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The Memorial Tunnel Fire Ventilation Test Program: The Memorial Tunnel Test Facility

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ABSTRACT

Many aspects of the Memorial Tunnel Fire Ventilation Test Program (MTFVTP) have made it the most comprehensive of its kind, but none more so than the test facility itself. The Memorial Tunnel test facility was truly state of the art in fire ventilation testing.

Starting with a two-lane mountain tunnel, the engineering consultants for the MTFVTP designed, managed construction for, and maintained a one-of-a-kind facility that allowed testing of seven ventilation concepts and was capable of withstanding nearly 100 fires—four of which were 100 megawatts (MW) (341 MBtu/h). This paper describes the test facility and the many modifications that were made to the Memorial Tunnel in preparation for the extensive testing.

THE MEMORIAL TUNNEL

The Memorial Tunnel is a two-lane road tunnel built in 1953 as part of the West Virginia Turnpike. It is 2,800 ft (853 m) long and it has a 3.2% upgrade from the south to the north tunnel portal. The cross-sectional area of the roadway portion of the tunnel is approximately 390 ft^2 (36 m^2). The cross-sectional area of the duct above the roadway is approximately 260 ft^2 (24 m^2). Figure 1 shows additional tunnel cross-sectional dimensions.

The original tunnel ventilation system was a full transverse type consisting of a supply fan chamber above the south portal and an exhaust fan chamber above the north portal. An overhead air duct, formed by a concrete ceiling above the roadway, was divided into supply and exhaust sections by a vertical concrete dividing wall. The width of the supply and exhaust air ducts varied linearly along the length of the tunnel, decreasing from south to north for the supply duct and increasing for the exhaust duct. Supply air duct discharge outlets were located near the roadway on the west side of the tunnel, while exhaust air ports were located in the tunnel ceiling. The supply outlets and exhaust ports were spaced throughout the length of the tunnel except that no openings were located in the immediate vicinity of the two portals.

FACILITY MODIFICATIONS

Many modifications were made to the Memorial Tunnel in converting it to a fire ventilation test facility.

Fan Rooms

The original central fans located in the north and south fan chambers were inadequate, both in operability and capacity, for the test program. These existing fans were replaced with six new, fully reversible axial flow fans—three in each fan room. To accommodate and support the new central fans and

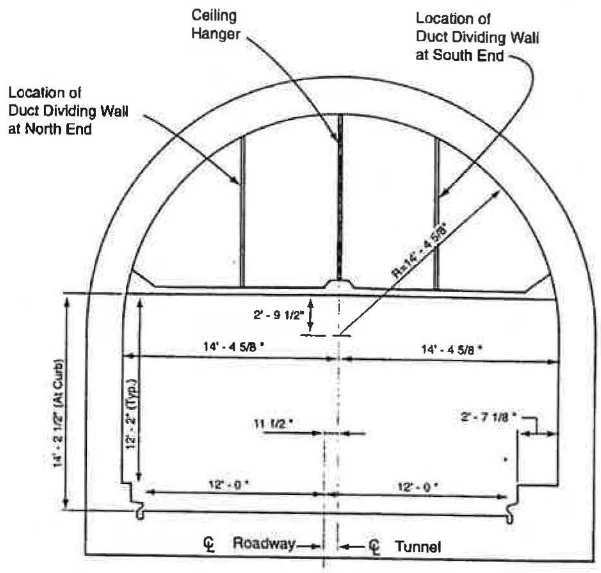

Figure 1 *Memorial Tunnel cross-section looking north.*

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associated equipment, new concrete bases for the fan rooms were constructed. Each fan was equipped with a 300-horsepower (hp) (224-kilowatt [kW]) motor with external auxiliary blowers for motor cooling. Each fan was rated to deliver 200,000 cubic feet per minute (cfm) (95 cubic meters per second [m^3/s]) of air at 5.2 inches water gauge (in. w.g.) (1,294 pascals [Pa]) total pressure and was designed to withstand air temperatures of 600°F (316°C). Adjustable-frequency controllers (AFC) for each fan facilitated operation at variable speeds in the range from 120 to 1,200 rpm in either direction of rotation. Fan controls were installed locally in the fan rooms for manual control and in the control trailer for remote operation. Fans and ductwork in the fan rooms were insulated in anticipation of high exhaust air temperatures. Due to the tunnel's close proximity to the interstate highway, especially at the north end, existing air intake and exhaust louvers were replaced with vertical discharge stacks to prevent smoke migration toward the interstate highway and to improve dispersion in the atmosphere.

Duct

Extensive modifications were made to the tunnel ceiling and the duct above the tunnel roadway. In particular, modifications included the following:

- damaged ceiling section replacement,
- installation of removable partitions in the duct dividing wall,
- installation of mid-tunnel duct bulkhead,
- insulation of the duct and ceiling hangers,
- alteration of ceiling exhaust ports,
- installation of single-point openings, and
- installation of oversized exhaust ports.

