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The Memorial Tunnel Fire Ventilation Test Program:
The Full Transverse Tests

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ABSTRACT

A number of tests of the Memorial Fire Ventilation Test Program were devoted to determining the effectiveness of a full-transverse ventilation system in limiting the spread of smoke and hot gases, with varying system configurations and airflow rates. The controlled fire, located at the approximate quarter point of the 2,800 ft (854 m) long tunnel, was varied in three levels of intensity: 10, 20, and 50 megawatts (MW).

Heavily insulated instrument "trees" at fixed cross-sectional locations throughout the roadway and in the plenum above the ceiling were equipped with thermocouples, bidirectional pitot tubes, and gas sampling tubes. The data-acquisition system (DAS) in a control trailer remote from the tunnel continuously recorded air temperatures, air velocities, and gas concentrations for subsequent analysis. A closed-circuit television (CCTV) system, composed of seven cameras inside the tunnel and immediately adjacent to its portals, facilitated observation of smoke movement at the monitors, which were also located in the control trailer.

A total of 19 full-transverse tests were conducted—9 with balanced supply-exhaust airflow rates and 10 with an imbalanced system configuration in which the exhaust flow rate exceeded the forced supply flow rate, causing the make-up air to be introduced through the tunnel portals.

This paper addresses results and conclusions drawn by its author on the basis of acquired data and observations as an eyewitness to these tests as a member of the joint test group.

THE TEST FACILITY

The ventilation system that had served the Memorial Tunnel since it was built in 1953 until it was abandoned in 1987 had also been configured and operated as a balanced, full-transverse system. It served the 2,800 ft (854 m) long, bidirectional roadway with a 3.2% south-to-north upgrade, which was part of the West Virginia Turnpike, connecting Charleston and Beckley. The plenum between the tunnel ceiling and the crown of the horseshoe-shaped tunnel bore had been partitioned into two parallel, tapered ducts, one to serve as supply and the other as exhaust duct. Intermittent flues from the supply duct extended down to supply ports near the roadway, adjacent to the southbound lane. Exhaust slots in the ceiling connected directly to the exhaust duct above, adjacent to the northbound lane. This configuration is depicted in Figure 1.

Except for structural rehabilitation work, installation of instrumentation and insulation, and preparation for subsequent tests, the existing air distribution system remained conceptually unchanged for the conduct of the full-transverse tests. Supply flues and exhaust ports were balanced to provide a uniform distribution of the increased supply and exhaust air capacity, respectively, over the full length of the tunnel. Steel pans, into which no. 2 fuel oil was remotely discharged and ignited, were installed in a fixed location at the approximate quarter point of the tunnel, 700 ft (210 m) from its south portal.

Prior to the first fire test, cold airflow assessment tests designed by the Joint Test Group (JTG) were carried out by an independent contractor. Preparation involved erection of an air velocity test rake in an unobstructed section of the tunnel. Vane anemometers on the test rake were positioned in the same relative horizontal and vertical positions as the pitot tubes on the instrument trees installed for the fire tests. Using the new central fans, a longitudinal airflow was then generated in the tunnel—first in one and then in the opposite direction—and air velocities measured by the vane anemometers were compared with those from pitot tubes for each corresponding location on the instrument trees. The differences between vane anemometer and pitot tube readings, expressed as ratios, were then applied as correction factors for each individual pitot tube.

VENTILATION EQUIPMENT

The existing central fans, housed in fan rooms above the north and south portals, were replaced with six new, reversible,

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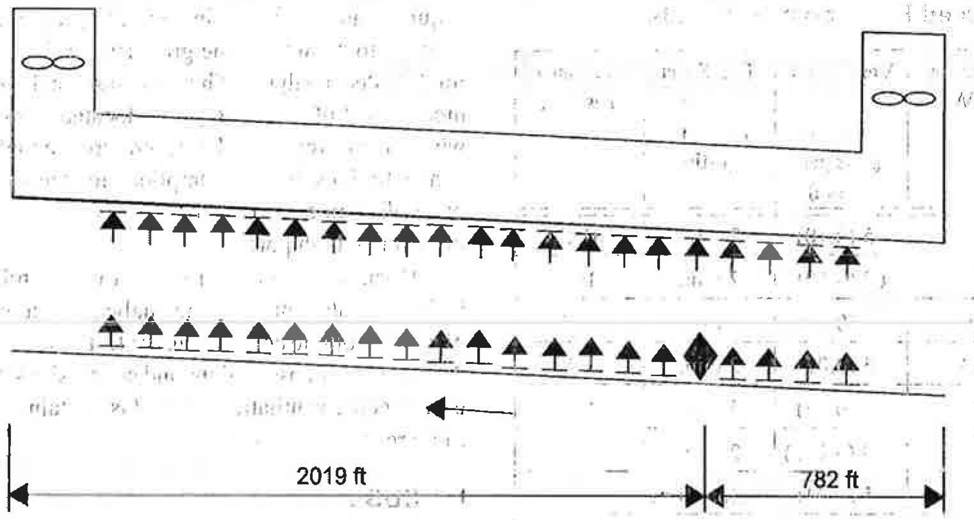

Figure 1 *Schematic diagram of full-transverse ventilation system.*

axial flow fans, three in each fan room. Three fans in the south fan room served the supply air system, and three fans in the north fan room generated the exhaust flow. The total capacity of each fan system, nominally 600,000 cfm (283 m^3/s), matched a theoretical distribution of 100 cfm/lane-ft (0.155 m^3/s per lane/m). Adjustable-frequency controllers for each fan provided the flexibility to vary fan speeds in the range from 120 to 1,200 rpm in both directions of rotation. In addition to local controls in each fan room, remote manual controls were located in the control trailer, where operation of all fan and support systems was remotely initiated and controlled, and where tests in progress were observed on closed-circuit television (CCTV) monitors and graphic computer displays of the data-acquisition system (DAS).

A comprehensive description of the test facility and the ventilation equipment is presented in a separate paper.

