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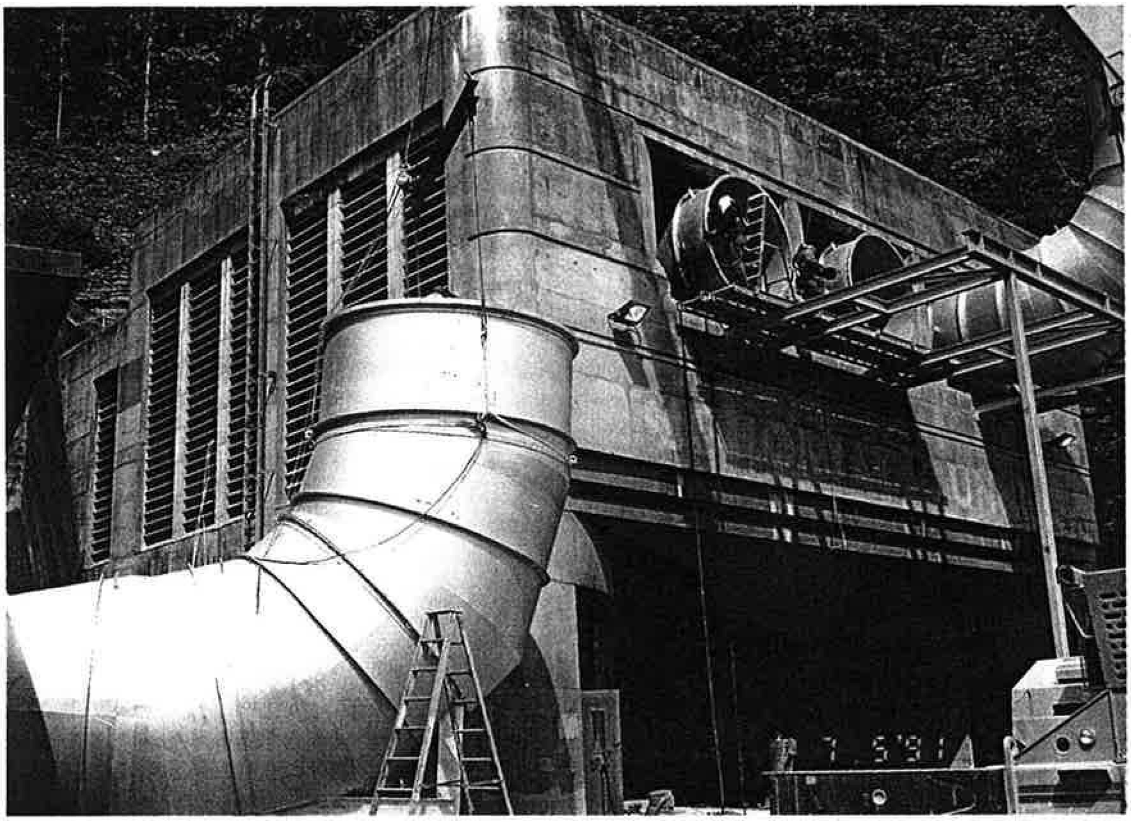

Workers install elbow duct section at the South Portal at the Memorial Tunnel in West Virginia. The abandoned highway tunnel was used for a six-year, $38 million program of fire ventilation tests.

The Memorial Tunnel Fire Ventilation Test Program

By Kelly A. Giblin, P.E.
Associate Member ASHRAE

When the 1999 edition of the ASHRAE Applications Handbook is published, the chapter on Enclosed Vehicular Facilities will contain significant new material on tunnel ventilation. The reason? The recent completion of a six-year, $38 million program of full-scale fire tests conducted in an abandoned highway tunnel in West Virginia, known as the Memorial Tunnel Fire Ventilation Test Program (MTFVTP).

But ASHRAE members don't have to wait until 1999 to learn about the test results. ASHRAE Technical Committee TC 5.9 will be sponsoring a symposium at the 1997 Annual Meeting in Boston detailing the history, scope, and results of the MTFVTP, which are briefly summarized in this article.

