville)	Va. Dept. of Highways and Transportation Wytheville, Virginia 24382 James Smith (703) 228-5571	4230	1 1	2 2	6
East River Mt. (I-77 @ W.Va border)	East River Mountain Tunnel Star Route Box 5A1 Rocky Gap, Virginia 24366 Charles Fore (703) 928-1994	5400	1 1	2 2	6
Hampton Rds (Norfolk)	Va. Dept. of Higways and Transportation P.O. Box 3447 Hampton, Virginia 23663-0447 Raleigh Yeatts (804) 723-0761	7479	1 1	2 2	55

<u>NAME</u>	<u>OPERATOR/CONTACT</u>	<u>LENGTH (FT)</u>	<u>TUBE</u>	<u>LANES</u>	<u>TRAFFIC 10³/day</u>
Downtown (Norfolk)	same as above	3350	1	2	25
Midtown (Norfolk)	same as above	4194	1	2	16
Baltimore Channel (Bay Bridge/Tunnel)	Chesapeake Bay Bridge and Tunnel District P.O. Box 111 Cape Charles, Virginia 23310 James Brookshire (804) 331-2960	5450	1	2	4
Thimble Shoal (Bay Bridge/ Tunnel)	same as above	5738	1	2	4
Deas Island (Vancouver B.C.)	Provincial Ministry for Trans. and Highways Frank Blunden (604) 525-5621	2165	1 1	2 2	72
Memorial (Beckley, WVa)	West Va. Turnpike Authority P.O. Box 1469 Charleston, West Virginia 25325 George McIntyre (304) 348-3740	2600	1	2	9.5

APPENDIX B
INTERVIEW TAPE LOG

<u>Tape</u>	<u>Contents</u>
A side 1	I-64 Hampton Rds
A side 2	I-64 Hampton Rds
A side 3	I-64 Hampton Rds
A side 4	I-64 Hampton Rds
A side 5	I-64 Hampton Rds
A side 6	I-64 Hampton Rds
B side 1	Baltimore Harbor
B side 2	Baltimore Harbor
B side 3	Baltimore Harbor; Norfolk end; Chesapeake start
B side 4	Norfolk Elizabeth River start
B side 5	Chesapeake Bridge/Tunnel
B side 6	Chesapeake Bridge/Tunnel
C side 1	I-95 Mall Tunnel
C side 2	I-95 Mall Tunnel; Holland Tunnel
D side 1	Lincoln Tunnel
D side 2	Lincoln Tunnel
D side 3	Lincoln Tunnel
E side 1	Queens-Midtown
E side 2	Queens-Midtown; Boston Callahan
E side 3	Boston Callahan
E side 4	Boston Callahan; Dewey Square
F side 1	Dewey Square; Blue Mt. (PA Turnpike)
F side 2	Blue Mt. (PA Turnpike)
G side 1	Pittsburgh
G side 2	Pittsburgh
K side 1	East River Mt. and Big Walker Tunnels, VA
K side 2	Lowry Hill Tunnel, Minneapolis, MN
L side 1	Wallace Tunnel, Mobile, AL
L side 2	Deas Island, Vancouver, BC
M side 1	Eisenhower Tunnel, CO
M side 2	Eisenhower Tunnel, CO

Tape

Contents

M side 3	Eisenhower Tunnel, CO
M side 4	Eisenhower Tunnel, CO
N side 1	Caldecott Tunnel, Oakland
N side 2	Caldecott Tunnel, Oakland
N side 3	Unintelligible Caldecott
N side 4	Caldecott Tunnel; CHiPs Sacramento
N side 5	CHiPs Sacramento
N side 6	CHiPs Sacramento

APPENDIX C
NOTES FROM TUNNEL FIRE STUDY INTERVIEWS

Monday 29 Nov 82

Admin Off. Mr. Yeatts, I-64 Hampton Rds Tunnel, Va.:

7200 ft long, straight, runs north-south but ends are designated east-west to match long-range direction. No shoulders, 2 lanes uni-directional, sidewalk, power for lighting, standby emergency generator with limited capacity (won't run ventilation system) dual power, no double loss in + 5 years. Serious fire would deactivate lighting probably. Key to fire prevention: keep flammable materials out of the tunnel. Fire extinguishers in niches @ 3-400 ft O.C.; theft no problem; shoulders probably no impact on this. Fire main with hydrants. Direct line to Hampton Rds FD. Four wreckers, patrol wagons, etc., ample vehicles.

Sound powered telephone system, two-way radios for tunnel comm. TV surveillance. 16 supply, 16 exhaust fans. One ventilation section = $\frac{1}{2}$ tunnel length. Assessment of suitability: hard to answer, no experience with adverse conditions. No real escape routes except ventilation spaces. Adequacy of drainage and storage? Large spill would be a problem. How about pumps and sumps? Would large spill be a problem? "I suspect so." Biggest problem would be disposal. Basic philosophy: prohibit hazardous materials. Reputable firms cooperative; not-so-reputable sneaking through real problem. No "significant" fires in Mr. Yeatts' tenure. FD has been called on occasion to assist.

Opinions on procedures allowing hazardous vehicles through tunnel: opposed to any use. Bridge + ferry OK in Hampton Rds with some flack. Grudging acceptance general. Maybe transit in early AM with escorts. Never during high-volume traffic times. Possible design changes: (reluctantly put forward) safety shoulder, expensive but perhaps useful. Preferred direction of response: with traffic. Sometimes against. Note tunnel has no cross-tube communication. Wreckers can be turned in tunnel. May take 2-3 hours to route traffic through one tunnel. This is longer than effort to clear tunnel normally takes. No system in place to double direction in tunnel. Traffic patterns typical: balanced as to direction except at extremes of weekends with beach traffic going to Va Beach: Friday afternoons and Sunday evenings. Automatic traffic counting. Deluge system to reduce temp., probably won't stop a fire. Fans will probably suffer but should be kept running, even to destruction. Expense of high temp. fans probably not justified.

Mr. Calvin Moxley, I-64 Hampton Rds Tunnel:

Several original vehicle fires (autos); none that spread beyond vehicle of origin. Regular practices and drills with local fire dept's. Tunnel hose outlets compatible with local FD equipment. Inspection stations busy checking cargoes. View on licensing or permit system: If only way across, might do it. Could not afford to stop traffic even in middle of the night. Both tunnels now at saturation point.

Emergency ventilation plans exist to sectionalize tunnel exhaust and supply in case of fire. Ventilation ducts contain water spray nozzles to cool fumes prior to fan. Drainage and sump system not designed to handle flammable liquid spills. Dumping of flammable liquids into river always a problem in Hampton Roads. Recommendations: explosion-proofing of equipment subject to flammable vapors. Restricting equipment from areas subject to fumes. Dampers could be installed but would never have been used in either Hampton Rd tunnel. Controls and actuators would have to be fireproof.

Against sprinkler system. "Described Seattle system too sophisticated for us, still don't like it. Cost would outweigh benefit. Maybe OK for mountain tunnel, but water would stay in underwater tunnel until pumped out." I-64 was suppose to have AM radio override for comm. between tunnel operators and drivers. Did not materialize.

Jim Harrison I-64:

Suggest closed circuit TV, AM-FM radio override (not foolproof yet), loud speakers, improvements to fire hydrant freeze protection. Wrecker with self-contained, non-aqueous fire-fighting equipment to save time and waste-water at fire scene. Emergency procedure training of operators may be large problem. No complete ops manual; word-of-mouth training only. Procedures designed to deliver fresh air to stalled motorists. Cars, then, may block firefighters from entering in direction of traffic; fumes may prevent them from entering wrong way. Test combined with training session may be good idea. Tunnel often unmanned. Officers seldom have opportunity to fight fire. Motorists normally get niche fire extinguisher and fighting fire when officials arrive. Maintenance of extinguishers sometimes a problem. CO₂ normally supplied. Cutting off pumps in event flammable liquid enters drain system desired but very difficult now (impacts dumping flaming liquid into river). Drains often blocked by dirt and sand. Drains on both sides.

AM rebroadcast too weak to adequately communicate. New systems also have power problems; only one system broadcasts emergency on normal AM station bands. Lighting in new tunnel would probably fail in big fire. Old tunnel lighting wiring embedded in concrete; would probably survive. Loudspeakers may be beneficial; need test or evaluations from existing system. Speakers would have to be maybe 100 ft o.c. Roof sectional dampers sounds like good idea.

Mr. Hatch I-64:

Has been with tunnel since open: No "significant" fires. Several "consequential" fires that were confined. Only one that burned up in tunnel. No flares in tunnel! Gasoline from accident almost reached flares set by trooper in tunnel. Sand used to soak up flammables, but this and asphalt still flammable. Proximity of local fire department a big factor; use personnel to direct traffic and create access for FD equipment. Hydrants OK.

Exterior inspection of passing vehicles and halting before portal very effective. Brake fires most common. Direct line to FD important, "life saver". Immediate response, also check on false alarms. Everybody has radio, so much dependence on that. Local fire chief concerned about tunnel fires; has good training program concerning tunnel and its operation. Stress total approach to prevention, not initial design (I think this is his point) as best solution to safety problem. Motorist attitudes seem neutral when taken together: some more careful, some less, some phobic, some manic. Trucks in only one lane necessary for later cleanup and access during fire.

Drainage system may be problem, since it automatically dumps to river. Toxic material (PCB's etc.) would be gone before it could be stopped. On other hand, holding volatile substances for later disposal is dangerous. Also, blocking traffic for any purpose is dangerous, causes accidents. Ventilation system seemed to work OK during fires experienced to date. Elimination of smoke important factor in retaining ability of trapped motorists to respond to directions in a rational and cooperative manner.

Three important things: communications, surveillance, reaction. Communication most important. Instructions to motorists in tunnel very important; should be combined with contingency plans, training, and practice. Fire extinguishers should be readily available since experience shows enough clear heads are often available to assist or anticipate officials in fighting and containing fires. Placement on both sides of roadway important, and at roadway level, not catwalk level. Catwalk cars needed. Gasoline or electric

power still problem. Need some form of non-roadway transport for delivery of monitors and for rapid response to emergencies. Traffic control system allows rapid response to in-tunnel stoppages. Goes with communication above. Heat sensitivity of materials important: aluminum, brass, etc. will melt at normal fire temperatures.

Monday December 6, 1982

Baltimore Harbor Tunnel, Mr. Jedrowicz, Associate Administrator:

Tunnel open Nov 1957. One major fire March '78. Outside east portal. Oil truck rammed by Coca-Cola truck: Coke truck fuel spilled, started fire in Coke truck, oil truck, and load of creosoted railroad ties. Fire contained by prompt response of local fire department. Fires inside tunnel (engine fires) contained by force in tunnel. External inspection important, surveillance prior to portal, suspect vehicles pulled over. Signs warning against hazardous materials. LPG, even on recreation vehicles, prohibited.

Tunnel police trained in firefighting. Fire stations very close to each portal, summoned by direct line. Close relationship, frequent visits, etc. maintained. Three governments involved: Baltimore City, Baltimore County, Anne Arundel County. Policemen stationed 800 yds apart in tunnel. Firefighting equip in tunnel: fire ext. also fire valves. Ext. in niche, CO₂. Fire ext. in tunnel effective; recommended. Police usually use, but motorists often help. Truckers good, usually have own fire ext. Access to tunnel against traffic, officer on scene diverts, slows, or stops traffic using traffic signals. 8" fire main through tunnel, valves 300 ft o.c. 500 gpm from city main, with booster pump. Firefighting equipment on wreckers, not sure if foam capability.