TEST OBJECTIVES

One of several goals, especially for the transverse tests, was to ascertain whether current practice (ASHRAE 1995) of providing a minimum of 100 cfm/lane-ft (0.155 m^3/s per lane-m) of exhaust capacity is a reasonable criterion for tunnel fire ventilation. Also, no conclusive data had ever been recorded about the intensity of elevated temperatures to which central exhaust fans may be exposed in case of a serious tunnel fire. In the past, this had given rise to the practice or guidelines (FHA 1984) that suggested that fans be designed to operate reliably at temperatures as high as 1000°F (538°C).

Another objective was to determine the impact of system response capabilities to a fire emergency of a given magnitude. Should a tunnel ventilation system that is inoperative at the time a fire breaks out be activated immediately, or should activation be delayed until motorists can be evacuated? Should a system that is already operating remain in its current balanced mode or should it be reconfigured; i.e., should the airflow rate of either the supply or the exhaust system be increased or decreased?

TEST PROCEDURES

Events, observations, and data were recorded at one-second intervals as a function of elapsed time from the instant of full fire pan engulfment. The starting times for the ventilation systems were varied according to the test plan, which is the subject of a separate paper in this symposium. In two of the full transverse tests, the fans had already been operational at reduced flow rates before the fuel oil was ignited; in two tests, the fans were started coincident with full pan engulfment; in two tests, the fan start was delayed until five minutes after fuel ignition; and in all remaining tests, the delay time was two minutes.

To facilitate a quick assessment during the conduct of each test, guidelines had been established in the test plan for monitoring temperature, carbon monoxide (CO) levels, and smoke concentration. Attention was focused on two instrument trees upstream and downstream of the fire at a distance of 200 feet (60 m) from the fire centerline. If temperatures 6 ft (2 m) above the roadway did not exceed 140°F (60°C), carbon monoxide (CO) measured five feet above the roadway remained at or below 1,000 ppm, and visibility was not obscured, results were deemed to meet established test guidelines at that location. After tunnel conditions reached steady state, the fuel flow was cut off, the fire in the pan(s) was allowed to burn out, and, following a careful safety inspection of the facility, preparations were made for the next scheduled test.

Occasionally, the period of fuel burnout in the fire pans was used to manipulate the system balance in an attempt to determine whether the effectiveness of a given configuration could be improved. Ventilation system performance would be judged by observing and interpreting recorded temperature and CO concentrations, as well as smoke conditions both upstream and

TABLE 1
Balanced Full Transverse Tests

Test No.	Fire Size (MW)	Ventilation Rate cfm/ln-ft (m^3/s per lane-m)	Fan Start After (Before) Ignition	Reference Test No.
1	10	65 (0.10)	2 min.	101 CR
2	20	65 (0.10)	2 min.	103
3	20	65 (0.10)	5 min.	107
4	20	45 (0.07)	2 min.	108
5	20	45 (0.07)	5 min.	109
6	20	100 (0.155)	2 min.	112 A
7	50	25 (0.04)	(before fire)	110
		65 (0.10)	0 min.	110
8	50	100 (0.155)	0 min.	113 A
9	50	100 (0.155)	2 min.	115 A

downstream of the fire. Special emphasis was placed on assessing the system's ability to overcome buoyancy.

The full-transverse fire test series was the first of several series planned and executed. In each test, considerable care was taken to avoid damage to the facility so as not to jeopardize the plan for subsequent tests. When it appeared prudent to do so, the planned sequence of tests would be modified to safeguard the facility.

TEST PROTOCOL

According to pre-established test procedures, the technical responsibility for the conduct of each test rested with the chair of the Joint Test Group (JTG) or designated representative. The on-site test program manager directed the activities of all personnel present during the tests and those responsible for test preparations, including the test supervisor, lead field engineer, field engineer, senior start-up engineer, and DAS technician.

The Joint Test Group was staffed by one or more members of the technical evaluation committee (TEC) of ASHRAE's Technical Committee TC 5.9 and several ventilation engineers. Technical and operational decisions, which evolved from discussion and reviews among group members, were implemented through direct interface with the test supervisor.

TEST DOCUMENTATION

At the completion of each test, the acting JTG chair and the senior ventilation engineer prepared a written synopsis on the basis of their observations during the test and of review of printouts from the DAS. These synopses by members of the JTG, as well as the original test plan (the phase I report prepared by members of the TEC), are contained in volume 9 of the comprehensive test report.

Upon completion of the entire test program, the data acquired and archived in the test program's database were reduced to "point-in-time graphics" and "time history graphs" for detailed analysis. This database included variables from more than 1,000 sensing points located throughout the facility, which measured tunnel temperature, tunnel air velocity, gas concentrations, fuel consumption, outside ambient dry-bulb and wet-bulb temperatures, barometric pressure, and wind speed and direction at both portals.

Documentation of results for all full-transverse tests, including data reduction and analyses, is contained in volume 3 of a nine-volume comprehensive test report (MHD/FHA 1995). A summary of observations and conclusions drawn from tests of each specific ventilation concept is contained in volume 1 of the same report.

DISCUSSION

A common observation applicable to all full-transverse tests, both balanced and unbalanced, was that the carbon monoxide concentrations never even approached the 1,000-ppm guideline anywhere in the tunnel except in the immediate fire location.

Concerns about the elevated exhaust air temperature to which central fans may be exposed in case of a fire emergency were also laid to rest, at least for full-transverse operation. In these tests, temperature as recorded by thermocouples at the instrument tree in the exhaust plenum near the fan inlets was 130°F (54°C). It occurred in test 19, with a 50-MW fire size and an unbalanced flow rate of 90 cfm/ln-ft (0.14 m^3/s per lane-m) exhaust air and 25 cfm/ln-ft (0.04 m^3/s per lane-m) supply air.

The analyses of test results presented in this paper are based on detailed reviews of the "point-in-time graphics" and "time history graphs" and in part on personal observations by the writer, who witnessed a number of these tests as a member of the Joint Test Group. For ease of reference, and to avoid repetitive descriptions herein, two locations in the tunnel upon which much attention was focused will be referred to as "checkpoints": checkpoint 1 corresponds to the location of instrument tree 302, a distance of 200 ft (60 m) south of the fire centerline, and checkpoint 2 corresponds to the location of instrument tree 307, placed about the same distance north of the fire.