Figure 2 illustrates the modifications that were made to the duct and tunnel ceiling.

Damaged Ceiling Section During construction of the interstate highway that bypassed the tunnel, blasting operations caused damage to a 200-ft (61-m) section of ceiling near the north end of the tunnel. Prior to any other modifications to the duct and tunnel ceiling, this damaged ceiling section was repaired. Repairs consisted of demolishing the damaged section and constructing an entirely new tunnel ceiling section.

Duct Dividing Wall Six large openings were cut into the dividing wall that separated the original supply and exhaust air ducts. Depending on the desired ventilation concept, these openings were either covered or uncovered using steel plates. The openings were located 20 ft (6 m), 600 ft (183 m), and 1,200 ft (366 m) from each ventilation building. Each of the six openings had an open area of approximately 180 ft^2 (17 m^2) with a height of 6 ft (2 m). With the openings covered, separate supply and exhaust air ducts were maintained for full transverse ventilation. With the openings uncovered, the wall was effectively removed, and, therefore, both the north and south fans could work to supply or exhaust air.

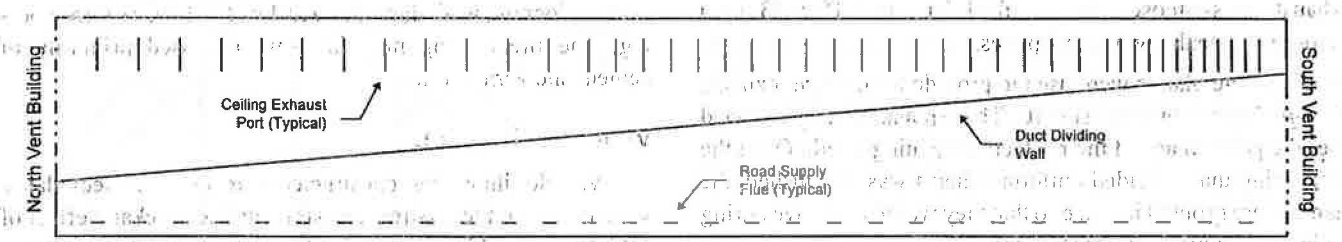

Figure 2a Original Memorial Tunnel duct and ceiling configuration.

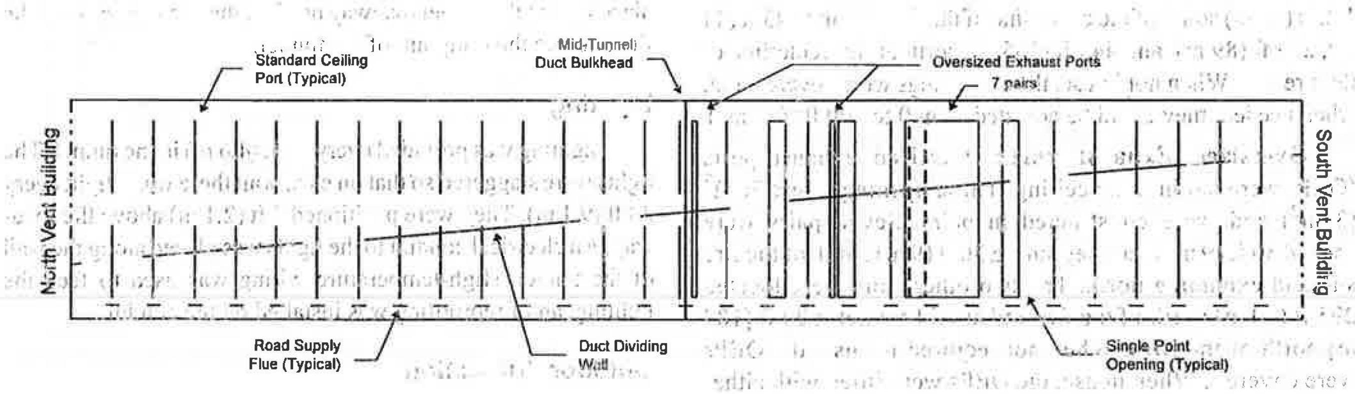

Figure 2b Illustration of the modifications and features of the reconfigured Memorial Tunnel duct and ceiling.

Mid-Tunnel Duct Bulkhead A bulkhead was installed at the midpoint of the duct. This bulkhead was equipped with openings that could be covered or uncovered using concrete-protected steel plates. The bulkhead, when intact, allowed for two-zone ventilation operation. With the openings in the bulkhead uncovered, the tunnel was ventilated as a single zone.

Insulation All of the ceiling hangers throughout the length of the duct were protected with approximately 9 in. (229 mm) of ceramic fiber insulating blankets. In addition, the floor of the duct was insulated with a sprayed-on, high-density, cementitious fireproofing based on vermiculite and cement to protect against structural damage that could have resulted from the repeated fires. The amounts and types of insulation necessary to ensure the integrity of the tunnel ceiling were determined by analysis prior to the design of the test facility.