Under-curb scupper. Felt adequate in event of fuel spill. Gutters cleaned every week (not completely maybe). Sumps adequate; performed so far as expected. Need explosion-proof pump motor. Midtunnel sump goes to portal sump for environmental reasons. Recommends direct discharge with filtering.

No TV surveillance; coming within year. Considered necessary in emergencies, allows better communication. Can be used to reduce need for tunnel monitoring by policemen. Have fire plans, exercises, training. Contingency plans include recommended operation of ventilation system for several fire scenarios. Study of possible automatic system underway. Sensors now automatically control fan speed. System has been effective during minor fires experienced to date. Ceiling dampers sound reasonable. Fans are designed for +1,000°F; on established PM program. At full capacity can produce 50 mph wind in tunnel. Tunnel radio used to communicate with motorists; AM only, radio must be on. Response time of police and FD important.

Drivers may be more careful in tunnels, but about 100 summons issued each month for lane changing (illegal) in the tunnel. Still, natural tendency for care in tunnel helps, except at night. Extra lanes or even tubes would be helpful. Sprinkler system considered, deleted from fear truck exhaust would set off sprinklers, cause panic because motorists would think tunnel had failed, i.e., was letting river in. Sprinkler system has good and bad points. Water may spread oil fire; would have no effect on engine fire. May knock down fire and reduce heat but would make lots of steam. Would cause accidents if activated without warning. Road would be extremely slick from road residue, which is never rinsed off in tunnel. Sprinklers more dangerous than helpful.

Lighting might fail during major fire. Luminaires exposed to flames and mechanical damage. Lighting on series patterns; whole tunnel not affected. Serious fire would require supplemental lighting, but this is standard on fire equipment. Hazardous materials excluded from tunnel; alternate routes available, no pressing need to accept risk of materials in tunnel.

Design of tunnels seems to be optimized as to level of risk; proximity and cooperation of local fire department of primary importance. Computerized vent control system desirable to assist operators in making proper decisions in event of emergencies. Satisfied ventilation required; cool fresh air in at bottom, hot exhaust out at top.

Six between-tube passages; could be important as survival feature if combined with proper signs and prewarning systems, such as radio. Radio system is installed; get many comments from motorists stating how comforting information messages over radio are in event of stoppages. Have signs saying "AM radios broadcast in tunnels". Equipment cost \$60,000. System modified to provide pre-recorded information messages twice during transit. Believes best ventilation arrangement during fire to be full exhaust, curtailed supply. No sprinklers.

Mall Tunnel, Washington D.C. (includes 3 tunnels):

Only one fire: engine wiring. Quickly extinguished without fire department response. No fire extinguishers in tunnel; no towing or emergency vehicles. Fire hydrants only. No manning. Emergency phones in mall; no phones, no nothin' in 9th and 12th street tunnels. Depend on passing motorists.

Water supply perhaps adequate. Drainage?: OK if working; cleaning a big problem. Clogging attributed to inlet design and holding basin. Could or should be much bigger. Emergency ventilation plan in "manual" (no enthusiasm matching I-64 or Baltimore Harbor). Control room manned 24 hrs. Smoke

detectors of fan outlets only. None in tunnel; cleaning water and diesel exhaust setting them off or damaging them would be problem. High speed fan test produced dust cloud, elicited response from fire department. Has not been repeated. No operating procedures to prevent dust accumulation followed.

No emergency exits except portals. No communication system, depend on fire department. One tween tube connecting door; normally locked. Radio rebroadcast not working from beginning. No plans to repair or replace. Tunnel too wide for effective system, maybe. No traffic figures made recently. Lose lighting? Possibly partially. Temperature resistance of stacks? No thought given. Fans wouldn't stand heat. No deluge system to keep fan cool on Mall Tunnel. Signs posted "Hazardous Cargo Prohibited"; no enforcement, no inspection. TV surveillance system disconnected (funding); system worked OK. Incident: empty gas truck hit wall, broke light fixtures. Full truck would have been disaster. No way to locate fire using general public phones, which are now only source of info to operators. (Don't think much of complex Seattle sprinkler system.) Aren't sure the kinds of fans installed. No effective lane control; lights are ignored. No effective traffic control short of police barriers set up manually after the fact.

Wednesday 8 December 1982, Lincoln Tunnel Admin. N.J.
Edward Bennett, Manager, Lincoln Tunnel
Frank Smyth, Manager, Holland Tunnel
Ray Scanlon, Port Authority Hazardous Cargo Expert:

Holland Tunnel incident, May 13, 1949. See report. No "significant" fires since then. Manned post at entrance to tunnel surveys vehicles, excludes those showing evidence of hazardous materials. Checks manifests of suspect trucks. Additional police officers assigned as vehicle inspectors during rush hours. Exclusion program backed up by 1) cooperation with other agencies to develop regulations and guidelines, 2) education of carriers and promulgation of regulations and guidelines, and 3) pursuit of violators through court and punitive action. Always policeman at entrance. Facility Operation Agents (FOA) in tunnel. TV cameras. Traffic detection loops in tubes.

Partial shutdowns at night for maintenance. Fire extinguishers in niches on both sides of roadway. Usually in place. 90% of fires extinguished by operators using in-place fire extinguishers. Some CO₂, some dry chemical. Extensive training for familiarization with equipment and operating in smoky tunnel. Expect to handle fire with tunnel equipment and personnel; would call local FD only upon indication that fire was too large to handle at first or if it grew beyond crew's ability to suppress. Sprinkler supply adequate. May accept redesign of scupper drainage system for new tunnel.

Tunnel ventilation system recommended for smoke removal. Ceiling dampers would be maintenance headache; suggest consumable ceiling panels. Fan construction or cooling should be such that operation during fire would be adequate to protect lives; undamaged survival of the fan should be secondary. Communications systems should deal with motorists both inside and outside tunnels. Motorists entering dangerous conditions despite warning signs or instructional messages seem to be the norm. Radio rebroadcast systems cannot incorporate the FM band.

Concerning Caldecott operation: tunnel is wider than others, with walkway at road level. Passing is permitted, contrary to most other tunnels. Speed limit is high (50 mph); most other tunnels have speed limits substantially lower than open roads. These factors tend to alleviate the normal apprehension of transiting motorists which has contributed to remarkable safety record of tunnels. Quantification of psychological effect of these factors impossible, but this appears significant despite its counter-intuitive thrust. Catwalk cars give valued mobility to operators in tunnel. (Vulnerability of tunnels to terrorist activities might change cost/benefit balance of study says Scanlon.)

Bob Martin, Triborough Bridge/Tunnel Authority, Brooklyn Battery and Queens Midtown tunnel:

Flammable and hazardous materials prohibited; no checks. Personnel at portals stop obvious violators. No shoulders; no lane changes allowed. Heavy traffic contributes to greater accident rate; traffic backs up through tunnel from toll booth, causing accidents, despite warning signs. Sharp curve on entry. Many rear-enders from interface between stopped and moving vehicles. Fires have never resulted from this condition.

Emergency vehicles are short wheel-based; normally approach emergency against traffic. TV monitoring. Telephone used for crew communication; no radio. Signal control stations supplement voice. Fire warning automatically activates traffic signals; traffic stopped at portal by attendant. Vehicle has fire extinguisher and hose. Hose never has been used to fight fire; cleanup only. Fire extinguishers 150 ft o.c. in niches. ABC powder preferred for better control of all fires.

From smoke bomb tests, best results achieved using all fans at high speed (exhaust) to remove smoke and fumes. Damage to ducts and fans accepted. Ventilation system expected to allow access to fire site, removal of motorists, and reduction of heat. Tunnel manned 0600-2400. No automatic fire detectors, smoke detectors, or automatic sprinklers. Water supply

unlimited. Sumps sufficient to take liquids dumped in tunnel. Disposal into river frowned on. Stairway exit to Governors' Island for Brooklyn Battery; to ventilation buildings at quarter points for Queens Midtown. Crossovers at mid tube and at ventilation buildings.

Escorted transit of tunnel may be possible. Direct link to NYFD. Fusible link panels? No thought; no fires. Fire extinguishers placed on bridges lost to theft. Sprinkler systems not recommended: have no effect on major fire, such as Caldecott. Fan systems, especially V-belts and motors inside fan ducts, not expected to survive, or maybe even operate for long, during fire.

Friday 10 December 1982

Sumner and Callahan Tunnels in Boston, MA, Mr. William Crowther:

No "significant" fires in Boston area tunnels in plus 50 years. Several single-vehicle fires. Fuel fires seem to be a result of tunnel upgrade (4%). Float of carburetor sticks in open position, allowing fuel to overflow and spill onto engine exhaust manifold. May spread to rest of engine compartment and perhaps to rest of vehicle. Unleaded gas seems to provide no natural lubrication to carburetor parts; this compounds problem. Grade not excessive, but backup delays are contributory, since still vehicle and idle engine speed mean more sticking and high spill volume. Magnesium engines also factor.

ABC extinguishers 85 ft o.c. Personnel in tunnel at all times; trained to fight fires. Could not extinguish magnesium fire! Wheels burn also. Magnesium oxide smoke foul-smelling and dense (white). Hazardous materials prohibited, even hay for race horses and building materials. Warning system: 28 phones 100 ft o.c.; available to guards or motorists. Well-marked and instruction placard included. No TV surveillance. No heat or smoke detectors; No traffic flow detectors. No such systems contemplated based on safety record of existing system and cost of new ones. Fire stations close by; their cooperation important factor.

Fire plan worked out 15 or 20 years ago; subject of annual meeting to review and update, retrain new personnel, etc. Local fire stations approx. one-fourth mile from portals. Motorists using fire extinguishers primary fire fighters; usually react quickly and effectively. Commuter tunnel with many repeat customers familiar with conditions and procedures. Fire extinguishers (ABC) in use recommended by fire underwriting firm. Towtruck at portal; does not respond to fire, experience indicates towtruck, because it responds with traffic while opposite number switches ends, cannot respond

to fire with traffic, so lets fire departments respond against traffic and stays put. Fire departments send equipment to both ends of both tubes. Fire alarm to department has no other information other than location, i.e., no phone, etc. 4" wet fire line, hose connections 100 ft o.c., no hoses.

Lines drained in winter; can be re-activated by FD. Procedures all in plan. Line has never been used. Confident that dangerous amount of flammable liquid could not settle in drainage system because of entry restrictions on all bulk liquid carriers. Exhaust fans increased to maximum and supply fan shut down in half of tube with fire; portion without fire not adjusted. No smoke test, but interviewee impressed with this procedure's effectiveness on several occasions, despite initial doubts. Motorists encouraged to remain with vehicle in event of fire (note: only small fires expected, not hazardous material fires). Callahan tunnel fans chain drive, Sumner direct drive. Both exposed to possible combustion products.

Emergency procedure training of all tunnel personnel imperative. Personnel participate in live-fire drills run by Logan airport. Places little faith in complex automatic systems. Concerning communication, bullhorns don't work: acoustics in tunnel atrocious. Will have radio system to rebroadcast all local AM stations with capability to override with emergency messages. No FM capability seems to be possible; AM capability viewed as useful and popular. No cross-tube connections in place or possible. Radio communication capability demands systems, personnel, and procedures able to gather information, make timely and sound decisions, and give accurate and helpful instructions. Irresponsible use worse than nothing.