Balanced Full-Transverse Tests

Table 1 gives an overview of the key parameters that governed the conduct of nine balanced tests, which have been sequentially numbered herein for ease of reference, but not necessarily in the order in which the tests were conducted.

Test 1 With a nominal heat release rate of 10 MW, temperatures at the 5-ft (1.5-m) elevation of both checkpoints, 200 ft (60 m) north and south of the fire, never exceeded the 140°F (60°C) guideline during the entire test. Smoke obscured visibility in the tunnel sections between the centerline of the fire and the two checkpoints almost immediately after full ignition of the oil in the 10-MW fire pan. However, smoke did not spread beyond those points and remained contained for the duration of the test. This test was basically staged as a commissioning test.

Test 2 With the nominal heat release rate increased to 20 MW and the same ventilation rate as in test 1, conditions in the tunnel were little changed. However, at checkpoint 2 the temperatures increased to 300°F (149°C) at the ceiling and 100°F (39°C) at the roadway level, remaining in that range until the fuel flow was cut off. At no time during the test did the smoke spread beyond the two checkpoints on either side of the fire. The slight increase in temperature toward the north side of the fire was evidently attributable to the buoyant effect, which the ventilation system could not effectively control.

Test 3 With the same fire size and the same supply/exhaust system capacities as in test 2, but with an increased delay in activating the fan system from two minutes to five minutes, the spread of smoke north and south of the fire was nearly symmetrical. However, within a minute after ignition, the temperature gradient at checkpoint 1 briefly reached 250°F (120°C) at the ceiling and remained near ambient at the roadway level. When the ventilation system was started, its effect became noticeable almost immediately. Within a minute after fan start, the temperature at the ceiling dropped to ambient at the entire cross section in that location and remained at that level for the duration of the test.

Conditions at checkpoint 2 north of the fire were similar to those in test 2, except that the temperature gradient escalated to 400°F (204°C) at the ceiling and 100°F (38°C) at the roadway level.

The comparison between these two nearly identical tests, except for the delay in fan start-up, seems to suggest that the more quickly a system can be activated, the more effective it is in controlling the spread of heat and smoke.

Tests 4 and 5 The ventilation system for these two tests was operated with the same balanced supply/exhaust airflow rates. Again, the only difference was the increased delay in fan start-up from two minutes to five minutes. In both tests the temperature at checkpoint 1 never exceeded the 140°F (60°C) guideline. Also, in both tests, the smoke that had spread in a stratified layer 5 ft (1.5 m) above the roadway to a point 200 ft (60 m) south of the fire receded to about 40 ft (12 m) from the fire within a minute or two after fan start.

At checkpoint 2 (north of the fire), temperature gradients were nearly the same in both tests. They reached 450°F (230°C) at the ceiling and 120°F (49°C) at the roadway and remained in that range until the fuel flow to the fire pans was cut off. However, smoke could not be controlled and continued to spread north. It eventually reached the north portal (six minutes after ignition in test 4 and about four minutes after ignition in test 5). Some dilution of the smoke in the lower half of the tunnel cross section was apparent, but it was not possible to clear the smoke entirely. The fact that it took about two minutes longer for the smoke to travel the 2,100-ft (640-m) distance to the north portal in test 4 than in test 5 was apparently due to the quicker fan response.

Test 6 With a balanced full-transverse system uniformly supplying and extracting air at the rate of 100 cfm/ln-ft (0.155 m^3/s per lane/m) and a two-minute delay in fan start, it became increasingly difficult to manage smoke movement. Smoke, which had already reached the south portal when fans were started, was somewhat diluted by the action of the ventilation system but was never fully controlled. North of the fire, smoke still reached the portal two minutes after fan start. Four minutes later, the 700-ft (215-m) tunnel section adjacent to the north portal had been completely cleared of smoke and in the remainder, smoke concentration was slightly reduced. However, the smoke never cleared entirely (except when the supply airflow rate was reduced to one-fourth the original rate after steady-state conditions had been established).

Within one minute after fan start-up, the temperature gradients at the two checkpoints south and north of the fire had reached 300°F (149°C) at the ceiling but remained near ambient at the roadway level. Just two minutes later, the temperature at checkpoint 1 had dropped to ambient from floor to ceiling, but at checkpoint 2 the temperature remained virtually unchanged. The chronology of events during the initial stages of this test, from one minute before fan start until six minutes after, is illustrated in Figures 2 through 5.

Test 7 This was the first 50-MW test undertaken in balanced configuration. Considering the fact that most tunnel ventilation systems are already operational when a fire breaks out, the supply and exhaust systems were activated prior to ignition with a minimal flow rate of 25 cfm/ln-ft (0.039 m^3/s per lane/m) and then increased to a "design flow rate" of 65 cfm/ln-ft (0.10 m^3/s per lane/m) at full pan ignition. At checkpoint 1 south of the fire, the temperature never exceeded the 140°F (60°C) guideline during the entire test, and smoke that had spread to that location two minutes after ignition cleared completely six minutes later.

At checkpoint 2 north of the fire, temperatures rose to 450°F (230°C) at the ceiling and 90°F (32°C) at the roadway within four minutes after ignition. Six minutes later, the temperature gradient increased to 900°F (482°C) and 300°F (150°C) at those elevations and did not drop significantly thereafter until the heat release rate was reduced by stopping the fuel oil flow. Smoke had already reached the north portal before the ventilation rate was increased and did not clear, except for some dilution in the lower part of the tunnel cross section.

Test 8 In this 50-MW test the ventilation system was activated at the time of full engulfment of the oil in the fire pans. At checkpoint 1 the temperature never exceeded the 140°F (60°C) guideline during the entire test. Smoke spread in a stratified layer 5 ft (1.5 m) above the roadway to a location 40 ft (12 m) south of the fire but never extended beyond.