Background

The need for validation of the methodologies and criteria used in the design of tunnel ventilation systems was recognized by the members of TC 5.9 more than 10 years ago. About that time, the Federal Highway Administration (FHWA) and the Massachusetts Highway Department (MHD) were beginning preliminary design for the construction of a massive highway/tunnel project in Boston known as the Central Artery/Tunnel (CA/T). TC 5.9, which included several members of the design team, convinced the FHWA and MHD to support a tunnel ventilation test program as part of the design effort.

In 1989, the FHWA and MHD authorized a subcommittee of TC 5.9 to develop a scope of work for a comprehensive fire ventilation test program in the Memorial Tunnel, which had been closed two years earlier when the West Virginia Turnpike was realigned. Shortly thereafter, the TC 5.9 subcommittee drafted a report that assessed the existing tunnel facilities, outlined the modifications required, indicated the ventilation equipment/configurations

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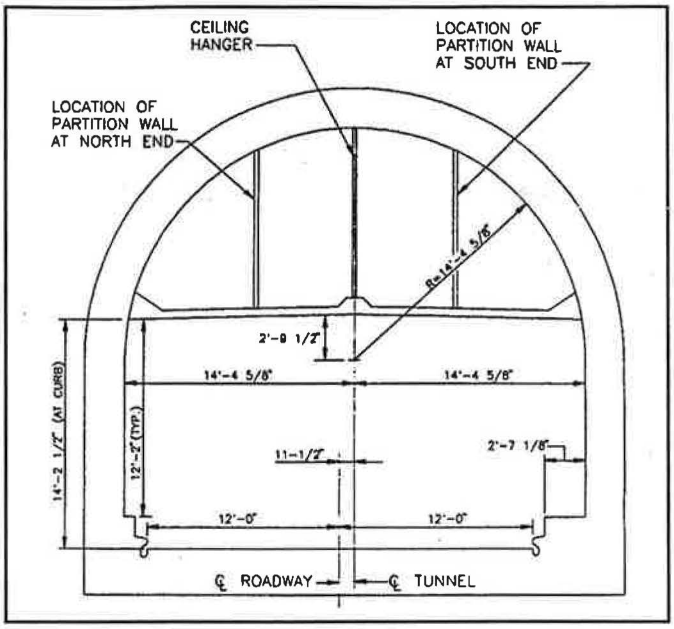


Figure 1: A cross-section of the Memorial Tunnel, looking north.

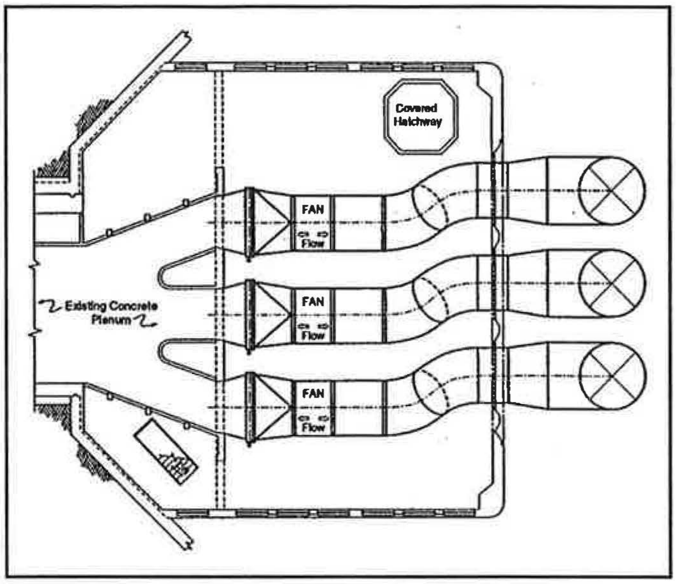


Figure 2: Layout of the fan room at the South Portal.

that should be tested, and specified the types of tests to be performed. Subsequently, the consortium designing the CA/T project developed construction plans and specifications for the tunnel modifications, while the TC 5.9 subcommittee completed a detailed test plan.