Ceiling Exhaust Ports The original ceiling exhaust ports were located above the east lane of the tunnel. These slots started 3 ft (0.9 m) from the east wall and were 4 ft (1.2 m) long. Spacing and open width of these ports varied. Beginning at the south ventilation building and extending north 409 ft (125 m), the ports were spaced 5 ft (1.5 m) apart and had an open width of approximately 1.75 in. (44 mm). For the next 1,100 ft (335 m), the ports were spaced 10 ft (3.0 m) apart and had an open width of approximately 3 in. (76 mm). For the final 1,179 ft (359 m), the ports were spaced 15 ft (4.6 m) apart and had an open width of 4 in. (102 mm).

The tunnel ceiling was modified to provide exhaust ports above both lanes of the tunnel. The new exhaust ports were spaced 15 ft (4.6 m) apart. They had an open width of 6 in. (152 mm) and a combined open length of 20 ft (6.1 m). The unused exhaust ports—those spaced 5 ft (1.5 m) and 10 ft (3.0 m) apart—were sealed with steel plates.

Concrete planks were used to provide for uniform exhaust through the ceiling exhaust ports. These planks were positioned over the ports to adjust their effective opening width. Once the positioning that provided uniform exhaust was established, the planks were grouted in place so that they would not move during testing and to minimize air leakage.

Single-Point Openings Single-point openings were cut into the ceiling. These 300-ft^2 (28-m^2) openings were positioned 142 ft (43 m) south of the centerline of the fire site and 143 ft (44 m), 293 ft (89 m), and 443 ft (135 m) north of the centerline of the fire site. When not in use, these openings were covered, but, when needed, they could be adjusted from 0 to 300 ft^2 (28 m^2).

Oversized Exhaust Ports Oversized exhaust ports (OEP) were cut into the ceiling. These openings were 30 ft^2 (3 m^2) and were constructed in pairs. Seven pairs were spaced 30 ft (9 m) apart beginning 30 ft (9 m) south of the fire site and extending north. The two other pairs were located 295 ft (90 m) north of the fire and at mid-tunnel (620 ft [189 m] north of the fire). When not required for use, the OEPs were covered. When in use, the OEPs were fitted with either fusible plastic panels or steel, spring-loaded dampers restrained with fusible links.

Roadway Trench

A pipe trench and a lower, back-filled trench were constructed beneath the tunnel roadway. They extended the full length of the tunnel. The lower, back-filled trench housed approximately 9,000 linear feet (2,740 m) of embedded electrical conduit for power feeds to jet fans. The upper, unfilled pipe trench, which had removable covers, was 4 ft (1.2 m) wide and 4 ft (1.2 m) deep. It contained more than 21,000 linear feet (6,400 m) of insulated chilled-water piping, fuel oil and gas piping, and fire protection piping, and more than 5,000 linear feet (1,525 m) of conduit for fuel oil and ignition control cables. Trench temperature in the fire zone was monitored by thermocouples.

Duct Bank

The existing duct bank along the tunnel roadway was refurbished and used as a raceway for temperature-sensitive cables such as the power feeds to the data-acquisition units and velocity cabinets and the fiber optic communication cables to the closed-circuit television and data-acquisition systems. Parallel to the duct bank, a new cable tray was installed to accommodate thermocouple wiring. Both the duct bank and the cable tray were completely insulated with ceramic fiber blanket insulation, varying in thickness from 1 to 10 in. (25 to 254 mm). More than 70 miles (110 km) of cable protected by approximately 380,000 board feet (900 m^3) of insulation were installed. Duct bank temperature in the fire zone was monitored by thermocouples.

Insulation

The walls and underside of the tunnel ceiling in the fire zone were covered with 6 in. (152 mm) of sprayed-on fireproofing, and the floor of the air duct received 4 in. (102 mm) of fireproofing. The fireproofing material was composed primarily of cement and vermiculite.

Vehicle Silhouettes

Vehicle silhouettes, constructed of rectangular steel plates, were placed in the airstream to simulate the blockage effect of vehicles stopped in the tunnel. They were raised or lowered as required by testing. Three silhouette sizes were used to represent passenger cars, vans, and tractor trailers. The silhouettes were placed along the tunnel roadway north of the fire site between the fire site and the midpoint of the tunnel.

Lighting

Lighting was provided every 15 ft (4.6 m) in the tunnel. The lights were staggered so that on each wall there was a light every 30 ft (9.1 m). They were positioned 7 ft (2.1 m) above the roadway. An electrical conduit to the lights was placed along the wall of the tunnel. High-temperature wiring was used to feed the lighting, and fireproofing was installed on the conduit.

Outdoor Substation

Electricity was supplied to the tunnel through an outdoor, 15-kilovolt substation that was installed for the purposes of the

MTFVTP. The test program placed a high demand for power on the local power company during a test due to the new fans, data-acquisition units, adjustable-frequency controllers, jet fans, and other electrical equipment.