Fire would disable entire tunnel lighting, requiring fire-fighters to provide own artificial lights. Sprinklers not considered an effective additional fire protection system. People more careful inside tunnel, but certain people inclined to caution or fearful on normal highways may get dangerously phobic when inside tunnels. Congested traffic often brings motorists unwilling to enter tunnels to portals. Minimum and maximum speed limits and "stay-in-lane" regulations enforces and violators cited. Exploiting tunnel phobia not considered effective safety ploy.

Prudential Tunnel is becoming longer (1800 to 3000 feet) through air rights enclosure. Existing tunnel has longitudinal ventilation with supply fan only; piston effect depended upon now to provide major portion. New part will have axial exhaust fans in unknown arrangement. Traffic patterns and control similar to I-95 Mall in DC: normal urban arterial traffic in multilane cut and cover enclosed roadway.

Dewey Square Tunnel, Boston 10 December 1982
Dept. of Public Works (Highway Dept.) for Massachusetts
Mr. Louis DeFranzo:

Tunnel part of downtown Boston's arterial system. No significant fires since opening in 1958. Some minor vehicular fires. No hazardous materials allowed in tunnel. No personnel in tunnel; have TV, also telephones. Large Boston FD station within 1000 feet of portal. Dry stand pipe through tunnel activated by gate valves outside tunnel. Type ABC fire extinguishers in niches about 300 ft. o.c., two units per niche. Regularly inspected. Believe public is aware of extinguishers because many are stolen. No shoulders, walkway only. Axial exhaust fans under control of tunnel monitors. System is old. Probably would not survive exposure to combustion products.

Radio system covering all AM bands has been installed in tunnel. Can be overridden to provide messages to motorists. Loudspeakers installed but not used for long time; now out of repair. Worked OK when kept up. (If so, why radio system?) Traffic pattern and control similar to I-95 Mall as portion of covered freeway. Tunnel has no assigned vehicles; depends on local law enforcement and fire prevention resources. No pedestrian exitways; have to leave at portals or at several mid-tunnel exit ramps.

Protuding fire hydrants subject to damage; recommend recess as standard feature. Recommend fireproof roof structure. Fully transverse ventilation may be too expensive, considering length. Sump and pumping system adequate but conditions hard on components. Long lead time for replacement. Major fuel spill would be a serious problem; sump won't hold it. Retrofit of sprinkler system rejected because of clearance problems. (No discussion of their fire prevention role.) TV components subject to high failure rate because of corrosive atmosphere in tunnel. Qualified security firms reluctant to work in tunnel environment. Trucking industry highly cooperative with tunnel authorities.

Monday 13 December 82
Blue Mt. Tunnels Control Room, Pa. Turnpike
Mr. Krotz:

One Accident in 1965-66: Tractor-trailer loaded with fish oil caught fire. (Responses and details unintelligible.) No automatic warning or communication equipment. Expect wrecker and fire truck to fight fire; no local FD. Fire truck has powder, foam concentrate, hoses. No water on truck; uses tunnel water from hydrants. Fire extinguishers in tunnel. Respondent has no recall of a fire in tunnel during his tenure (post '66). CO₂ extinguishers, 6" fire main. 35,000 gallons of water on hand for fire fighting.

Only supply fans, no exhaust. Tunnels are self-ventilating as far as CO concentration is concerned. Four people monitor tunnel. Gasoline trucks delivering to turnpike stations only allowed through, and then only with traffic stopped. Other hazardous materials and other circumstances prohibited. No organized preportal surveillance. No lane changing in tunnel. Drivers more careful in tunnel; more alert. Sprinklers? Unintelligible response. Traffic lights supplemented by attendants arrival at portals depended upon to stop traffic. Smoke from fish oil fire exited tunnel successfully without mechanical help.

Tuesday 14 Dec 82

Fort Pitt Tunnel, Pittsburgh

Mr. M. A. Schrauder, Manager of Pittsburgh Tunnels

Mr. Francis Mies, Manager of Pittsburgh Tunnels:

One Fire: Deliberately set and car abandoned in empty Squirrel Hill tunnel about 2 a.m. City fire department summoned; fire extinguished. Minor engine fires put out with fire extinguishers in tunnel. Squirrel Hill has alarm buttons; Fort Pitt fire alarm system being rehabilitated after several years' out of commission. Tunnel crews respond to fire on wrecker trucks; quick thinking motorists often fight fire with tunnel fire extinguishers. ABC powder. Additional help summoned by radio. Crews concentrate on emptying tunnel, stopping traffic at portals.

Ventilation system; each end of Fort Pitt has three supply fans for supply; no constant exhaust. Large exhaust fan activated to exhaust air through supply duct in case of emergency. Liberty has no fire main; other two have hydrants, but dependence placed on fire extinguishers. No meetings or training sessions with local fire departments. Recent reorganization has disrupted tunnel crew training. No flammable liquids allowed through tunnels. No mention of active surveillance. Cross-tube doors are not marked during present rehab.

Pittsburgh FD has requested reinstallation of old alarm and standpipe systems in tunnels; will be too expensive, although alarm systems have been refurbished. Manager feels he's caught between tight budget restraints on one hand and non-quantified safety recommendations on the other. Would like to see quantified cost/benefit analyses of safety impact of tunnel design choices. 86,000 cars/day. Prefers another method to sprinkler system, considering sub-freezing winter temperatures. Tunnels require clearance for catwalks, cameras, signs, etc. Catwalk in Fort Pitt has railing removed.

30 November 82

Chesapeake Bay Bridge Tunnel

Mr. Brookshire

Mr. James Barkroft, Chief of Police, Gene Barry, Supt. of Maintenance:

Single tube, 2-way traffic. No sprinklers. No fire detection system, no TV. Tunnel manned by at least one person. 6" fire main; hydrants 300 ft. o.c., no hoses. Fully transverse ventilation. Wrecker/ fire truck has 500 gallons water with foam, CO₂ fire extinguishers, hoses. Dry chem. fire extinguishers² 100 ft o.c. Wreckers stationed at on-shore sides of islands so both sides of one fire can be served.

One fire; truck blew tire, continued to drive, overturned, caught fire. Supply turned off, exhaust on full. Wrecker put out fire before fire department arrived. Ventilation system effective enough to allow firefighting without breathing apparatus. No damage to ventilation equipment greater than soot deposits. Chesapeake Beach fire department normally called (breakdown fence access to highway available in emergencies); is professional FD at south end of Bridge/Tunnel. Regular familiarization tours scheduled at least annually. Can call FD dispatcher via radio link. Ocean Beach FD normal backup to Chesapeake Beach. No fire extinguishers stolen; are beneficial during initial response to fire.

CO₂ vs ABC powder. Powder messy but more effective on more different kinds of fires. Prohibition of hazardous cargo major factor in preventing major fires. Restrictions may impose hardships, but protecting structure given primary consideration. How about permit or escorted transit at low traffic times? Would depend on frequency and amount of disruption of normal service. Do restricted space and traffic controls encourage greater care on the part of drivers? Believe they do, but this greater care may not offset the actual problems caused by lack of space. Knowledge that vehicles will be checked causes many potentially dangerous vehicles to avoid the bridge/tunnel. Shoulders in tunnel might encourage vehicles with problems to pull off and stop, creating a much more dangerous situation than continuing out portal. Might also provide sleeping area for transiting motorists. Thus safety feature would be turned into a dangerous condition by public using it as a convenience feature.

Automatic sprinkler system not deemed beneficial for Bay Tunnels. Tunnel not constantly manned; some blind spots at ends from station. Depend on motorists calls from telephones, all of which are well-marked, with instructions for use, and location-coded for pin-pointing origin of call. Heat from truck exhaust may set off sprinklers. 150,000 gallon water

supply; fire hydrant adequate. Compatible with all local fire department equipment. No idea of temperature of air in exhaust fan during 1979 truck fire. No damage to fan. Suggest no communication system will effectively communicate with all motorists: AM radios may be missing or off; loud-speakers cannot overcome traffic noise. Also, man giving instructions must be knowledgeable and wise enough to give effective instructions. Can only be helpful if combined with TV surveillance system.

30 November 82

Norfolk, Elizabeth River Midtown and Downtown
Mr. Yeatts:

No "significant" fires; small vehicle fires only. No resulting damage to tunnel fabric. Never had vehicle completely burn. Downtown 3300; midtown 4400 ft. Midtown tunnel has CO₂; downtown has ABC powder. Like CO₂ better: doesn't create mess, extinguishes more fire, leaves cars in better condition. 300 ft o.c. Both tunnels have automatic sprinklers: Gainwell Deluge systems. Designed only to cool air entering exhaust system. One tunnel has only fan-room sprinklered. Automatic heat detectors activate deluge systems.

Standpipe in tunnel with booster pump for 1000 gpm flow. Ventilation is exhaust only (one tunnel). Expect to increase exhaust in event of fire. Both tunnels manned. Manning may be dropped when incorporated into Interstate system. Personnel at portals would stop traffic. Fire stations are within one half mile of each portal. No direct lines; must call by telephone. Tunnel vehicles have fire hoses, fire extinguishers, foam applicators. Emergency response plan worked up by city.

Hazardous materials prohibited. Inspection stations at each portal. Easy alternate routes available between Norfolk and Portsmouth. Belt-drive centrifugal at downtown; Joy Axial at Midtown. (portion of interview missing) Tunnel equipment has self-contained breathing apparatus on board.

21 February 83

Deas Island Vancouver B.C. 2,165 ft long 72,000 ADT
Provincial Ministry of Transportation and Highways
Frank Blunden, Dist. Hwy. Manager
Sydney Watson, Chief Operator
Mike Moore, National Inst. LTD, Contractor (expected; no show):

Is a commuter tunnel. About a year ago had head-on in two-lane tube resulting in fire. Sprinkler system under construction and not used. Fire extinguished by fire department. Other small fires in past; old sprinkler system

reported to extinguish some of these. Operators monitor traffic with TV cameras; detect fires visually. No telephones operative; no pull-boxes in tunnels. No automatic traffic counters or movement indicators. Two fire stations available; one at each end. Lane lights indicate closed lanes, but reliance placed on personnel or RCMP highway patrol to actually stop traffic. Wrecker has self-contained fire extinguishing equipment, dry chemical extinguishers every 70 ft in tubes. Effective in putting out small fires.

Tubes have connecting doorways, but no real room for people to stand in other tunnel, since there's no walkway. Ventilating fans are 2-speed reversible; fire department will direct use of fans. During head-on just inside south end, north fan put on exhaust. Did not clear fumes from burning fires. Fire department standpipes outside each end and at every third door; supplied from municipal water system. System is dry; needs about 4 minutes to charge standpipe/ sprinkler system inside tunnel. New system has not been used as yet. Hazardous materials prohibited. Drainage system not fireproof. Believes motorists drive more slowly and carefully in tube, but special entry conditions at portals congest entering traffic, which opens up as motorists accelerate through tunnel.

17 February 1983

Wallace Tunnel Mobile AL

Gordon Prescott Manager I-10 Tunnel

also involved with Bankhead I-10 4,251 ft:

Tunnel not manned. 25 cameras in tunnel; two men monitor in central control room. Surveillance includes approach interchanges. Supply ducts under roadways, 290,000 CFM normal, 700,000 CFM max. 2½" hoses in tunnel; expect professionals to extinguish fire, not motorists. Pull boxes in tunnel but depend on TV monitors.