At checkpoint 2, temperatures rose to 450°F (230°C) at the ceiling and 90°F (32°C) at the roadway within two minutes after ignition. Eight minutes later, the temperature at the ceiling increased to 900°F (482°C) and 300°F (150°C) at the roadway. It remained at those unacceptable levels until the fuel oil flow was stopped and the fire was allowed to burn out. Contrary to the preceding test, smoke spread only about 1,000 to 1,300 ft (300 to 400 m) north but never reached the portal. Continued operation of the ventilation system resulted in a somewhat diluted

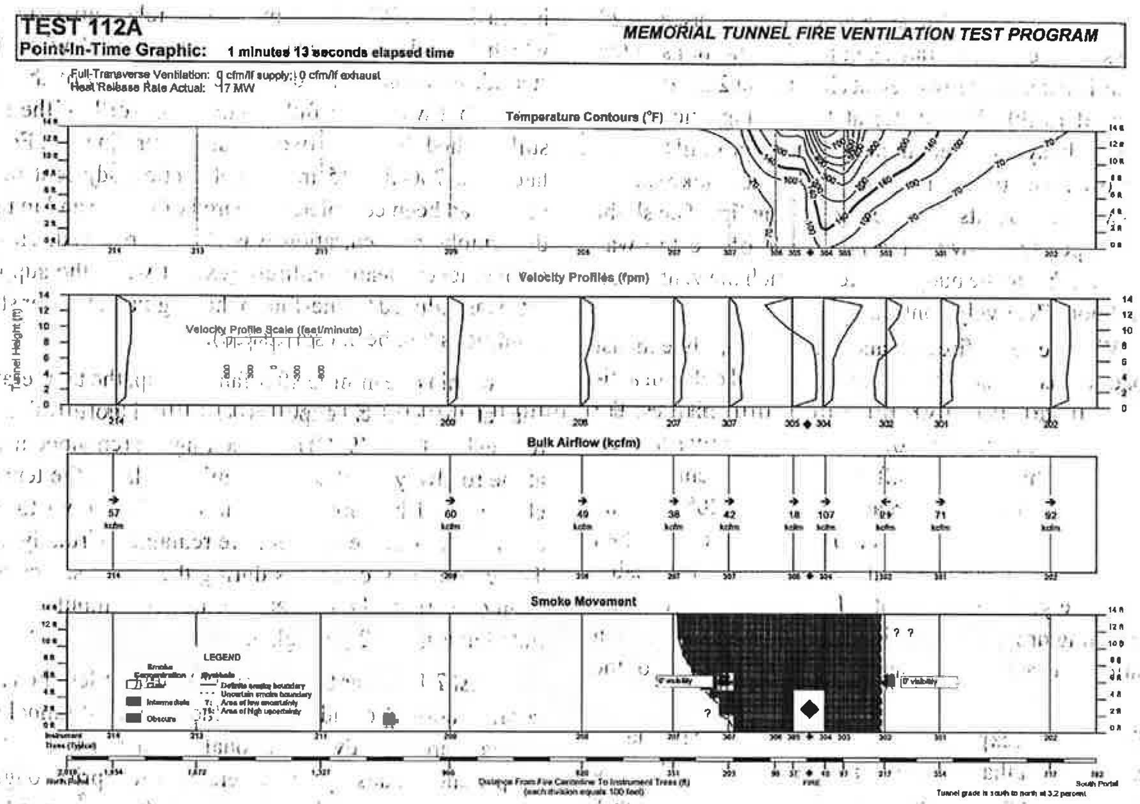

Figure 2 Tunnel conditions during test 6—one minute before fan start.

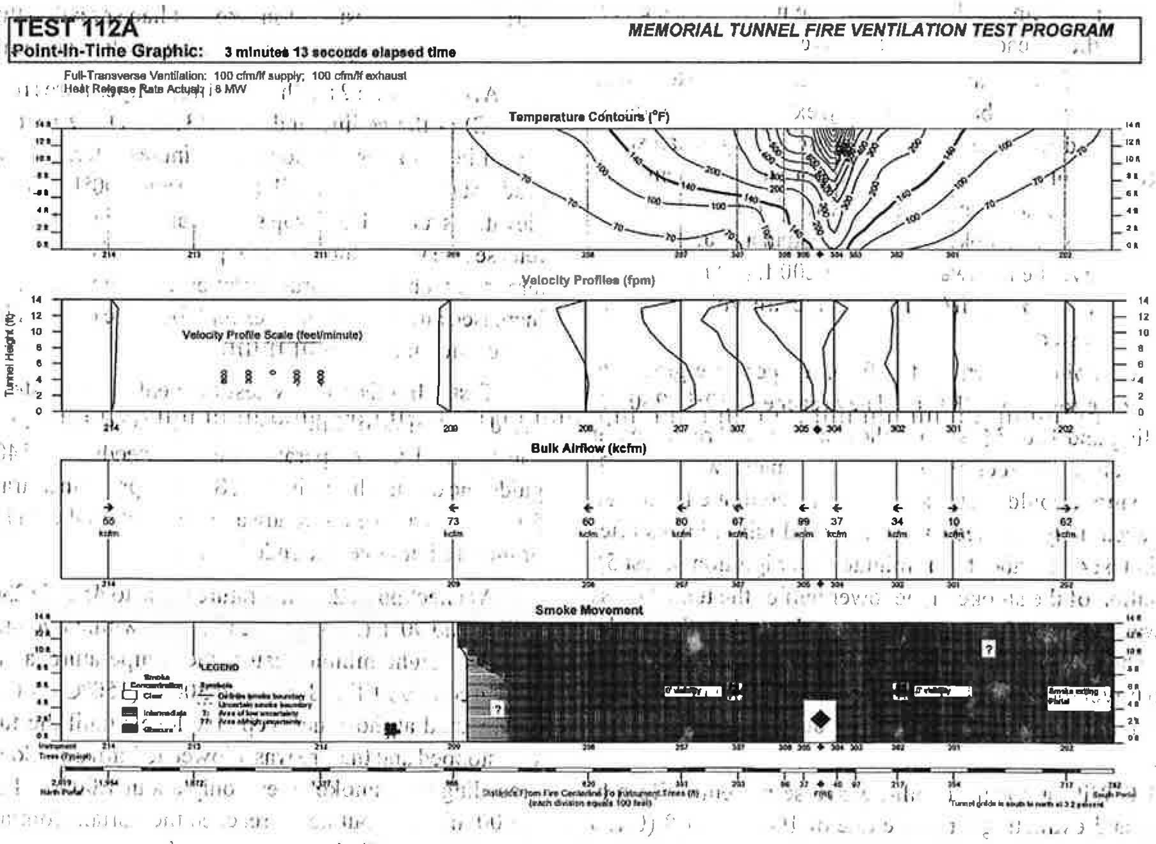

Figure 3 Tunnel conditions during test 6—one minute after fan start.