Electrical Equipment Rooms

The four existing electrical equipment rooms that serviced the tunnel had aging equipment that was water damaged. This old equipment was removed and the walls were waterproofed before the new equipment was installed.

A 15-kilovolt–480-volt substation was installed in the northeast and southeast electrical equipment rooms. The new equipment had the capacity for the new fans, adjustable-frequency controllers, chilled-water system, foam suppression system, data-acquisition system, and other general power needs such as power to the control trailer. New electrical boxes and conduit from the tunnel power substation to the lighting, cameras, data-acquisition units, and other equipment were installed. In addition, an uninterruptible power supply was installed in each of the four rooms to ensure that vital instrument circuits and equipment remained energized in the event of site loss of power.

Modifications for Jet Fan Tests

In order to prepare the Memorial Tunnel for longitudinal ventilation using jet fans, major modifications to the facility were necessary. After testing was completed with the ceiling in place, all instrumentation and equipment were removed from the tunnel, and the tunnel ceiling was removed so that the jet fans could be installed in the crown of the tunnel.

After ceiling removal, all equipment and instrumentation were reinstalled, and then the jet fans were installed in groups of three. Five groups of jet fans were installed to conduct 12 tests, after which an additional three groups of jet fans were installed. The spacing for all the groups was approximately 300 ft (91 m).

The three jet fans in a group were installed so that the center of each fan was 7 ft, 5 in. (2.3 m) from the tunnel ceiling and 8 ft (2.4 m) from one another. Each jet fan was equipped with a 75-hp (56-kW) motor rated to deliver 91,000 cfm (43 m^3/s) of air at an exit velocity of 6,730 fpm (34 m/s). The jet fans were fully reversible and were designed to withstand air temperatures of 570°F (299°C). The tip angle and tip diameter of the fans were 19.5 degrees and 53.8 in. (1,367 mm), respectively. The fans had an inside diameter of 54 in. (1,372 mm) and an outside diameter of 62 in. (1,575 mm).

TEST SUPPORT SYSTEMS

To make testing possible, numerous support systems were added to the Memorial Tunnel to transform it into a state-of-the-art testing facility.

Control Trailer

The control trailer was the operations center for all test activities. Test operations were remotely initiated and monitored from this trailer. The control trailer housed panels with controls for the central fans, jet fans, the fuel oil delivery system, and the foam suppression system. It also contained two banks of closed-circuit television (CCTV) monitors that received transmissions from each of the CCTV cameras. In addition, the control trailer contained the computers and many other elements of the data-acquisition system. The control trailer also accommodated a radio base from which the activities of the highway personnel that monitored the nearby interstate were coordinated.

Instrumentation

Specific instrumentation was provided to monitor and record the following variables during the fire tests:

- air temperature,
- air velocity, and
- gas concentrations.

The instruments were installed on 15 instrument trees (identified as loops) spaced at various cross sections throughout the tunnel, portal-to-portal. Diagrams of the general instrument locations, both with the ceiling in place and with the ceiling removed, are shown in Figure 3.

The measurement of tunnel air temperature was accomplished through the use of thermocouples located at each of the 15 cross sections throughout the tunnel. The thermocouples had an expected accuracy of ±0.75% and were capable of measuring air temperatures from 32°F to 2500°F (0°C to 1371°C). Additional temperature measurements were taken at locations 50 ft (15 m) outside each tunnel portal.

The instrument trees located at 10 of the 15 tunnel cross sections were equipped to measure airflow by a modified ASHRAE traverse method. The measurement of air velocity was accomplished using bidirectional pitot tubes. The differential pressure across the pitot tubes was measured by transducer assemblies that were housed in velocity cabinets located at the instrument trees. These transducer assemblies were designed to measure very low pressure ranges (0 to ±0.25 in. w.g. [62.2 Pa], 0 to ±1.0 in. w.g. [248.8 Pa], and 0 to ±1.6 in. w.g. [398.1 Pa]). The air temperature in the vicinity of the bidirectional pitot tubes and the ambient barometric pressure were used in combination with the measured differential pressure to calculate the air velocity.

The gas sampling system drew gas from specific tunnel locations to gas analyzers located in the electrical equipment rooms. Gases were analyzed for carbon monoxide (CO), carbon dioxide (CO_2), and total hydrocarbon content (THC). The analyzers were housed in climate-controlled cabinets. Methane gas (CH_4) was monitored at the fire location through the use of individual in-situ electrochemical cell detectors located behind the tunnel wall. Carbon monoxide concentration was also monitored using electrochemical cell-type analyzers at the control trailer for personnel safety.

Additional instrumentation was provided to monitor

- ambient weather data at two meteorological stations;
- conditions at the fire pans including pan weight, fuel oil flow, pan water temperatures, and instrument well temperatures;

- status of the foam suppression, compressed air, and chilled-water systems;
- internal cabinet temperatures for the data-acquisition units (DAU) and velocity cabinets; and
- fan status including vibration data and winding and bearing temperatures.