One vehicle fire, recreational van's fuel pump hose ruptured, raw fuel caught fire. Lots of smoke. Van burned completely because smoke prevented firemen's access. Firemen recommended minimum ventilation during fire; Mr. Prescott believes full ventilation may have facilitated access and allowed extinguishing of fire before burnout. Occurred about 2:00 a.m. No other cars entered tunnel; light traffic was stopped by personnel. Reports motorists do not heed lit warning signs.

Linen fire hoses no good; prefer poly-ethylene. Fire extinguishers in tunnel not used on real fire yet. Occasionally stolen. Commercial wrecker used to remove breakdowns. No lane changing restrictions. Foam capability in low-point sump. Hazardous materials prohibited by signs; spot-check enforcement only. Another commuter tunnel. High-volume traffic produces piston effect. No sprinkler systems.

Would advocate manual actuation if sprinklers were present. Believe sprinklers would be helpful but full of problems. Hazardous material transit with permit? Would be opposed even with escort, for legal liability reasons, not safety reasons. Reasonable alternate routes available.

24 February 83

Lowry Hill Tunnel, Minneapolis, MN

Edward Schanus:

No flammable or explosive materials (20 lb LP tanks on campers okay). No inspection or enforcement by tunnel operators. Tunnel not manned; TV camera surveillance. No "significant" fires. One was result of collision. Ceramic tiles spalled from heat. City FD responded to fire and extinguished with dry chemical. Call phones in tunnel. Believe TV detected fire. Five extinguishers in each barrel, 20 lb dry chem. in niches. Several have been discharged or stolen. No shoulders, but tunnel is in densely populated area with light traffic in early morning, allowing mischievous drivers access and opportunity.

Dry fire line needs to be charged from convenient hydrant above ground. Only two outlets per tube; no sprinklers. Feel no need for additional fire prevention systems in tunnel. Motorists generally familiar with tunnel and show no signs of greater care.

Four 150 Hp fans; one runs at low RPM 24 hours. Auto CO₂ system controls additional fans. Fans supply through louvers in ceiling. Cannot judge effect ventilation had on fire. Efficacy of ventilation for smoke removal would depend on position of fire. Drains often fouled by debris and tracked-in dirt, especially in winter. No cross-tunnel doors; only escape out portals. Believes officials necessary to halt traffic; signs usually ineffective.

Big Walker Tunnel, Virginia

18 February 1983

Mr. Jim Smith:

No "significant" fires. Telephones in tunnel; "fire" and "help" buttons 100 ft. o.c. Portal traffic control lights. Tunnel fire truck, pumper, with foam capability. Volunteer fire departments about 6 miles away; would be called by phone. Fire extinguishers in niches; would expect motorists to use effectively. No standpipe. In event of fire would shut down all supply fans, activate exhaust fans full speed. Some hazardous materials restricted (gasoline but not fuel oil prohibited). Fans are chain-driven centrifugal.

18 February 83
East River Mountain Tunnel, West Virginia
Mr. Charles Fore:

No "significant" fires; one truck brake fire. Apparently observed entering tunnel; immediate response. Telephones and fire/help buttons to control room. Same fire truck as at Big Walker. No stand pipe. Exhaust fans activated for truck fire; effective in removing smoke. 6-7000 vehicles/day. 5654 ft. Fire extinguishers in tunnel; none stolen. Drainage system often stopped up with soda and beer cans, styrofoam cups. Treatment plant serves tunnel drainage, provides water for washing. Believes supply fans could serve ventilation needs of tunnel; doesn't think any ventilation system would help in major hazardous material fire. Solid state fan and lighting control system reliable but impossible to fix on site upon breakdown. Highly susceptible to lightning transients.

Eisenhower Tunnel 9 March 83
District 1 Office, Colorado Highway Dept.
Mr. Phil McOllough, District Engineer and Manager of Eisenhower Tunnel
Mr. Dick Johnson:

No "significant" fires; all minor mechanical or cargo fires. Fuel tank fell off auto, dragged out of portal, burst into flame. All fires extinguished very quickly (within minutes). Tunnels tend to be safer because curves are gentle and intersections or transition points are generally missing. Hazardous loads rerouted over passes, weather permitting. Amounts of flammable liquids controlled depending on packaging. When pass closed, tunnel cleared to run all hazardous material trucks at 750-1000 foot intervals through, hourly. Portal guards inspect trucks; expect cooperation from truckers and get it. Fires detected through TV surveillance, tunnel phones, people in pulpits or on catwalks, frequent work crews. Tunnel not normally manned. 11 traffic control stations (800 ft. l.c.) with loop detectors. Computer sets speed limits; warns of stoppages.

Crews on combination wrecker/fire truck (Holland Tunnel Design) respond. Rescue truck at east portal with large dry chemical extinguisher. Goes in with traffic normally. Fire extinguishers in niches, fire hydrants 250 ft o.c.; 120,000 gallons storage. Stand pipe has not been used for fire fighting. Ventilation system can draw out blue smoke from supercharged failures, but after very long lag. Vehicular movement through long tunnel sets up piston effect in direction of travel. Residual flow would carry combustion products away from traffic for some period after fire, creating safe area in front of fire until firefighters arrive.

Cross-adits 200 ft o.c. identified over doorways as "Fire Exit". Tunnels drain east; waste treatment plant at east portals. Flammable liquids would gather in sedimentation tanks, which overflow to underground holding tanks. All equipment is explosion proof; all entries gas-tight. Plan to manage spill promulgated. Valves positioned manually. Some volunteer fire departments within 10 miles can be summoned. Professional units at Idaho Springs 18 miles east. No special training in fighting "tunnel fires"; compatibility of equipment has been checked. Departments summoned by phone only.

Believe exhaust necessary for safety of tunnel occupants during fire, provide access for firefighters. Dearth of fire history leaves lack of definitive answers to design problems, need well-thought-out test program. Cross-adits with signs and location lights highly recommended; could have saved lives at Caldecott. Stand pipe never yet used to fight fire. Presence re-assuring, can be used to clean up afterwards, but assumed ineffective on flammable-liquid fires. Remote tunnel should have 500 gpm (two fire hose) minimum flow capability with 150,000 gallon minimum storage if 500 gpm source is unavailable.

Colorado Highway Department performs accident rate analyses on segments of highways to identify high-risk areas and the features making them so. Cost/benefit analyses are performed on improvements to alleviate these features. Use \$170,000 per fatality in addition to actual medical costs and property damage. Has similar studies for tunnels. Believes adequate lighting to be a cost effective safety benefit. Backup condition develops at short tunnels east of Idaho Springs when skiers return to Denver Sunday evenings producing many rear-end collisions at entrances to poorly lit tunnels.

Westbound traffic experiences 3000 ft rise up to and through tunnel (high point is at west portal) whereas eastbound traffic has only 1000 ft rise to west portal and downgrade through tunnel. Significantly more failures in westbound tube vs. eastbound as a consequence.

Caldecott Tunnel, Oakland, California
10 March 83:

7 April 82 only "significant" fire; about 10 single-vehicle fires or fires involving two vehicles in collision annually. Hazardous material prohibited from 3-5 pm; tunnel operators have no enforcement responsibilities or authority. No portal inspection. California automobile inspection requirements more stringent than other states.

Fire alarm boxes and telephones only detection systems; no manning, no TV in tunnel; only approaches monitored. Use to have "fire" and "help" buttons, but usually both were pushed. "Fire" button has been eliminated. Must call fire departments; approximately 7 minute response time. Fire extinguishers (10 lb dry) 120 ft o.c. in tubes. Fire department vehicles usually beat state wrecker to accident site, so no extensive fire fighting equipment is on wrecker. (Description of fire department response: "Orinda enters against traffic" reveals typical incident occurs in eastbound (upgrade) tubes similar to Eisenhower.)

Stand pipes with hydrants 250 ft o.c.; connected to city water. Has capacity in excess of 500 gpm. Drainage system can divert hazardous liquid to holding tank. Ventilation system only needed in old bores; new westbound tube is self-ventilating from traffic flow. Old (middle) tube still needs supplemental ventilation even with westbound traffic. Natural flow from bay inland not as effective in old tubes as in new; slower upgrade traffic doesn't induce flow as readily as faster down-grade traffic.

Ventilation automatically activated by CO monitors at early stage of 7 April fire; soon shut off because CO level fell below actuation point. Fire department did not want exhaust fans reactivated by override. Fire department considered knowledgeable and responsible agents in this. Do not believe exhaust system would have had any effect. West portal placement of fans means combustion products would have had to be pulled from far side of fire. No formal training or exercises with fire departments, but 8-10 small fires per year keeps them in practice.

Sprinkler system would have had no effect. Foam would have impeded traffic. Sprinklers would have no controlling effect on commonly occurring under-hood or inside-passenger-compartment automobile fires. Hydrant system positive benefit.

Alternate routes available for hazardous materials but only along long stretches of roadway less suitable than US 24. Believe accidents rate inversely proportional to lane width; don't know of any studies supporting narrower lane widths for safety. Don't believe bus driver would have been deterred from passing gas truck by narrower tunnel on 7 April. 2-lane segment of San Mateo bridge has far more rear-end accidents than 3-lane segment with shoulder. Tunnel has 4 cross-adits. Not marked as emergency exits; not recommended as refuges during fire: not ventilated; no place at other end to avoid traffic. No provisions for handicapped access.

Posey-Webster (same crew as Caldecott):

One small vehicle fire; fire department turned fully transverse ventilation system full on, went to fire and extinguished it.

California Highway Patrol Office
Sacramento, California 11 March 83:

CHiPs report did not address post accident conditions. Would not hazard guess as to tunnel roadway features contributing to accident or fire. Re foam: ex-firefighter interviewed says foam would impede motorists trying to leave area of a fire (Russ Meyer says foam is no slicker than wet pavement); tunnel full of foam bubbles would be disconcerting at best.

APPENDIX D
OBSERVATIONS OF EUROPEAN TUNNELS

1. Autostrada Tunnels Near Genoa, Italy

The following information was obtained during a visit to the Azienda Nazionale Autonoma delle Strada (ANAS), Genoa, Italy, on September 7, 1983. Mr. Neonnio Paolucci, chief engineer of ANAS, was in charge of the group that conferred with the investigator and accompanied him on an inspection tour of some of the tunnels. The ANAS office is at Via Savona 3, Genoa, Italy, telephone (010)594485. Mr. Paolucci's private number in his office is (010)542535.

The tunnels visited are on the main autostrada (or super-highway) which runs from Pisa along the Mediterranean coast passing through LaSpezia, Rapollo, Nervi, Genoa, Savona, Albenga, Imperia, San Remo, and Ventimiglia to the French border. There are similar tunnels on three autostrades leaving Genoa and Savona for Turino and Milano.

Autostrades in Italy were built on a competitive basis by private companies bidding to design, build, finance, operate, and maintain a section until the debt is retired by collected tolls, when the entire highway becomes the property of the Italian state.

The autostrades have over 500 kilometers of roadway in tunnels along these routes. There are approximately 90 tunnels, from less than 100 meters to as long as 3,000 meters. Most are between 100 and 600 meters. The tunnels are lined with reinforced concrete in a circular arch design. In some cases, the lining seems to be of stone or concrete blocks. Most of these highways are now dual-divided with either four lanes, two in each direction, or six lanes, three in each direction. Initially, sections of this autostrada were constructed with only two lanes, half of the roadway which exists today, with one tube carrying two-way traffic.