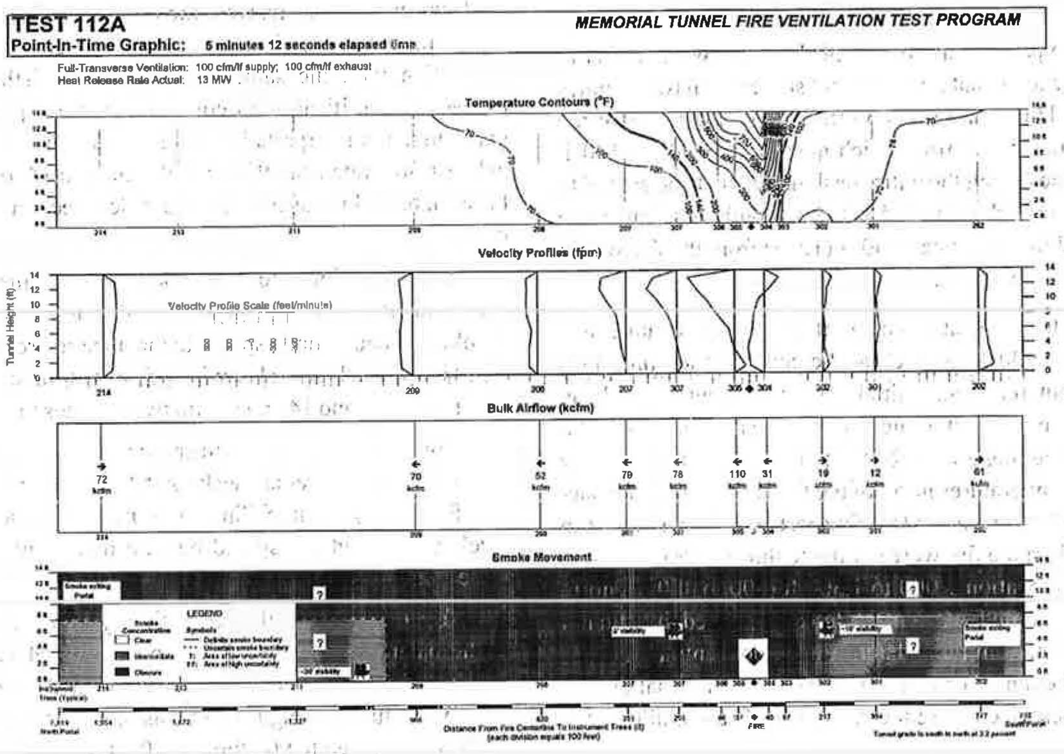

Figure 4 Tunnel conditions during test 6—three minutes after fan start.

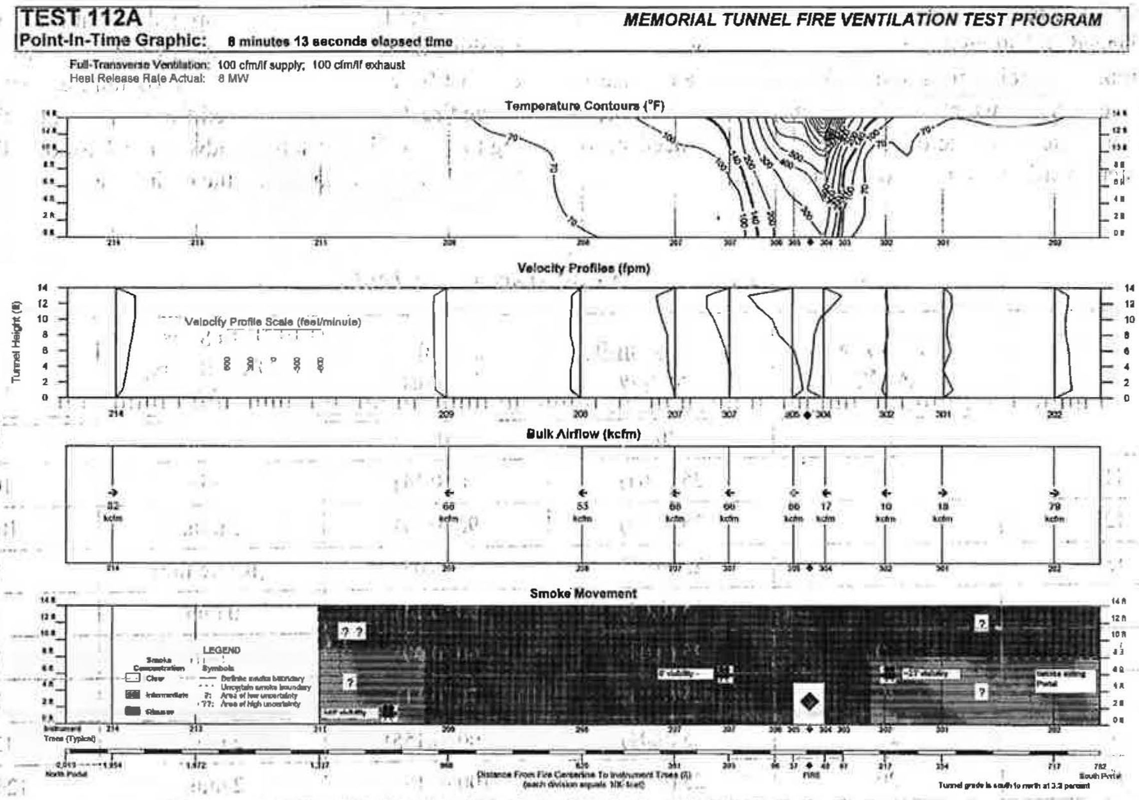

Figure 5 Tunnel conditions during test 6—six minutes after fan start.

concentration but was unable to clear the tunnel of smoke entirely.