Data-Acquisition System

The collection and reduction of test data was accomplished using the data-acquisition system (DAS). The DAS consisted of five DAUs, five input/output computers (IOC), two engineering workstations, and three personal computers.

The DAUs—three in the tunnel and two in the electrical equipment rooms—received input from all instrumentation and relayed it to the IOCs in the control trailer via fiber optic cable. All data points were continuously scanned and relayed at a rate of once per second. For protection, the three DAUs in the tunnel were encased with a thermal insulating shell and cooled internally by the chilled-water system. The two DAUs outside the tunnel were equipped with air-conditioning units. The internal temperature of the DAU cabinets was monitored by thermocouples.

The IOCs obtained raw data from the DAUs and performed the conversions and calculations necessary to make the data understandable using a custom-designed software package called EPICS (Experimental Physics and Integrated Control Systems). The IOCs processed more than 1,400 data points and 1,650 calculations per second. The IOCs transmitted information over an ethernet line to the two workstations.

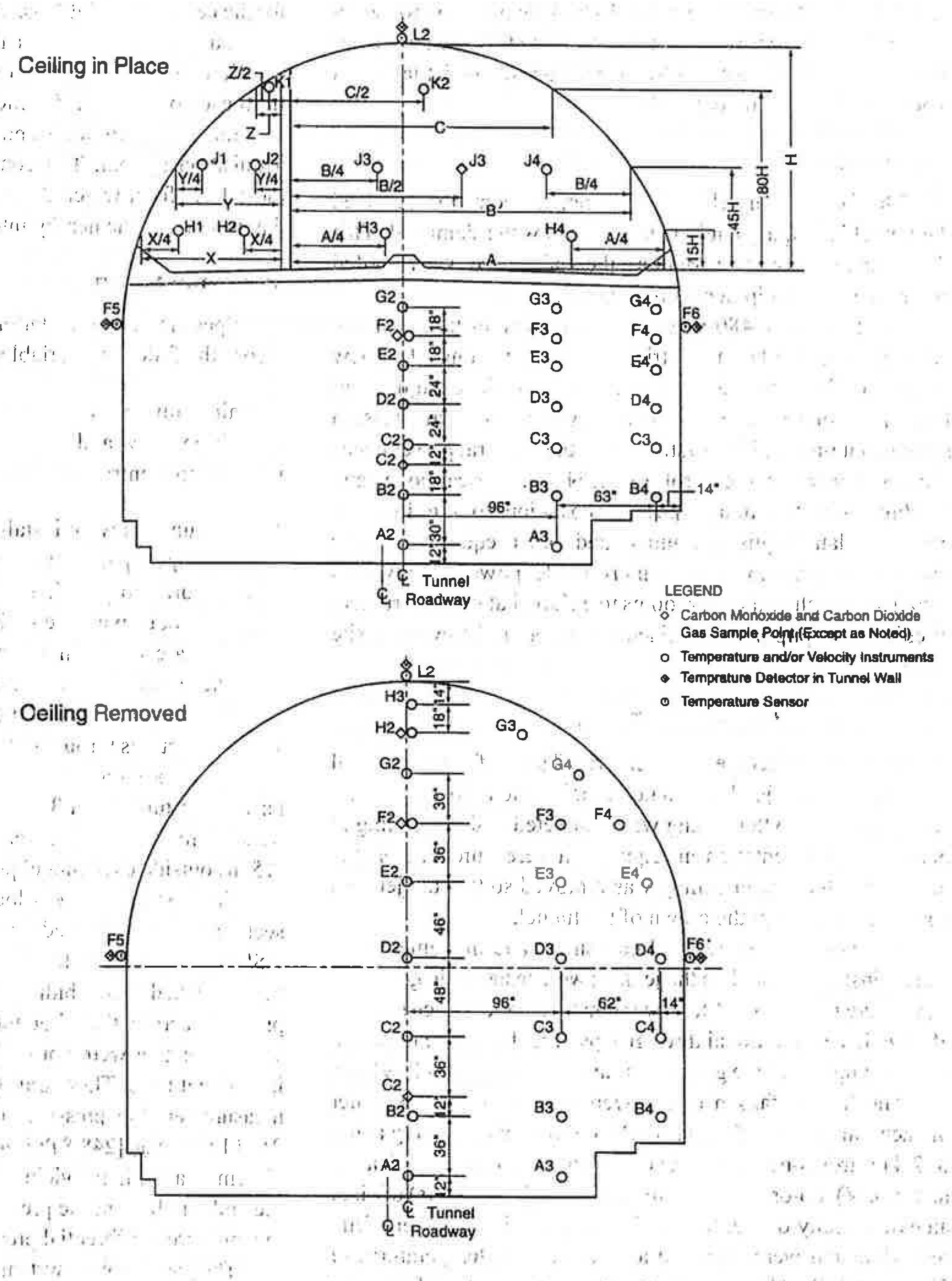

Figure 3 General instrumentation locations, sections looking north.