The roadway is approximately 12 feet wide. Two-lane bores have a sidewalk about 2 feet wide on either side; between the edge of the sidewalk and the tunnel wall there is an 8- or 10-inch gutter which carries away water seeping down the wall. Each tunnel has a proper name appearing on a sign on either side, as do the bridges. The length in meters is usually given.

These tunnels have no tile or other reflective surface on either the walls or a ceiling, nor the high quality lighting system which we see in the United States and in some of the longer mountain tunnels between Italy, France, and Switzerland. Tunnels are never washed.

Tunnels under 1,500 meters (5,000 ft) have no ventilation system, no emergency call (SOS) boxes within the tunnels, no fire hydrants with fire mains, and no niches with fire extinguishers. Ventilation is induced by the piston effect of the moving traffic; only tunnels longer than 1,500 meters (or about 5,000 feet) have mechanical ventilation, fire protection, or user safety systems. These are equipped as follows:

1. Ventilation controlled by a system of carbon monoxide (CO) analyzers and opacimeters which automatically turn on fans at low speed if the concentration of CO exceeds 100 parts per million (ppm) or if opacity exceeds 15%. Fans are vane axial installed in the ceiling arch above the roadway to boost the the piston effect in the direction of traffic. They are uniformly spaced along the tunnel at approximately 150 meter intervals, one fan at each location. If CO concentration rises above 150 ppm or opacity above 30%, fans are switched to high speed. An alarm sounds if CO rises above 200 ppm.
2. Fire mains with hose valves spaced about every 100 meters in the tunnel.
3. SOS call boxes at the hose valves. These have an intercom to the central control room, a pushbutton to request mechanical assistance, and another to request an ambulance. (A fire warning would have to go over the intercom.)

ANAS engineers demonstrated a new type of CO monitoring system. Located in the passageway between the two bores of one of the longer tunnels, the sampler consisted of a single infrared analyzer which compares the tunnel air to standard gas from a bottle mounted in the unit. Six points in the tunnel were sampled in sequence.

There is no traffic signal system in any of the tunnels.

There are no laws in this part of Italy restricting any kind of hazardous cargo from using the autostrada or any of its tunnels. This investigator observed many gasoline and fuel oil tank trucks which appeared to be in the 8,000- or 9,000-gallon range. Propane, liquid petroleum, and trucks carrying pressurized gases were also numerous.

There are no heat, fire, or smoke detectors installed anywhere in these tunnels. A fire would be reported only by a user talking to the central control room, which typically supervises an entire length of autostrada under the jurisdiction of one company.

Local fire departments are depended upon to control fires in these tunnels. The control room must call the appropriate fire department through the commercial telephone system; there are no direct lines. Training and practice sessions are conducted on a semi-annual basis to familiarize the firemen and the autostrada personnel with the problems associated with tunnel fires. Obviously, there are many fire jurisdictions involved.

The lighting in the tunnels varies considerably. Fluorescent and low-pressure sodium are the most common fixtures, with low pressure sodium in the entrance and exit zones to boost the lighting level there. In some instances, high-pressure sodium lights have been used in the entrance transition zones. This investigator felt the lighting to be adequate. (Some of the driving was done during bright daylight on a sunny day.)

The shorter tunnels (less than 1,500 meters) seem to be adequately ventilated by the piston effect. When traffic stops, this effect is lost. There are signs in-between tunnels requesting stopped motorists to turn off their motors until they can proceed. Thus is this problem dealt with on Italian autostrada. This investigator walked through several of the tunnels while inspecting various features. The piston effect is extremely strong; large amounts of air moved through the tunnel by the moving traffic.

The Italians have taken a very practical approach to the tunnel design and construction here. Given the number and length of tunnels, economics dictated minimum expenditures on construction, operation, and maintenance of these tunnels, except for the longer ones. A lighting system is the most common refinement; everything else apparently has been ruled out as too costly.

Over the years of heavy traffic, the walls and arches of these tunnels have become flat black, the poorest reflective surface. Although the lighting is adequate under the circumstances, one cannot help wonder if these dirty walls and obscured, high level lighting are truly economic on a total life cycle cost basis. The Italians say that, on a total life cycle cost basis, this approach, dark walls and no washing, is the least expensive.

The Italians invented jet-fan piston-effect ventilation to keep costs manageable. ANAS engineers indicated that jet-fan ventilation design has advanced beyond that installed in the longer tunnels near Genoa. Current thinking, based on tests and modeling, places fans in the ceiling only near the entrance and exit of a tunnel, with no fans in-between. Two fans are installed side by side--the number of such sets of

fans at the entrance would vary with tunnel length. Fan, motor, conduit, automatic control, and maintenance would cost less with this new approach, they said.

There are serious drawbacks to the approach the Italians have taken, but these disadvantages surface only during emergency conditions, during accident or fire. The Italians apparently accept these potential hazards, believing any additional sophistication in these directions would be prohibitively expensive, considering the total length of tunnel on these highways, making the project economically infeasible.

2. Celle Ligure, Italy, Tunnel Fire

Mr. Paolucci and his staff at ANAS thought this investigation concerned tunnel ventilation, not fire prevention and control. Consequently, they were not prepared to discuss the fire which occurred on May 21, 1983 in the Pecorila Galleria, near Celle Ligure. We went to the tunnel, however, and walked its entire length, inspecting the point where the fire seemed to be the worst and where the pavement in the roadway was rough with holes.

Mr. Paolucci told me that the accident and fire was in litigation, so he and his staff were prohibited from providing any detailed information regarding the fire or its consequences. He did state, however, that the accident was a result of a minor accident which occurred near the exit portal of this 662-meter-long, two-lane, uni-directional tunnel. As a result, traffic backed up within the tunnel. A truck owned by a Spanish firm carrying fish and allegedly speeding was unable to stop and collided with the stopped vehicles inside the tunnel. The driver chose to drive in the middle of the road, that is, between the two lines of vehicles, thereby smashing cars in both lanes. As the result of the collisions (exact number unknown at this time), there was a fire caused by the ignition of gasoline and other fuels from ruptured tanks. Nine persons burned to death, but apparently only because they could not leave vehicles distorted by the collisions. There were some 20 other persons injured in the accident and fire. The truck driver lived, but was badly injured. He is in the hospital and under guard because he will be jailed until a verdict is rendered in his trial. He may have been drunk, but that is not certain.

Help was summoned to the scene by witnesses using a portal SOS box. Details concerning how the fire was fought, how long it burned, and a host of related questions will have to await the end of litigation. A copy of the report will be obtained with the aid of Mr. Paolucci and the American Counsel in Genoa as soon as it is available.

As was stated, this tunnel is 662 meters long, almost 2,200 feet. Since the walls of these tunnels are flat black from the years of use, it was impossible to ascertain from the smoke patterns on the wall and ceiling which way the smoke went from the fire scene. The only real evidence of the fire are the ruts in the pavement about half-way through the tunnel and the obvious damage to the lighting fixtures no longer functioning. A temporary string of mercury vapor bulbs has been installed high on one wall to provide lighting until the damage to the lighting system and pavement can be repaired. Mr. Paolucci said that, because of the heavy traffic and the hazards of putting two-way traffic in the companion bore for the time it would take to repair the tunnel, repairs had been indefinitely delayed.

3. St. Gotthard Tunnel

The St. Gotthard Tunnel is the longest road tunnel in the world, 16.3 kilometers, portal to portal or slightly over ten miles. The tunnel lies completely within Switzerland and passes between the Swiss Cantons of Ticino on the south and Uri on the north. Tunnel construction started in 1969 and opened to traffic in 1980. The connecting roads north and south of the tunnel each have four lanes of traffic; the tunnel has only two lanes.

The tunnel was designed by Electrowatt in Zurich. The tunnel has two bores; the larger, which handles the traffic, is a typical mountain tunnel with an arched ceiling. The traffic lanes are 7.8 meters wide and the ceiling $4\frac{1}{2}$ meters high. Fresh air and exhaust air ducts are placed in the arch above the ceiling. The second bore is a safety or service tunnel, built to the east of the main tunnel and positioned to be the start of a second traffic bore if and when such a bore is ever constructed. The safety tunnel has a $7\frac{1}{2}$ meter square cross-section (which is sufficient to accommodate a small jeep) and is equipped with supply ventilation entirely separate from that in the traffic bore.

The main traffic tunnel has enlargements at both sides of the tunnel every 750 meters to provide a parking space for cars. It has sheltered rooms every 250 meters for the safety of persons in the tunnel. These sheltered rooms are between the main and safety tunnels. A stainless steel, 24-hour-rated, fire door separates the main tunnel from the safety space. There is an SOS box in the safety space with two fire extinguishers and an intercom to the control rooms at either end of the tunnel. Another fire door leads to the safety tunnel. Escapees can travel by jeep or on foot to a portal.

There are four vertical or inclined shafts to the surface along the tunnel. These shafts were bored by machine. They are partitioned to form two ducts, one for fresh air and one for exhaust. Fan rooms are located above the tunnel where shaft and tunnel meet.

The roadway is 1,081 meters above sea level at the north portal and 1,145 meters at the south portal. These low-altitude access roads make this tunnel safe and convenient year-round because snow removal is not as difficult at these altitudes as in high-altitude mountain passes.

The tunnel bores have been lined with reinforced concrete. A poured ceiling forms the duct space above the roadway. Traffic bore sidewalls have a void space behind for handling seepage. Each side of the roadway has a slightly elevated sidewalk .7 meters wide. Underneath are cable ducts and a fire main connected to fire hydrants spaced at intervals along one side. The wall lining panels are light tan epoxy.

The tunnel ventilation is a fully transverse system divided into nine sections. The total capacity is 2,150 cubic meters per second, enough to accommodate a calculated 1,800 vehicles per hour per lane (3,600 vehicles per hour both lanes). There are six fan rooms: one at each portal and one under each of the four vertical shafts. Each duct, whether supply or exhaust, has just one fan, an axial flow with controllable pitch blades and two-speed motors. The fans are 3.42 meters in diameter, although some smaller systems have smaller fans. Motors are installed in the hub, and are cooled by a separate fan and duct. The fans are placed above the roadway ceiling; a removable panel provides access underneath the fan. The fan supports are designed to allow fan removal through the ceiling opening by a special truck that lowers the fan and carries it out of the tunnel.

There is space above each fan to open and remove the upper half of its housing tube, exposing the motor, blades, bearings, and hydraulic pitch controlling mechanism for service. All of these components can be changed with the fan in place.

Each fan has heavy-duty multiblade dampers between fan and air shaft and between fan and duct. Damper and duct arrangements bypass the fans so that stack effect ventilation can be used when traffic and atmospheric conditions permit.

Switchgear, batteries, and transformers serving the lighting and ventilating fans for that section of tunnel are installed in auxiliary spaces in each fan room. Air conditioning units keep these rooms at a comfortable temperature year-round. Each fan room has a control panel for the systems in

its tunnel section. Each section has a carbon monoxide (CO) analyser in the fan room to operate the fans and stack effect ventilation bypass. It controls through the computer, by a separate automatic fan control system independent of the computer system, and can be manually overridden from the central control rooms or locally.

The total connected load for the ventilation system is 23,000 kilowatts. The longest ventilation sections are approximately 2,500 meters, under the highest mountain peaks. The fresh and exhaust air ducts above the ceiling vary in cross section area depending upon the length of the particular ventilation section being served. Generally speaking, in the north sector, where there are more frequent shafts to the surface, the fresh air duct is 7.3 square meters and the exhaust 5.7 square meters. In the south sector, where the ventilation sections are longer, the fresh air duct is 13.5 square meters and the exhaust 10.5 square meters. Note that the fresh air ducts are larger than the exhaust air ducts in both cases. The system is fully transverse: small ducts behind the sidewalls serve outlets above the sidewalk on one side of the tunnel. Exhaust air ports are spaced every 25 meters along the roadway ceiling.