Test 9 The parameters for this 50-MW test were similar to those in test 8, except that fans were not started until two minutes after ignition. This delay had no effect on temperatures at the checkpoint south of the fire, which never exceeded the 140°F (60°C) guideline during the entire test. Smoke that had spread to that location above the 5 ft (1.5 m) elevation before fans were started receded to a distance of 40 ft (12 m) from the fire within two minutes after fan start.

North of the fire, at checkpoint 2, the temperature had already reached 600°F (315°C) at the ceiling at the time fans were started but remained initially near ambient at roadway level. Only one minute later, the temperature had risen to 700°F (370°C) at the ceiling and to 200°F (110°C) near the roadway level. Tunnel temperatures north of the fire remained in an unacceptable range for the remainder of the test. Smoke conditions in the tunnel north of the fire were similar to those in test 8. Smoke had spread to a location 1,000 to 1,300 ft (300 to 400 m) north of the fire by the time fans were started and reached, but did not exit, the portal three minutes later. Smoke concentration at the lower half of the tunnel cross section became somewhat diluted only after the heat rate was reduced when the fire was allowed to burn out.

Unbalanced Full-Transverse Tests

Table 2 summarizes the key parameters for the conduct of 10 unbalanced, full-transverse tests. They have been sequentially numbered herein for ease of reference but are not necessarily in the order in which the tests were conducted. Also, in actual testing, the sequence of balanced and unbalanced ventilation system configurations were intermingled.

Tests 10, 11, 12, and 14 These four tests, with virtually identical system parameters, were the first in a series of 20-MW fire sizes immediately following the 10-MW commissioning test. Repetition with the same supply/exhaust airflow imbalance allowed for verification of consistency in test procedures, data gathering, and interpretation of results. Even a reduction in the exhaust flow rate from 90 to 60 cfm/ln-ft (0.14 to 0.09 m^3/s per ln-m) in test 14 produced no noticeable effect on system performance.

At checkpoint 1 south of the fire, the temperature never exceeded the 140°F (60°C) guideline during any of the four tests. Smoke that had initially spread to that location receded to a point 40 ft (12 m) south of the fire within three to four minutes after fan start in tests 10 and 14 and within two minutes in tests 11 and 12.

North of the fire, heat and smoke were similarly well under control. Temperatures at checkpoint 2 ranged from an average of 350°F (177°C) at the ceiling to 100°F (38°C) at the roadway level. Smoke did not spread beyond that point during any of these tests.

Test 13 In this test the ventilation system had been operated in the balanced mode with 25 cfm/ln-ft (0.04 m^3/s per ln-m) supply and exhaust flow rates prior and up to the time of fire ignition. When full pan engulfment was observed, the exhaust flow rate was increased to 90 cfm/ln-ft (0.14 m^3/s per ln-m).

Results did not differ noticeably from tests in which the ventilation system was activated only after ignition. At checkpoint 1 the temperature never exceeded the 140°F (60°C) guideline. Smoke that had initially spread to that location receded to a point 100 ft (30 m) south of the fire within six minutes after the exhaust flow rate was increased. Two hundred feet (60 m) north of the fire, temperatures ranged from 400°F (204°C) at the ceiling to 100°F (38°C) at the roadway level. Smoke did not spread beyond that location during the entire test.

TABLE 2
Unbalanced Full Transverse Tests

Test No.	Fire Size (MW)	cfm/ln-ft (m^3/s per lane/m) Supply	Exhaust	Fan Start After (Before) Ignition	Reference Test No.
10	20	25 (0.04)	90 (0.14)	2 min.	102
11	20	25 (0.04)	90 (0.14)	2 min.	102 R
12	20	25 (0.04)	90 (0.14)	2 min.	102 R1
13	20	25 (0.04)	25 (0.04)	(before fire)	104
		25 (0.04)	90 (0.14)	0 min	104
14	20	25 (0.04)	60 (0.09)	2 min.	105
15	20	25 (0.04)	70 (0.11)	2 min.	106
16	20	25 (0.04)	100 (0.155)	2 min.	126 B
17	20	25 (0.04)	100 (0.155)	2 min.	126 BR1
18	20	65 (0.10)	100 (0.155)	2 min.	128 B
19	50	25 (0.04)	90 (0.14)	0 min.	111

Test 15 In this 20-MW test the exhaust flow rate was reduced to 70 cfm/ln-ft (0.11 m^3/s per ln-m) but the supply flow rate remained the same—25 cfm/ln-ft (0.04 m^3/s per ln-m). This change had virtually no effect on the performance of the system. Temperature and smoke migration both south and north of the fire were about the same as with the 90 cfm/ln-ft (0.14 m^3/s per ln-m) exhaust flow rate (see Figures 6 through 8).

Tests 16 and 17 With these two tests the effort to determine a suitable ratio of supply/exhaust flow rates for a 20-MW fire size continued. The exhaust flow rate was increased from 90 cfm/ln-ft (0.14 m^3/s per ln-m) to 100 cfm/ln-ft (0.155 m^3/s per ln-m) and the supply airflow rate was kept at 25 cfm/ln-ft (0.04 m^3/s per ln-m). However, the effect of changing the system imbalance was negligible in both tests, and results of the two tests were nearly identical.

At checkpoint 1 the temperature never exceeded the 140°F (60°C) guideline. Smoke that had initially spread to that location receded to a point 40 ft (12 m) south from the fire a little more quickly, within two minutes after fan start. At checkpoint 2, temperatures ranged from 250°F (120°C) at the ceiling to ambient at the roadway level. However, smoke migrated north to a point 1,000 to 1,300 ft (300 to 400 m) from the fire centerline. The system was able to dilute the smoke density but could not clear the tunnel entirely.