The workstations were UNIX-based systems that logged and archived each analog data point and final calculated point. There were two workstations for redundancy. These workstations ran a graphic user interface with a series of displays that presented the information to the operator in real time in an easy-to-use format. This aided in test monitoring. The workstations also accepted and relayed operator inputs to the IOCs. The three personal computers were networked to the workstations as remote terminals for monitoring purposes.

Fuel Delivery System

Four steel pans were installed at the approximate quarter point of the tunnel (782 ft [238 m] from the south portal) in which the oil fires were burned to generate nominal heat release rates ranging from 10 MW to 100 MW (34 MBtu/h to 341 MBtu/h). Based on engineering estimates, a 48-ft^2 (4.5-m^2) exposed fuel surface area produces a nominal heat release rate of approximately 10 MW (34 MBtu/h). Pan sizes of 10, 20, 30, and 50 MW (34, 68, 102, and 171 MBtu/h) resulted in the desired flexibility to vary the total heat release rate. For example, the 20-, 30-, and 50-MW (68-, 102-, and 171-MBtu/h) pans were used to generate a 100-MW (341-MBtu/h) fire. The fire pans were set about 30 in. (762 mm) above the tunnel floor and were filled with 6 in. (152 mm) of water on which the measured supply of fuel oil was floated.

Delivery of low-sulfur number 2 fuel oil to the pans was actuated remotely from the control trailer, as was ignition. Fuel-oil-handling equipment included a 5,000-gallon (18,927-liter) storage tank located near the south portal and three fuel oil pumps with flow-regulating valves. The tank was equipped with an anti-siphon valve to prevent oil from draining from the tank when the pumps were not running. Fuel was pumped from the storage facility outside the tunnel through piping installed in the trench below the roadway. Fuel oil was introduced into the pans through a length of pipe containing multiple holes and located under the water in the pans. This pipe sparger enabled fuel to be added to the pans without causing undue fluctuations in the heat release rate. The fuel oil level in the pans was regulated by weigh cells under the fire pans, which provided feedback to automatic controllers in the control trailer. The ignition system included an electric, remote-controlled gas pilot lighter with flame sensors supplied from a liquid propane (LP) gas piping system.

The fuel pan area had a containment berm, located down-grade of the pans, to contain any fuel spillage. Thermocouples were provided in each fuel pan to monitor a possible overflow, pan water temperature, and instrument temperature in the pit below the pans.

Closed-Circuit Television System

A CCTV system was installed to visually monitor the fire ventilation tests. The CCTV system consisted of seven cameras: two located 200 ft (61 m) north and south of the fire and designated the fire zone cameras, one located 1,100 ft (335 m) north of the fire and designated the north roadway camera, two located outside the tunnel and aimed at the tunnel portals, and two located at the north and south meteorological towers and aimed at the highway. The north roadway camera was installed after 13 tests had been conducted when the need for an additional camera to monitor smoke movement north of the fire was identified. The three cameras inside the tunnel had only zoom capability. The remaining cameras were equipped with pan, tilt, and zoom capability. All cameras had remote operating capability from the control trailer. The two fire zone cameras were cooled with chilled water and were provided with compressed air to clear the lenses of soot when necessary. The CCTV system also consisted of recording equipment as well as two banks of monitors, with each bank containing a monitor for each camera. In addition to these 7-in. (178-mm), black-and-white monitors, a 17-in. (432-mm) color monitor that could receive input from any of the seven cameras was installed in the control trailer.

Meteorological Stations

Two towers located outside the north and south tunnel portals were provided with meteorological instrumentation to monitor and record ambient dry-bulb and wet-bulb air temperatures, barometric pressure, wind speed, and wind direction.

Chilled-Water System

A chilled-water system composed of a 70-ton (246-kW) chiller, a 120-gpm (7.6-L/s) pump, and a piping distribution system protected in the pipe trench was installed to provide cooling to CCTV cameras, velocity cabinets, and each DAU in the tunnel. A 50% glycol solution chilled to 44°F (7°C) was circulated to each protected component at a rate of 5 gpm (0.3 L/s).

Foam Suppression System

A foam suppression system was installed as a safety precaution and to ascertain the impact of ventilation on foam discharge and foam system effectiveness. The foam suppression system was installed both with the ceiling in place and with the ceiling removed for longitudinal ventilation using jet fans.

The foam was a 3% aqueous-film-forming foam (AFFF) solution formed by mixing foam concentrate with fresh water. The water was stored in a 15,000-gallon (56,781-L) fire water storage tank, and the foam concentrate was stored in a 500-gallon (1,893-L) foam concentrate tank. The foam was mixed outside the south portal and pumped to an array of foam discharge nozzles. The nozzles covered a 90-ft (27-m) section of the tunnel and were located above or to the side of the fuel pans.