At the most-centrally-located fan room, there is a separate ventilation system supplying fresh air to the safety tunnel. There are three fans: one for normal ventilation, one spare, and a larger one for emergency conditions. Safety tunnel air is supplied at a pressure higher than the traffic tunnels.

The lighting system was designed to provide obstacle identification day and night at the limits of the stopping distance. A continuous, single-lamp strip of 40-watt fluorescent lamps is installed in the eastern lateral corner of the tunnel section. The road-level illumination meets international and U.S. DOT recommendations. The output of each lamp can be regulated in steps to adjust illumination to the traffic volume.

Every tenth lamp is fed permanently through a static inverter connected to a 220-volt battery system, retaining one-tenth of the illumination in a power failure. In addition to this normal tunnel lighting system, there is an incandescent emergency lighting system on the tunnel east wall about 50 centimeters above the sidewalk at 50-meter intervals. These lamps are connected directly to the battery system and, upon notification of an emergency, come on automatically to provide lighting lower than the normal lighting at the corner of the ceiling above. Additional high-pressure sodium fixtures installed near the portals are automatically adjusted to outdoor illumination.

The illumination level of the tunnel can be controlled manually from the control room. Some statistics: the number of fixtures, 14,000; the installed lamp load, 1,000 kW; and annual energy consumption, 4,000,000 kilowatt hours.

All tunnel systems can be controlled by a Siemens computer located in the south administration building using software specific to St. Gotthard. Each system can also be operated either by its own separate automatic system or manually from the north or the south control rooms and from panels in the fan rooms.

In terms of fire prevention, this tunnel is covered under European Common Market regulations which prohibit vehicles carrying any cargo classified as hazardous in a published list. These regulations also require that vehicles carrying these cargoes have placards depicting the hazardous material and the best fire control method, i.e., foam, water, or powder. The St. Gotthard Tunnel is not a toll facility and does not cross an international border, so there are no custom inspections at the portals. Most Swiss and Europeans are law-abiding in regards to this particular law, however, and the tunnel personnel believe hazardous cargoes transit the tunnel seldom, if at all.

The tunnel has three fire detection systems. The first is a series of detectors installed on the ceiling at 25-meter intervals. These detectors are manufactured by Cerberus, a subsidiary of Electrowatt. They have two stages; the first stage more sensitive than the second. Upon sensing a fire, the following occurs: The supervising personnel in the control room are alerted by optical and acoustical signals; the position of the detected fire is shown on a special panel-display in the control room; the TV system is switched on; the tunnel illumination rises to maximum level; the emergency lighting is turned on; and the ventilation system is switched over to "Fire Program". When the less-sensitive second stage of a fire detector is activated, the fire department is summoned.

The second means of detection, SOS cabinets, allow a person calling the control room to hear and speak despite noise in the tunnel. These cabinets also have two dry powder fire extinguishers. If a fire extinguisher is removed from the cabinet, an alarm sounds in the control room and tunnel systems respond as they do when the first stage of a fire detector is triggered. If the control room decides that help is needed, a message appears on a screen in the box indicating in several languages that help is on the way.

The third means of detection, traffic loops, are embedded in the roadway and tie into the computer, which keeps track of the traffic flow. The system is sensitive enough to detect

a single vehicle stopping. An alarm is sounded and the monitor automatically shows the view from the nearest TV camera. Traffic signals turn red or flash yellow behind the vehicle involved on both roadways to warn motorists that there are problems up ahead.

There is an emergency fire station near each portal, each equipped with three fire engines. All three can attach to the fire line hydrants in the tunnel and have ample hoses for fighting fires. One is equipped with foam and the others with dry powder; all are equipped with first aid kit, resuscitators, and all other normal emergency equipment. They also serve as tow trucks, with equipment necessary to free people from damaged vehicles, perform minor repairs, and tow the vehicles from the tunnel. Each is equipped with a two-way radio which transmits in the tunnel through a relay system.

When a vehicle enters one of the tunnel turnout spaces, detection loops in the pavement alert the control room and television monitors cover the area. Each safety room is equipped with fire detectors tied into the computer, a first aid kit, and battery-powered emergency lighting.

Each of these interacting systems is described in more detail below.

Traffic Control System. Traffic signals are placed on both tunnel sidewalls every 250 meters. They are normally off, but can be switched on manually by police personnel if needed. In case of fire or excessive concentration of carbon monoxide, they are automatically switched on as described above.

SOS Stations. Alarm boxes installed inside the tunnel allow the road tunnel patron to summon help in case of need. They are placed every 125 meters on the west side and every 250 meters on the east. Each box contains a telephone direct to the control room, a single alarm button in case the telephone is not operating or cannot be used, and two portable fire extinguishers. The alarm boxes are marked by illuminated signs. Lifting the telephone receiver or removing a fire extinguisher prompts the traffic lights to interrupt traffic flow and activates the TV system.

Television System. 83 television cameras are placed every 250 meters or so, affording the control room staff a view of any situation along the tunnel through ten monitors. The cause of a disturbance can be identified and appropriate countermeasures initiated without delay. The TV system does not operate continuously; it is automatically activated under circumstances described above, but it can be switched on manually if required.

Radio and Broadcast Facilities. Overhead cables connect to a repeater system and allow reception and transmission of all eight frequencies used by the police and maintenance organizations of both Cantons. According to the Swiss, communication from the control rooms to service vehicles is vitally important in an emergency. The radio system is arranged so service is not disrupted, even if several cables are damaged. The same aerial cable also transmits FM broadcasts from both Cantons for reception by standard car radios. Important messages relevant to the safety of the travelers may be passed to drivers tuned to these frequencies, interrupting the FM broadcast program. The same equipment permits national car telephone service-equipped vehicles to call anywhere in the world.

Electrical Power Supply. Electrical power comes from two different networks, with a line voltage of 50 kV. If one supply networks fails, the other can take over 75% of the total tunnel load, corresponding to 1,500 vehicles per hour in each direction. Emergency power supplies are installed in each fan room and control room. They consist of static converters connected to 220-volt batteries. The overall load of the tunnel is distributed as follows: 86% for ventilation, 4% for illumination, and 10% for auxiliary equipment.

Control. The whole tunnel installation is supervised and operated from two control rooms, one on each end of the tunnel, under the auspices of the particular Canton involved. Signals from both the supervisory and control instruments, as well as calls from the SOS boxes, are directed to these control rooms. Each end controls the tunnel for three weeks in turn. About 4,000 signals are transmitted to the control room from 11 remote stations in the tunnel. These display the traffic situation and plant status on panels and print statistics in German and Italian. The control rooms are quite striking. They are loosely divided into two areas: the police and safety functions supervised by the police, and operations supervised by technical personnel. The police service is manned continuously. Its major functions are supervising the traffic flow on access roads and inside the tunnel; operating the communication installation, SOS, telephone, and Telex; and organizing emergency services. The major functions of the operators are supervising all mechanical and electrical systems, maintaining the facilities, and assisting in case of accidents or shutdown.

There is no doubt that a tunnel of this great length presented the Swiss design engineers with unique traffic control, safety, fire, and other emergency problems which far exceed those encountered in shorter tunnels. The solutions developed for this tunnel are apt; apparently little has been spared to make this tunnel as safe as possible.

The Swiss should be commended for this tunnel's design and construction. Design, materials, equipment, and workmanship are absolutely first class and extremely high quality. Although the tunnel is three years old, it appears brand new. The equipment rooms are extremely well maintained. Paint looks new and everything is extremely clean. The only fire protection system missing is an automatic sprinkler system. Electrowatt engineers said they had considered the possibility of installing a sprinkler system during preliminary design, but had rejected the idea because of the danger of superheated steam being produced, explosive reignition of fumes, and possible destruction of stratification where hot air and smoke is high and fresh air low.

Electrowatt indicated that the fire detectors were now working well. Initially, the first stage was a little too sensitive and they had many false alarms triggered by passing diesels. This has been corrected now. With a tunnel of this length, it is important that a fire be detected early and its location be clearly defined, so the Swiss depend on the fire detectors as their primary fire prevention weapon. This first defense is backed up by the SOS boxes and the traffic control loops. With the safety tunnel and the safety rooms, patrons have a safe haven and escape route near at hand.

The ventilation system has no spare fans installed. If a fan fails, ventilation is boosted in adjoining sections to supplement the lost ventilation. Fans can be replaced quickly, however, and several spare fans are on hand. Electrowatt indicated that a fan could be changed in 4 to 6 hours. This involves shutting down one lane, usually during the early hours of the morning when traffic is lightest.

Electrowatt acknowledged severe problems with the computer software. It is still not functioning after three years, and the operators now prefer the manual or the automatic backup systems. If and when the software is functional, Electrowatt anticipates additional problems getting operating personnel to use it after having satisfactorily operated the tunnel without software for so long.

4. Seelisberg Road Tunnel

The Seelisberg Tunnel is a twin-bore, 9.25-kilometer-long tunnel on the Swiss National N-2 motorway connecting Basel and Chiasso. It is the longest twin-bore tunnel in the world. The St. Gotthard, Mont Blanc, and Frejus tunnels are longer, but they have only a single bore with opposing traffic. The Seelisberg Tunnel is 35 kilometers from the St. Gotthard tunnel on the same route. It bypasses a steeply

sloped mountainous point which juts into Lac Lucerne, where a shoreline highway would be very costly and longer than the tunnel.

There are two ventilation shafts from the tunnel to the surface, with fan rooms at each intersection, creating six ventilation sections along the 9.25 kilometers of tunnel. The portals are at an altitude of 485 meters, or about 1,500 feet above sea level. The roadway grades are very slight, .45 percent at the northern section and .6 percent in the south. Two normal cross-sections have been used. Near the portals a conventionally-driven, full horseshoe section was adopted. In the middle areas, a mechanically-driven circular section was used. In the horseshoe section, ducts for exhaust and fresh air are above a ceiling, with a partition separating the two ducts. In the circular section the exhaust air is above the ceiling and fresh air below the roadway. The roadway inside the tunnel is 7.5-meters wide with .8-meter-wide walkways on both sides. In both tunnel cross-sections, the fresh air is introduced on one side just above the sidewalk and the exhaust air leaves through openings in the ceiling. Two fan rooms are at the portals and two are in the tunnel. One shaft is 275 meters tall and the other runs horizontally 640 meters to the surface. The shafts are circular with a partition to form two ducts, one for fresh air and one for exhaust air. The walls of both tunnel sections have a curved panel mounted free of the structural lining to provide a space for seepage. Most of the conduits and cable ducts are under the sidewalks with the fireline and culverts for drainage.

Ventilation for both bores has been calculated for a maximum load of 3,600 cars per hour, or 1,800 cars per lane hour. At maximum ventilation the system can deliver 3,540 cubic meters per second of air to the tunnel. Both bores are divided into six ventilation sections and each section is equipped with intake and exhaust ducts similar to the St. Gotthard installation. Fresh air flues blowing air into the roadway are installed every 8 meters. Exhaust ports are installed in the ceiling on 16-meter centers. Fans are West German-manufactured TLT with two-speed motors in the hub and controllable pitch blades. Dampers are provided in the same manner as described in the St. Gotthard tunnel. Engineers of the Canton involved insisted that fan removal and replacement be accomplished not from the main traffic lanes but from the large cross passages between the two bores at the fan rooms.