The Test Facility

Located near Charleston, W. Va., the Memorial Tunnel was constructed in 1953 and later became part of the Interstate Highway System. The two-lane tunnel is 2800 ft (853 m) long and has a 3.2% grade from the south to the north portal. It has a total cross-sectional area of 650 ft^2 (60.4 m^2), including a 390 ft^2 (36.2 m^2) vehicular area and 260 ft^2 (24.2 m^2) ceiling plenum (see *Figure 1*). The ceiling plenum, which was later removed for longitudinal jet fan testing, was divided into supply and exhaust sections whose areas varied linearly along the length of the tunnel. Supply outlets were located near the roadway surface, while exhaust inlets were in the tunnel ceiling.

The modifications made to the tunnel for the test program included the installation of new central fan plants in both the north and south fan rooms (see *Figure 2*). Three 300 hp (224 kW) fully reversible axial flow fans with external cooling were installed in each fan room. Each fan was capable of moving 200,000 cfm (94.4 m^3/s) at 5.2 in. water gauge (1294 Pa), and was rated to withstand temperatures up to 600°F (316°C), and had adjustable frequency drives capable of varying the fan speed between 120 and 1200 rpm in either direction. These fans would be used in the full and partial transverse ventilation tests.

A mid-tunnel bulkhead was installed in the existing ceiling plenum to allow for two zone ventilation. In addition, openings were made in the wall dividing the supply and exhaust sections of the ceiling plenum to allow for airflow patterns that would occur without that wall. When the transverse tests were completed, the ceiling plenum was removed and the jet fans were installed. Twenty-four 75 hp (56 kW) axial flow jet fans were suspended from the tunnel ceiling in equally spaced groups of three. Each fan was capable of moving 91,000 cfm (43.0 m^3/s) at an exit velocity of 6730 fpm (32.4 m^2/s), and was rated to withstand temperatures up to 570°F (299°C).

In addition to the above fan systems, the test program required the installation of equipment to simulate tunnel fires; a chilled water plant to provide cooling to instrumentation and equipment; a fire suppression system; and data acquisition, control and monitoring equipment. The latter included instrument trees located strategically throughout the tunnel to measure air temperature, air velocity and gas concentration.

Air temperature was measured through the use of thermocouples. Air velocity measurements were taken using differential pressure instrumentation with three different ranges. The gas sampling system analyzed levels of carbon monoxide, carbon dioxide, and total hydrocarbon content. There were also two meteorological stations outside the tunnel portals. In total, over 1400 instrument sensing points recorded data once every second during the tests, yielding up to 3 million points of information for each of the 98 tests conducted.

The Test Plan

The stated objectives of the MTVFTP were to:

- *Develop a comprehensive database regarding temperature and smoke movement from full-scale fire ventilation tests which would permit a definitive comparative evaluation of the capabilities of transverse and longitudinal ventilation systems to manage smoke and heat in a fire emergency; and,*
- *Determine, under full-scale fire test conditions, the relative effectiveness of various ventilation system configurations, ventilation rates, and operating modes in the management of the spread of smoke and heat for tunnel fires of varying intensities.*

To accomplish these objectives, the various fan systems were tested for fire sizes of 10, 20, 50 and 100 megawatts (MW). For perspective, a 20 MW fire is representative of a truck or bus fire, while a 100 MW fire represents a fire involving a fuel spill. Variations were also made in airflow quantity, longitudinal air velocity near the fire, and fan response time.

In addition tests were conducted to assess the impact of longitudinal air velocity on foam suppression system performance.

The original test plan issued in July, 1990 outlined 18 test sequences totaling 130 individual tests. However, six months into the actual testing, it became apparent that six of the sequences could be deleted, and only 98 individual tests were eventually conducted.