For the tests conducted with the tunnel ceiling in place, the nozzles were installed at the ceiling, 14 ft (4.3 m) above the roadway. The nozzles were placed in two rows parallel to the tunnel roadway and spaced 10 ft (3.0 m) apart. Each row contained nine nozzles that were spaced 10 ft (3.0 m) apart. With the ceiling removed, the nozzles were mounted on the west wall of the tunnel adjacent to the fire, 7 ft (2.1 m) above the roadway. The piping and discharge nozzle layout of the two foam suppression system configurations is shown in Figures 4-6.

The foam suppression system was manually initiated at the control center. The average time for the foam to discharge from the nozzles after initiation of the system was approximately 30 seconds. During discharge, the measured volume flow rate of the foam was approximately 200 gpm (12.6 L/s) for the overhead discharge system and 125 gpm (7.9 L/s) for the sidewall discharge system.

ANCILLARY FACILITIES

Ancillary facilities were also included as part of the test site. These facilities were used to coordinate and control many of the daily program activities and are detailed below.

Administration Trailer

The administration trailer was the hub of the test program's daily activities. It contained the resident engineer's and the lead

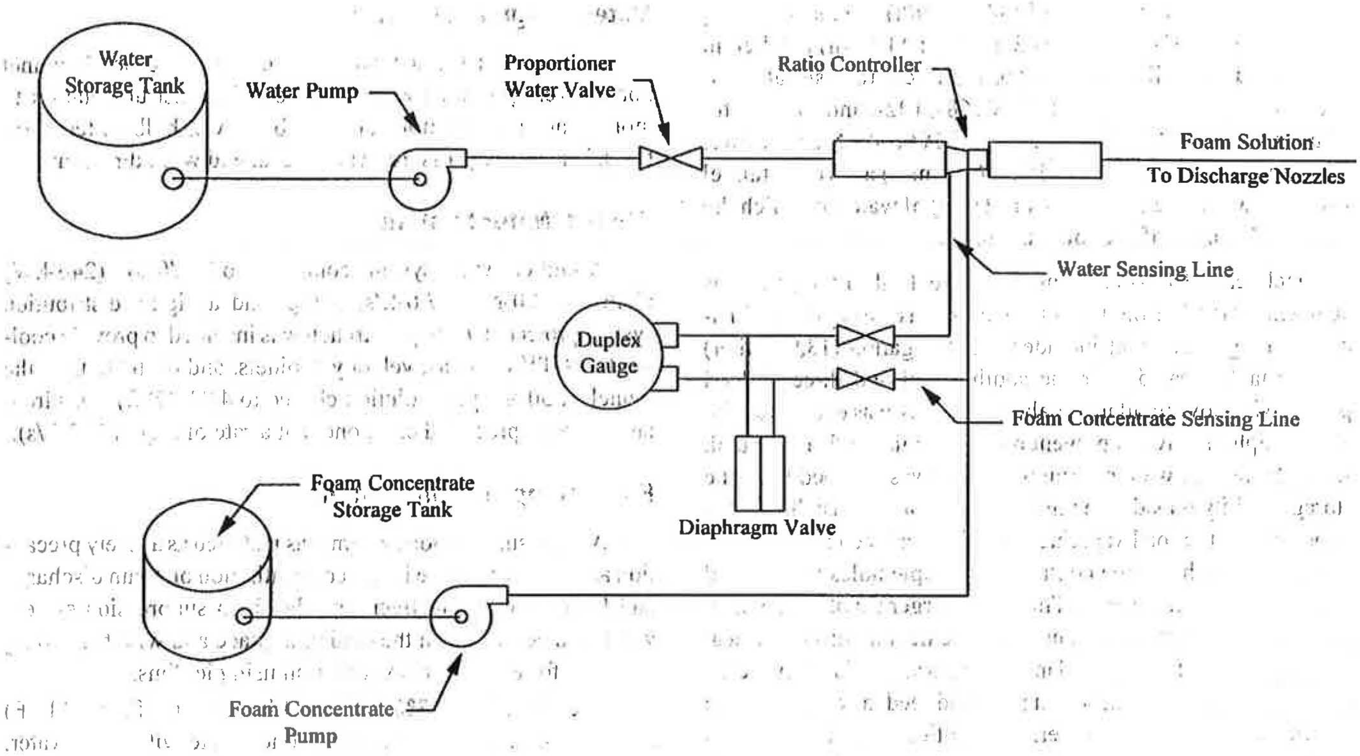

Figure 4 Flow schematic of the foam suppression system.