Continuous fluorescent strip lighting with several degrees of intensity to adjust for day- and night-traffic are installed in one upper corner of each traffic bore. Lighting

is augmented with high pressure sodium fixtures at the entry portals. Emergency lighting is provided as described for the St. Gotthard tunnel.

The general installations of fire safety and traffic controls in the Seelisberg Tunnel are similar to those in the St. Gotthard Tunnel, except there is no safety tunnel. The safety rooms are in cross-passages between the two tunnels and are equipped similar to those at St. Gotthard. Fire detectors, with single-level sensitivity unlike those at St. Gotthard, are spaced 30 meters along both ceilings. This type has been a problem, since hot diesel truck exhaust often set them off.

TV cameras are installed every 30 meters for traffic control. The SOS boxes are identical to St. Gotthard's, with two manual fire extinguishers, an alarm button, intercom, and warning lamps.

Three-color traffic control lights are installed in each lane at each cross-tunnel. These can be manually or automatically operated. Magnetic roadway loops are tied to a computer similar to the St. Gotthard installation.

Carbon monoxide and visibility-level detectors are similar to St. Gotthard. This facility has a control room at each portal. Differences of opinion between Cantons have prompted certain compromises in control room design.

The fire station, some distance from the south portal, is equipped with three impressive Mercedes Benz fire engines that look somewhat like American soda and beer delivery trucks, with corrugated roller doors on each side. One truck is equipped with foam, the other two with dry powder. All trucks have hoses compatible with the fire hydrants in the tunnel. The trucks can tow a vehicle, extricate any people trapped in a distorted vehicle, and render first aid. All the firemen are trained to give emergency medical aid, although an ambulance is on hand. Police cars regularly transit both bores of the tunnel every hour or so.

In the three or so years that Seelisberg and St. Gotthard have been open to traffic there have been no serious fire incidents. There have, however, been numerous small fires involving the same problems which we experience in the United States, that is, motor, upholstery, brake, and tire fires. These are detected by the several methods described under St. Gotthard. The fires have been extinguished by dry powder fire extinguishers from the SOS boxes or by fire equipment. There have been no injuries and no reported problems with ventilation or system operation.

This facility is not under computer control even after three years in operation, a matter of great concern to Electrowatt. This is being diligently worked on, however, and they expect the computer control system will soon be functioning normally.

Fire tests were conducted in the Seelisberg tunnel in 1980 using simulations of credible incidents. Three simulations were performed.

1. An automobile carburetor fire was started. The motorist used one of the SOS box fire extinguishers, removal of which alerted Control. The motorist was unable to extinguish the fire, but the responding fire equipment did.

2. A truck's load was set afire. Fire detectors activated the fire emergency program. Fire trucks responded, one with difficulty with smoke.

3. Heavy accident involving overturned bus and cars on fire. Again Automatic Fire Emergency program was activated. Due to heavy traffic in the tunnel, the fire equipment took 25 minutes to arrive and start fighting fire due to stalled traffic in way.

The Swiss were satisfied by the response to these test emergencies and felt they learned much about the functioning of the fire emergency systems and personnel.

5. Frejus Road Tunnel

The Frejus Tunnel lies between Lyon, France, and Turino, Italy, and is the shortest route between Brest, Paris, and Lyon in France and Turino, Milano, and Rome in Italy. There is a railroad tunnel at the same location through which the fastest trains between Paris and Rome pass.

The tunnel is about 13-1/2 kilometers or 8.4 miles long, making it one of the longest road tunnels in the world. The grades in the tunnel are gentle, about 1/2 percent. Both portals are roughly 1,000-meters (3,000-feet) high.

The tunnel has a single bore constructed in the typical mountain tunnel horseshoe configuration. It is lined with reinforced concrete; the fresh air and exhaust ducts are located above a false, reinforced-concrete ceiling. A vertical partition divides the fresh air from the exhaust. Ventilation is fully transverse, with flues from the fresh air duct carried down the side walls to introduce air just above the sidewalk. The exhaust air leaves the tunnel through ceiling ports and the exhaust duct above, the same system used in the St. Gotthard, Seelisberg, and other mountain tunnels in Europe.

The 9 meter roadways are wider in this tunnel than in others, providing 15-foot traffic lanes. There is a .9-meter-wide, elevated sidewalk at curb height at each side, with space for cable ducts and the water main for fire hydrants below. The tunnel is enlarged every 2.1 km into an emergency car park, with a safety area opposite.

Shafts connect with the surface 4.2 kilometers from the Italian portal and 5.8 kilometers from the French portal. These shafts provide exhaust and fresh air to fan rooms located at the bottom of each shaft beside the main tunnel.

Because this tunnel crosses a border, it is a cooperative endeavor between Italy and France. There were some philosophical differences in ventilation and other construction, design, and operating features of the tunnel: the air shafts located on the French side have a single shaft with a partition to separate fresh and exhaust ducts; on the Italian side there are two smaller shafts, one for fresh and one for exhaust air.

The highways leading to this tunnel are not yet complete. Coming from Turino, the road is winding and difficult to drive. A new highway from the portal 10-kilometers south will provide more convenient access. It is complete and will be open in about 60 days. A superhighway from this point to the autostrada near Turino is being planned and should be complete in about 4 years. Similar conditions exist on the French side.

The traffic during this investigator's visit was very light. None of the ventilation system fans were operating. Our escort noted that there were times when heavier traffic required the fans to operate.

There are control rooms on each end of the tunnel. They are not as elaborate as those in the Swiss tunnels, but they were none-the-less effective and practical.

The ventilation is fully transverse. There are four fan rooms, one at each portal and one at each shaft. There are two fans on each duct, four in each portal fan room and eight in each of the others, for a total of 24. The ventilation system has been designed for an upper limit of 1,800 vehicles per lane hour, or a total of 3,600 vehicles in both directions per hour. Maximum capacity is 1,580 cubic meters per second of fresh air and 1,300 cubic meters per second of exhaust air.

There are carbon monoxide (CO) and smoke-level sensing systems, one set of sensors in each section. The system maintains 100 parts per million CO, allowing a maximum

excursion to 150 parts per million. Atmospheric clarity is 15% to 30%. This design differs from the Swiss one, with two fans on each duct. The fans are axial flow with two-speed motors (1,000 and 1,500 rpm) located in the hub, with 18 hydraulically-controlled fan blades.

The internal fan rooms are at the side of the main tunnel between the roadway bore and the shafts to the surface. Each internal fan room consists of a large gallery excavated between the main bore and a shaft. This gallery is equipped with an overhead crane. On each side of a gallery there are two exhaust fans and two supply fans for the ducts serving both directions of the roadway on that side. The crane can lift a fan and drop it on a truck where it can be carried to the roadway and out of the tunnel. Fans can also be serviced in position: the upper half of the circular fan housing is removable for access to the blades, the blade control mechanism, the motor, and the bearings. Each fan is supplied with an automatically-controlled, heavy-duty, multiblade damper between the fan outlet and the tunnel ducts. If a fan is to be removed, a heavy plate is bolted on the shaft access to isolate the open fan section from the supply or exhaust shaft. Each fan room contains transformers and switchgear for the fans, lighting, and other systems in its section. The French supply 20 kV and the Italians 16 kV, increased by transformers to 20 kV to match the French potential.

Steps had been taken at the portal buildings to prevent recirculation of exhaust or vitiated air. This was presumably the case at the shaft outlets also.

The Frejus Tunnel has lighting fixtures on both sides of the roadway in the corner between wall and ceiling. The fixtures are not continuous. Design illumination is 50 lux (lumen per square meter). Each fixture is a combination of fluorescent and low-pressure sodium, with both tubes mounted behind a glass or plastic clear lens. Entry zone lighting is augmented by more low-pressure sodium fixtures on the walls and ceiling. Intensity can be varied according to outside conditions.

This tunnel has niches on both sides of the roadway; one side contains a fire hydrant and an SOS box, the other side an SOS box only. The SOS boxes contain fire extinguishers which, if removed, sound an alarm and automatically shift the system into the fire mode, a pushbutton for fire or emergency, and a telephone. The telephones require one to place his head between two lobes containing loud speakers. There are signal lights spaced every 600 meters on both sides of the tunnel which normally burn green. In case of fire, lights turn red or flashing-yellow behind the point of emergency and green ahead.

The presence of magnetic loops was not determined.

The tunnel has 83 television cameras and two monitors in the control rooms at each end of the tunnel. These monitors can tune to one camera each, or can pass from camera to camera to follow a vehicle through the tunnel.

Tunnel wall panels are free of the wall to allow seepage to flow into drainage below. On the French side these are fire-retardant, impregnated wood panels with a painted surface of some kind. On the Italian side they are concrete and look unfinished. The tunnel is washed at least twice per year.

The French and Italian emergency ventilation modes differ in a fire. The Italians select full supply air and use exhaust only when smoke becomes a problem. (The Italian engineer conducting the tour was unable to explain the French method.)

Outside each portal is a fire station, equipped with three fire engines. These fire engines are very similar to Seelisberg's. One engine is equipped with foam and the other two with powder. All have hoses compatible with the fire hydrants in the tunnel, which have nozzles with both French and Italian threads. Fire trucks also double as tow trucks, and have dollies, jacks, equipment for removing people from damaged vehicles, first aid kits, and stretchers.

The Frejus Tunnel has been well-designed and well-constructed. Tunnel authorities depend upon a patron's call from an SOS box or removal of a fire extinguisher to notify the control room of a problem. These do pinpoint the location, however, so TV cameras can observe the problem area, the computer can automatically place the particular ventilation sections and the tunnel ventilation system in the fire mode, signal lights are adjusted as previously described, fire fighters are alerted, and the engines dispatched. The fire mains are pressurized year-round. The fire main is buried in the concrete beneath the roadway and the fire hydrants are the regular street-type that do not freeze.

The safety areas in this tunnel exist only at 2.1 kilometer intervals; there is no safety tunnel as in St. Gotthard. There are fire doors at the fan rooms, however, with separate ventilation available to protect these potential refuges.

Hazardous cargoes are prohibited per European Common Market hazardous cargo regulations.

About three months ago, a truck carrying plastic burst into flame for some unknown reason. The truck driver used an SOS box to call for help, and the fire was expeditiously extin-

guished. The tunnel roadway was damaged and the walls and ceiling blackened, but no one was injured or killed. Here again, litigation is involved and tunnel personnel will not discuss this matter in any detail.

6. The Great St. Bernard Tunnel

The investigator only drove through this tunnel late one afternoon; there was no formal visit. The tunnel lies on a highway connecting Aosta, Italy, and Montreux, Switzerland. It is 5.8-kilometers long, shorter than the other tunnels visited on this trip, and also higher. The road leaving Aosta to the tunnel is narrow and two-lane; and it winds up the mountain with many switchbacks. A toll (about \$10 for small car and driver) is collected at a small town some distance from the tunnel. The tunnel highway climbs from this town to the tunnel covered by avalanche sheds most of the way. There is no portal because the snow-shed-covered highway leads directly to an underground area resembling a large parking garage. Here are immigration and customs facilities for both Italy and Switzerland and a parking area, gas stations, restaurants, stores, and restrooms.