Test 18 This test was designed to evaluate the performance of an unbalanced transverse system with the maximum (available) exhaust flow rate of 100 cfm/ln-ft (0.155 m^3/s per ln-m) and an increase in the supply airflow rate from 25 cfm/ln-ft (0.04 m^3/s per ln-m) to 65 cfm/ln-ft (0.10 m^3/s per ln-m). The fire size was again 20 MW.

Due to an apparent downdraft from the south to the north portal prior to fan start, temperatures at the checkpoint south of the fire had increased to 300°F (149°C) at the ceiling but remained near ambient at the roadway level. About three minutes after fan start-up the temperature at the ceiling also had dropped to ambient and did not escalate again. Smoke that had spread to that location prior to fan start began to slowly recede, but after 16 minutes only the lower half of the tunnel cross section had cleared completely.

North of the fire, at checkpoint 2, the temperature had risen to 250°F (120°C) at the ceiling and remained near ambient at the roadway level at the time of fan start. Twelve minutes later, it had escalated to 350°F (177°C) at the ceiling and 85°F (30°C) at the roadway and remained in that range thereafter. Smoke also had spread to about 500 ft (150 m) by the time the ventilation systems were activated and to a distance of 1,300 ft (400 m) four minutes later. Thereafter, the system was able to dilute the smoke concentration somewhat but could not clear the tunnel entirely.

Test 19 Whereas all preceding unbalanced transverse tests were conducted to evaluate system capabilities in response to 20-MW fires, test 19 was the only unbalanced system test with a 50-MW heat release rate. Both supply and exhaust systems were started at time of full pan engulfment.

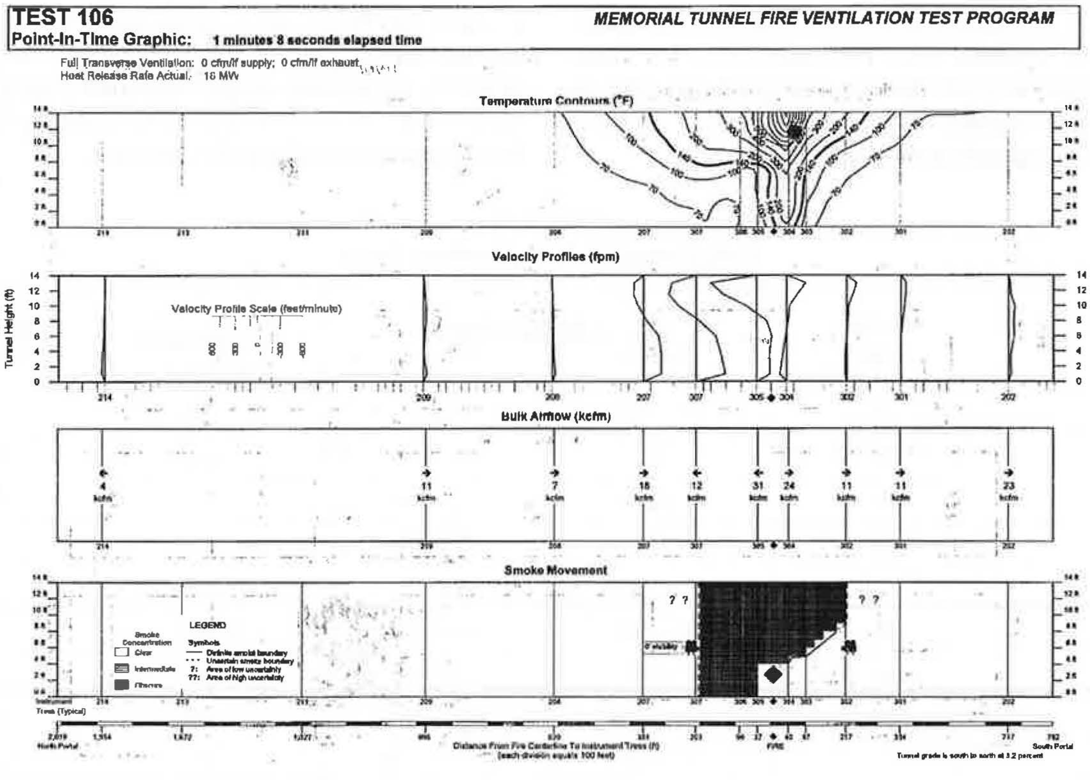

Figure 6 Tunnel conditions during test 15—one minute before fan start.