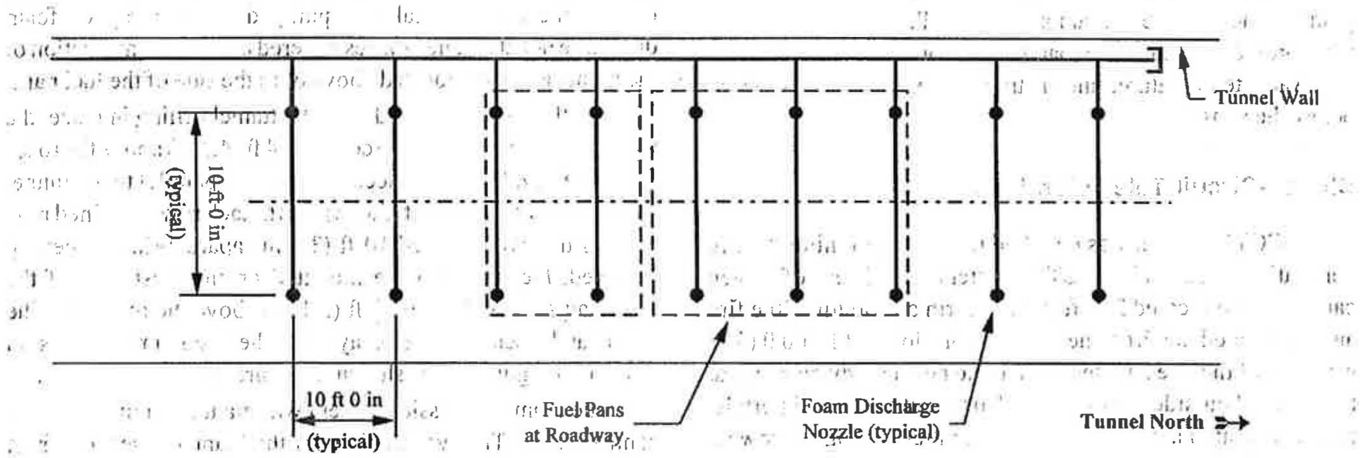

Figure 5 Overhead discharge foam suppression system configuration, plan view.

field engineer's offices. All staff meetings, status meetings, and meetings with the contractors were held here.

Document Storage

All test data tapes and video footage for every test were kept in fireproof cabinets to safeguard this information from any unforeseen accident.

Guard Station

The test site had round-the-clock security for the duration of the test program. A guard station staffed with security personnel was located at the entrance of the test site to ensure that only authorized personnel were allowed access.

DURATION

The design and construction of the test facility took approximately 43 months. The notice to proceed for the design of the test facility was issued on October 19, 1989. The design of the test facility concerned the facility modifications and instrumentation and support systems design. Final design of the facility modifications was completed in June 1990. The facility modifications contract was awarded in November 1990, at which time construction of the test facility began.

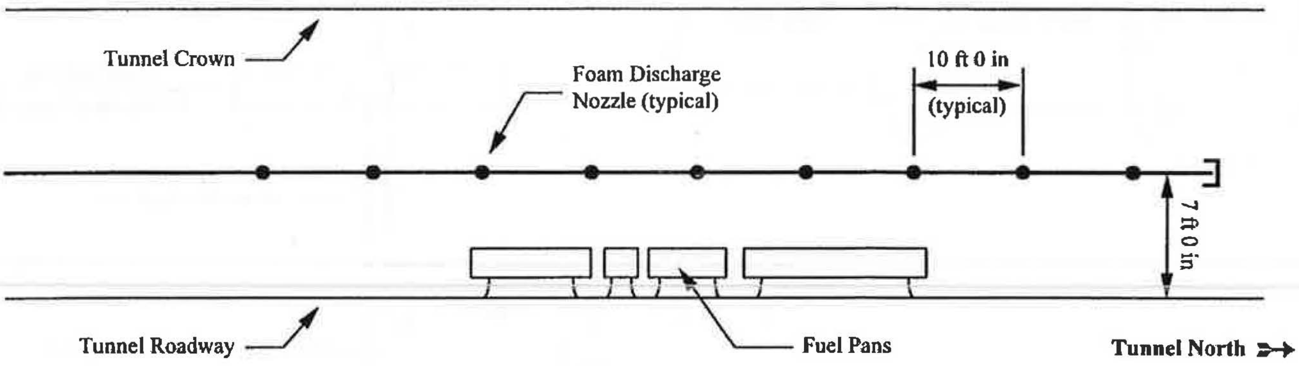

Figure 6 *Sidewall discharge foam suppression system configuration, profile view.*

Final design of the instrumentation and support systems was completed in May 1991. The instrument installation contract was awarded in January 1992, at which time instrumentation and support systems were added to the Memorial Tunnel.

Construction of the test facility was completed in April 1993. Two commissioning tests were held on May 18, 1993, and July 1, 1993, to verify that all systems were functioning properly. Actual fire ventilation testing began in September 1993. Testing with the central fans (ceiling in place) was completed in July 1994. At this time, the modifications to the test facility in preparation for jet fan testing were made. These modifications were completed in December 1994, at which time testing resumed. Jet fan testing was completed in March 1995.

ACKNOWLEDGMENTS

The authors acknowledge with appreciation Michael A. Whelan, lead start-up engineer for the MTFVTP, for his input on the many elements of the Memorial Tunnel test facility.