The tunnel appears similar to the other mountain tunnels: roadways, sidewalks, and walls have similar dimensions. The ceiling on the Italian side seems to be constructed of Q-deck. On the Swiss side it appears to be reinforced concrete. From the placement of fresh air and exhaust air flues and ports it seems that there are three air ducts above the ceiling. Two fresh air ducts on either side with flues coming down to supply air openings just above the sidewalk and a centrally located exhaust duct with exhaust ports located in the middle of the tunnel ceiling. There are SOS boxes spaced frequently along both sides of the tunnel roadway. Pictures clearly indicate a fire hydrant, fire extinguishers, an alarm button, and an intercom to talk with the control room. There are signal lights on both sides spaced about 500 or 600 meters apart. These have three lights, red, yellow, and green; the green lights were illuminated in both directions. Every 500 or 600 meters there is an enlargement in the tunnel to provide a parking area. Some places were much wider with doors suggesting fan room at this point.

The walls and roadway seem to be more rough than the other tunnels seen on this trip. The walls are very dirty, almost flat black, and show water staining in some areas.

7. The Mont Blanc Tunnel

The Mont Blanc Tunnel opened in 1965. It is 11.6-kilometers long and passes under the Alps near the highest mountain in Europe, Mt. Blanc. Because of its location, it has become a very heavily travelled route between France and Italy. Truck traffic is particularly heavy.

The tunnel has two lanes of opposing traffic. The cross section is the typical horseshoe, but the air ducts are underneath the roadway, so it has the arched circular ceiling typical of the tunnels seen around Genoa. The walls are reinforced concrete with textures depending upon the lining. Years of heavy diesel traffic have made these walls flat black.

Initially, lighting and ventilation were designed for 600 vehicles per hour, of which 10% were to be trucks. In two years of operation this 600-vehicle limit was exceeded many times. In heavier traffic the atmosphere in the tunnel becomes extremely smoky, which made the illumination appear inadequate and visibility a problem.

After two years the lighting and ventilation systems were improved and the tunnel now operates with satisfactory carbon monoxide levels. Visibility continues to be a problem, however, but the brighter lighting has helped to keep it at satisfactory levels. There is talk of a second bore at Mont Blanc, which would help the situation considerably, since the traffic would be two lanes in one direction, adding piston effect ventilation to the mechanical.

Since the mountain range above this tunnel is extremely high, (2,480 meters of rock above the tunnel at one point, a minimum of 1,000 meters) intermediate shafts to the surface for ventilation were considered economically unfeasible. Consequently, all ventilation had to come from the portals. In order to provide the large ducts necessary, they were constructed under the roadway. The initial system had four fresh air ducts and one exhaust duct. Since the tunnel is 11.6-kilometers long, the ducts serving each tunnel half from each portal fan room would be 5.8-km, or 18,900-feet long. Design engineers felt that a single fresh air duct would be too long to assure even distribution to the roadway, so the total length was divided into four ventilation sections, each 4,700 long. Each 4,700-foot section has its own supply duct and fan in the fan house. Fresh air flues discharge air just above the sidewalk on one side of the tunnel. Initially, the fifth duct was for exhaust, and its capacity was approximately 1/3 the total supply capacity. Ducts high on the sidewall at rather large intervals carry the exhaust air down to the exhaust duct below the roadway. The other 2/3 was exhausted out the portals. This ventilation system was classified as a semi-semi-transverse system. The improvements made after the traffic increased beyond the initial design level converted the single exhaust duct into a supply duct on the theory that more fresh air was needed to dilute the smoke. All of the exhaust leaves through the portals. The velocity in the roadway at maximum ventilation is about 17 miles per hour.

Each duct is equipped with two large bottom-horizontal-discharge, centrifugal fans in the ventilation building. Each fan has inlet boxes and shafts extend out each side of the fan to a large motor on one side and a small motor on the other. These two-speed motors, driving the fan through reduction gear boxes, produce fan speeds of 1/4, 1/2, 3/4 and full.

The inlet boxes prevent air movement within the fan room. Each fan has multiblade dampers at inlet and outlet for isolation. Fans are of French manufacture; motors Italian. Fans, motors, and components can be removed by an overhead crane to an area under a hatch where a truck crane can lift to the surface. The fan rooms contain switch gear for the fans and lighting and were very neat, well painted, and clean.

There are carbon monoxide (CO) and opacity sensing systems in the tunnel periodically spaced along its length. These sensors relay information to a panel in each control room, where CO and smoke levels are recorded on strip charts. There is one set of sensors for each ventilation section, or five in one control room, a total of ten for the entire tunnel.

The initial lighting had 40-watt fixtures suspended over each lane in the tunnel. These fixtures were not continuous and were spaced about 4 meters apart. When lighting and ventilation were upgraded, every other fluorescent fixture was changed to low pressure sodium at the same wattage rating. The original wiring and switchgear were retained. The more efficient lighting increased illumination level while at the same time the sodium/fluorescent mix kept color rendition and visibility at a satisfactory level. The number of low pressure sodium lights increase in the transition zone near each portal.

There are enlarged areas for parking disabled cars spaced every 600 meters in the tunnel. Each one of these has two floor-to-ceiling, air conditioned glass enclosures. One contains an SOS box, which in this case includes a dry powder fire extinguisher, a pushbutton to summon help, and an emergency telephone. The glass was described as high-tempered, which should have some nominal resistance to fire.

There are no loops in the roadways, but TV cameras spaced through the tunnel with monitors in each control room instead. If the operator in the control room receives notification of an alarm or other emergency, he places the ventilation system on fire mode (full ventilation, it being all supply). Lighting is increased and traffic signals are turned yellow or red behind the incident and green ahead.

Fire equipment responds from Courmayeur on the Italian side. Posted on a wall in the control room is a list of tasks for the operator to follow should there be a fire in the tunnel. These include notifying the police and customs and immigration personnel on the Italian side, setting ventilation and signal lights, calling the fire department, and so on. There is no computer to do these tasks automatically.

The fire equipment at Courmayeur has dry power and light water on board, with hoses compatible with the fire hydrants in the tunnel. The tunnel authorities also respond with foam-equipped jeeps.

This tunnel is quite different from Frejus, St. Gotthard, and Seelisberg. The lack of intermediate ventilation shafts present a much different ventilation problem. The ducts underneath the roadway are very large and in certain areas have a cross-section almost 40% of the tunnel itself. A cut-back was made in ventilation capacity at the beginning because of the high cost, and when this route opened up economical freight shipments by trucks through the tunnel, traffic increased since opening day. It is very smokey in the tunnel and the walls have become almost completely black. Fire safety arrangements are not as sophisticated and extensive as those for Frejus and St. Gotthard. The glass-enclosed safety rooms, even though they have a ventilation connection from the supply air duct, appear to offer poor refuge for personnel because of the glass walls and their size: too small for the number of people that might need them in heavy traffic. There is no safety tunnel, no fire detection devices, no traffic loops in the roadway, and the fire truck must come from a town some distance from the tunnel portal.

Hazardous cargoes are prohibited in this tunnel in accordance with the European common market regulations. This regulation is easily enforced, since this is an international border with immigration and customs inspection of all passing vehicles.

8. Postscript

The Swiss and Italian approaches seem to illustrate the opposit ends of tunnel design philosophy: the Swiss have spared no expense to make their few but massive and vital transportation links as safe and comfortable as possible, while the Italians, with hundreds of short tunnels to contend with, have been forced by geography into a bare bones approach. The Celle Ligure incident, on which the complete story has yet to be told, is too isolated a data point to prompt any valid conclusions about the relative merits of either approach, if one can accept a price tag on human lives.

The Swiss philosophy seems to have anticipated recommendations made in the body of this report by a number of decades. Faced with the classic choice "Your money or your life", most of us would choose the former.

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Figure 11 - View of damage from May 13, 1949, Holland Tunnel Fire
[New York, New York (also see cover)]

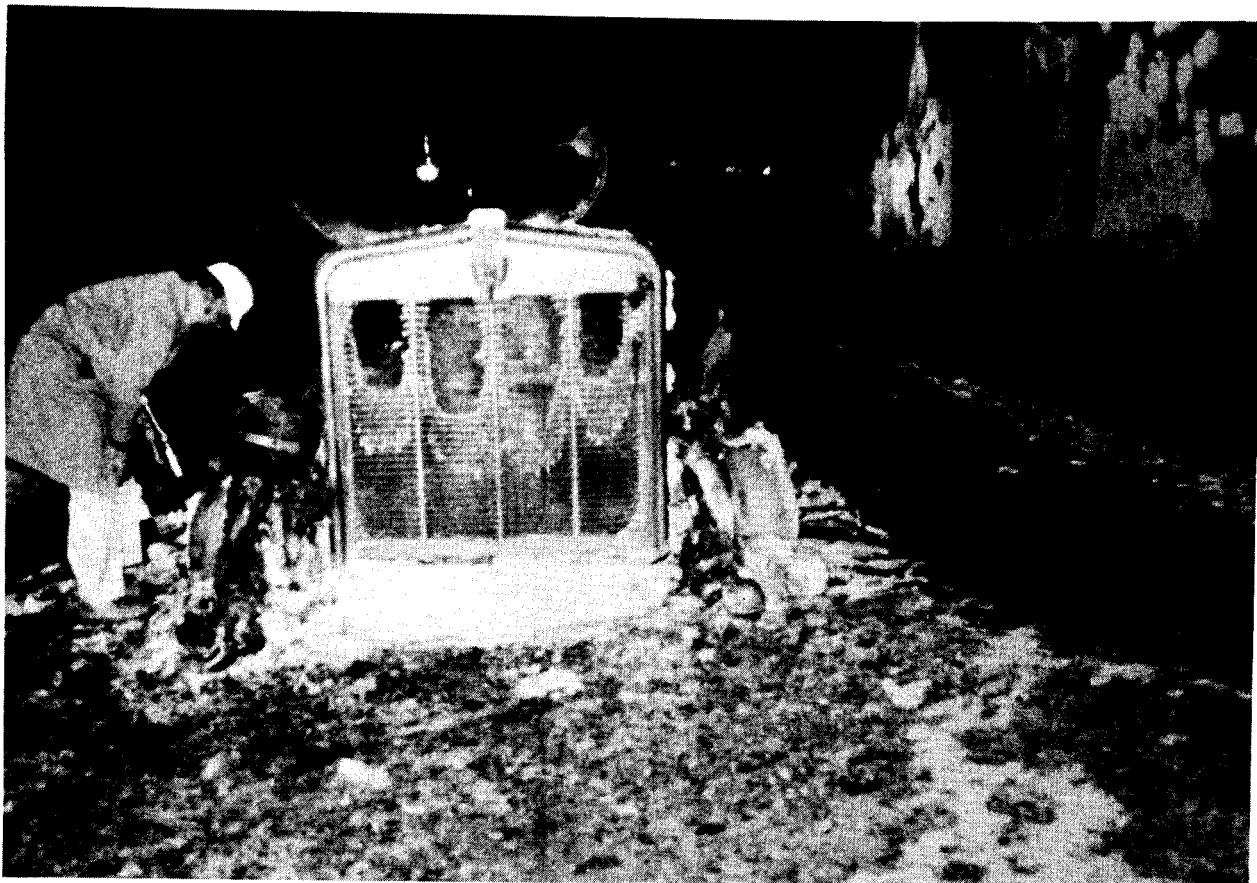


Figure 12 - View of damage April 7, 1982, Caldecott Tunnel fire. High temperatures from fire melted or burned most of the truck in foreground. Noted tiles spalled off the wall and other damage to interior of tunnel.

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