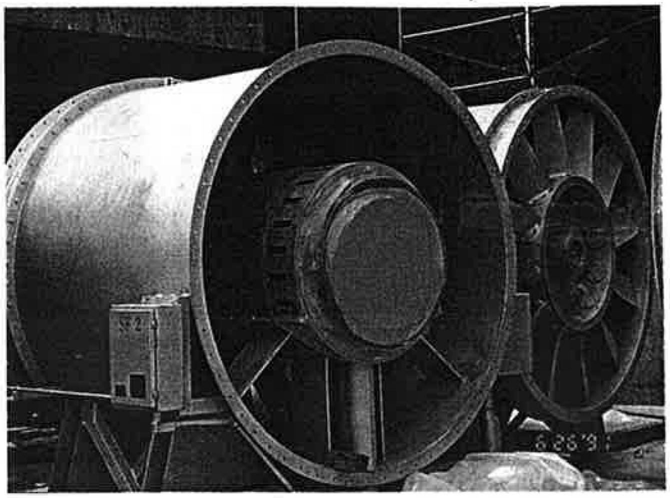
Full Transverse Ventilation Tests

Full transverse ventilation, whereby a distribution pattern of forced air is uniformly supplied and exhausted the full length of the tunnel, was tested for fire sizes of 10, 20 and 50 MW. Both balanced (equal supply and exhaust) and unbalanced (excess exhaust) flows were tested.

The test results showed that balanced full transverse ventilation provides insufficient smoke management capabilities for fire sizes of 20 MW and greater, and cannot create longitudinal airflow in the tunnel. Unbalanced flows generated enough longitudinal airflow to provide effective temperature management up to the 20 MW fire size, but smoke migration was still a problem at that level.

Partial Transverse Exhaust Ventilation

A partial transverse exhaust ventilation system extracts air in a uniform pattern throughout the length of the tunnel, with no supply air provided. This type of system was tested for both 20 and 50 MW fire sizes. For a 20 MW fire, an exhaust rate of 80 cfm/lf (0.124 m^3/s/lm) contained smoke and heat effectively within 200 ft (61 m). An exhaust rate of 100 cfm/lf (0.155 m^3/s/lm), the current standard recommended in the ASHRAE Applications Handbook, limited acceptable smoke and heat migration to within about 700 ft (213 m) for a 50 MW fire. Like full transverse ventilation, it was also sensitive to the fire location because it offers no control over the direction of longitudinal airflow.



300-hp (224 kW) central axial fans were placed through hatch in ceiling into fan room.

Partial Transverse Supply Ventilation

A partial transverse supply ventilation system distributes air in a uniform pattern throughout the length of the tunnel, with no air exhausted. This type of system was tested for only 20 MW fires. Although capable of providing longitudinal airflow to the tunnel, partial transverse supply ventilation did not provide adequate smoke and temperature management.

Two-Zone Partial Transverse Ventilation

This ventilation scheme is not sensitive to fire location because the direction of the longitudinal airflow can be controlled. This is accomplished by operating one zone in the partial transverse supply mode, and the other in the partial transverse exhaust mode. Tests with fire sizes of 20, 50 and 100 MW were conducted. For a 20 MW fire, a ventilation rate of 100 cfm/lf (0.155 m^3/s/lm) contained temperatures within 100 ft (31 m) of the fire, and smoke migration within 200 ft (61 m) upgrade and 150 ft (46 m) downgrade of the fire. Stratification of the smoke at the ceiling required air velocities of 350 fpm (1.78 m/s) upgrade and 150 fpm (0.76 m/s) downgrade of the fire. The 50 MW fire required a ventilation rate of 150 cfm/ft (0.232 m^3/s/lm) to achieve the same results.

Partial Transverse Ventilation with Single Point Extraction

Single point extraction (SPE) systems use a series of large exhaust inlets with normally closed dampers, located the length of the tunnel. The inlet dampers are opened to provide smoke extraction at a point nearest the fire (or other optimum location).

This type of system was tested with fire sizes of 20 and 50 MW. The tests revealed that SPE was effective at controlling temperature and smoke migration for 50 MW fires when a ventilation rate of 110 cfm/lf (0.170 m^3/s/lm) was employed.

However, the most critical variables for SPE systems were found to be the size and location of the exhaust inlet. Inlets upgrade from the fire location provided significantly better performance.

Partial Transverse Ventilation with Oversized Exhaust Ports

This system uses a standard partial transverse exhaust system supplemented with larger, normally closed emergency exhaust ports containing fusible link dampers or drop out panels, which can open locally to the fire. For these tests, the oversized exhaust ports were installed in pairs above the fire test area in the plenum ceiling.

The tests showed that the plastic drop out panels did not fuse until nearly twice the intended temperature, while the fusible link dampers provided quick response. Compared to conventional exhaust ports, this system displayed significant improvement in smoke and temperature management using ventilation rates as low as 85 cfm/lf (0.132 m3/s/lm).

Point Supply and Point Exhaust Operations

The purpose of these tests was to determine the minimum air velocity required to prevent backlayering, the movement of smoke in the opposite direction of the exhausted air. This value, which can be calculated theoretically, is known as the "critical velocity."

The tests revealed that, for 10, 20 and 50 MW fires, the measured critical velocity was higher than the theoretical values calculated. A velocity of at least 440 fpm (2.24 m/s) was required to prevent backlayering for fire sizes of 25 MW and lower. For a fire approaching 50 MW, the necessary velocity was at least 540 fpm (2.74 m/s).

Longitudinal Ventilation with Jet Fans

Fifteen tests for fire sizes of 10, 20, 50 and 100 MW were conducted for this method, which uses jet fans that discharge air at high velocities, which generates longitudinal airflow. The jet fans, installed the length of the tunnel as indicated above, induce the longitudinal airflow by impulse rather than moving the air directly.

The test results indicated that this method was effective for smoke and temperature control for each fire size where longitudinal air velocities of 500 fpm (2.54 m/s) were created. However, the thermal effects of the fire and the area and grade of the tunnel were found to be significant factors in the ability of the system to achieve this velocity. Thus, the air velocity needed to overcome these effects may exceed the minimum velocity to prevent backlayering.

Natural Ventilation

Two tests were conducted to assess the impact of natural ventilation due to grade and the thermal effects of the fire. The primary observation from these tests was that smoke could spread upgrade quite rapidly, filling the tunnel within 3 to 5 minutes for 20 and 50 MW fires. The average smoke velocities measured for these fire sizes were 435 fpm (2.2 m/s) and 780 fpm (4.0 m/s) respectively, traveling upgrade. Natural airflows essentially kept the tunnel downgrade of the fire free of smoke.

Foam Suppression System Tests

A foam suppression system was employed for six of the tests to determine the impact of longitudinal air velocities on the performance of the suppression system. Four 50 MW fire tests using the various transverse ventilation schemes described previously were conducted using an aqueous foam fire suppression system. Two additional tests were made with the jet fan systems for 50 and 100 MW fire sizes. The tests showed that the effectiveness of ceiling-mounted discharge nozzles was not impacted by even the highest longitudinal air velocity of 825 fpm (4.20 m/s), with the fire being extinguished within 30 seconds. Where sidewall nozzles were used, the suppression time increased to two minutes.

Conclusion

The MTFVTP represents a unique opportunity to assess and validate the various models, theories, standards and methodologies used in tunnel ventilation design against actual, full-scale test results.

The data gathered will have international appeal, and will likely be of interest to tunnel owners/operators, firefighting personnel and academia, as well as tunnel design engineers. ASHRAE can be proud that it played a major role in advancing this field into the 21st century.

Finally, it should be noted that savings in design and construction of the CA/T project which provided funding for the MTFVTP will more than recoup the $38 million cost of the program. The members of TC 5.9 hope to see you at the MTFVTP symposium in Boston. ■

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