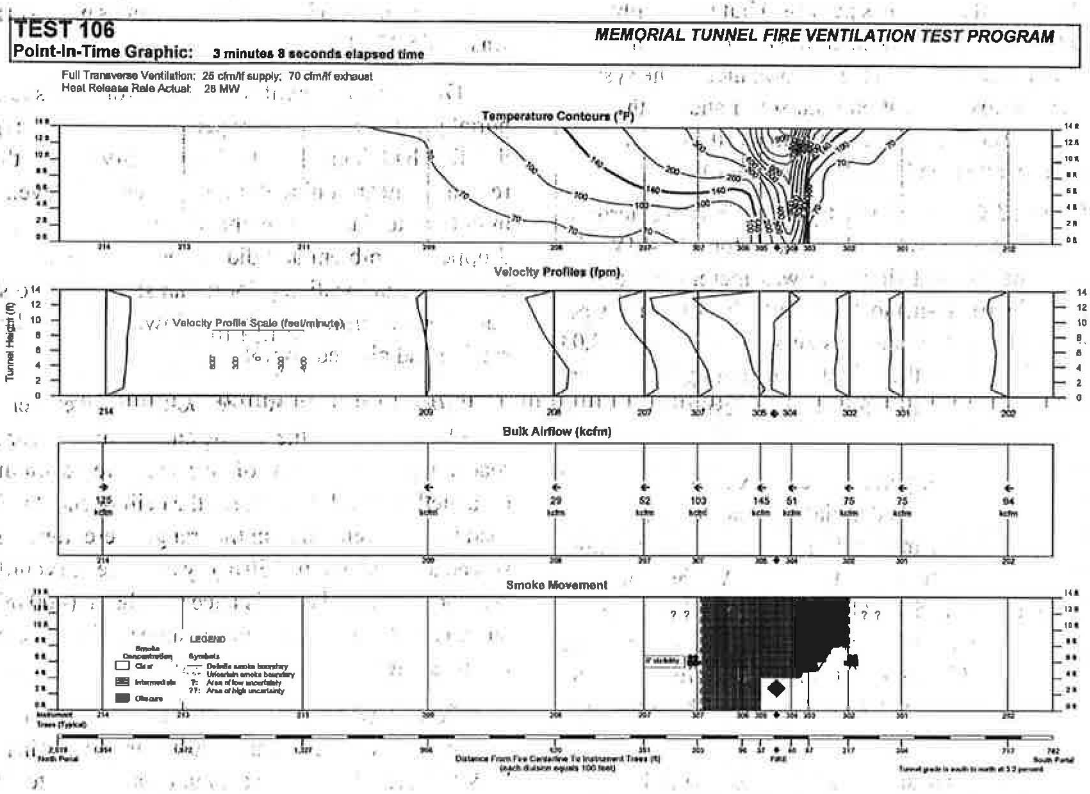

Figure 7 *Tunnel conditions during test 15—one minute after fan start.*

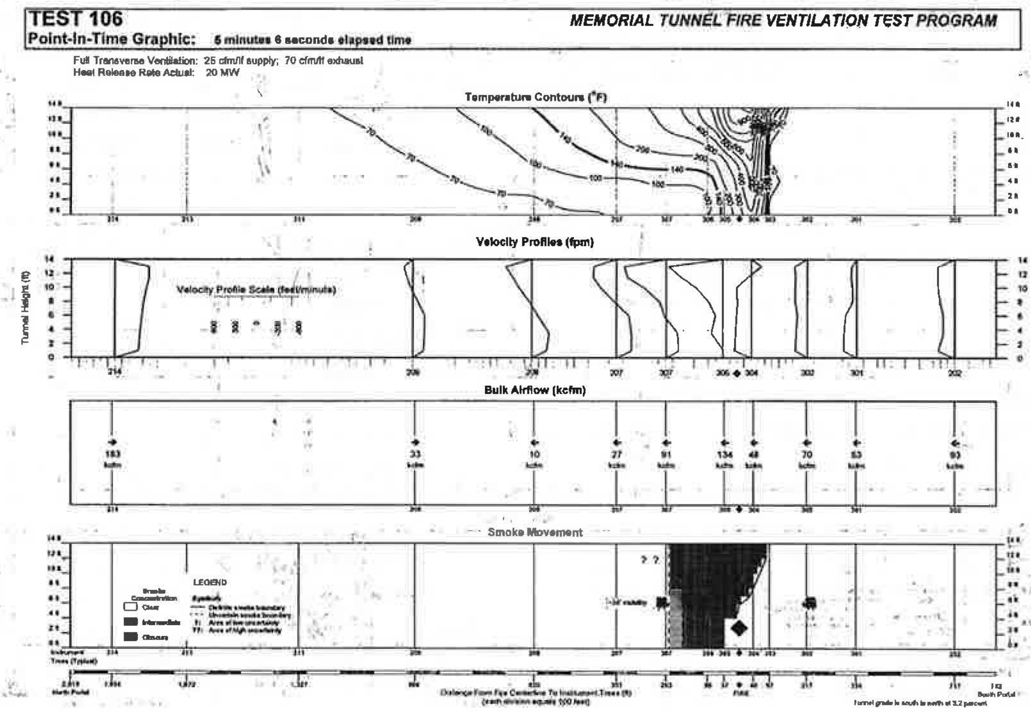

Figure 8 *Tunnel conditions during test 15—three minutes after fan start.*

At the checkpoint 200 ft (60 m) south of the fire, temperature and smoke conditions did not differ markedly from the 20-MW tests. One minute after ignition and fan start, the temperature at the ceiling had risen to 140°F (60°C) but remained at ambient near the roadway level. One minute later the temperature at the ceiling also had dropped to ambient and remained at that level thereafter. Stratified smoke layers at the ceiling had also advanced to that point within two minutes after ignition but then receded to a distance of 100 ft (30 m) from the fire in the three minutes following. This smoke pattern did not change.

At checkpoint 2 the temperature at the ceiling 200 ft (60 m) was more indicative of the increased heat rate. Within six minutes after ignition it had increased to 800°F (430°C) at the ceiling and 200°F (93°C) at the roadway. Two minutes later, temperatures had further escalated to 900°F (480°C) and 300°F (149°C), respectively. Thereafter, temperatures north of the fire remained at intolerably high levels. Surprisingly, however, smoke had spread only up to the 200-ft (60-m) checkpoint within one minute after ignition and never advanced beyond; nor did it clear, however.

CONCLUSIONS

The conclusions that may be drawn from any of the full-transverse test results will necessarily have to be limited to this particular test facility, a tunnel of given geometry as herein described with a 3.2% upgrade and the fire located in its lower quadrant that resulted in significant buoyancy or updraft. Any extrapolation to a tunnel of different geometry, location, or elevation requires a detailed analysis of all variables.

Also, a series of other tests conducted as part of the Memorial Fire Ventilation Test Program has demonstrated that the effectiveness of transverse ventilation systems can be enhanced with certain physical or operational alterations or additions. These include operation of transverse systems in a two-zone configuration, in partial transverse exhaust mode, and with oversized exhaust and single-point extraction openings. Discussions of these enhancements are the subject of separate papers in this symposium.

Conclusions drawn from these transverse tests, operated in balanced and unbalanced configurations, may be summarized as follows.

1. The only 10-megawatt test conducted showed that with a relatively small fire, equivalent in magnitude to a burning passenger vehicle, the balanced full-transverse system was able to limit the spread of smoke beyond the fire zone and to dilute the heat emitted. This was evidenced by the fact that temperatures did not exceed the 140°F (60°C) guideline and smoke was well contained between the two checkpoints at a distance of 200 ft (60 m) on both sides of the fire centerline.
2. With 20- and 50-megawatt fire sizes, the full-transverse system had a limited effect in retarding smoke and heat flow through the tunnel. The system was found to be incapable of reversing the direction of longitudinal flow of heat and smoke, regardless whether the flow rate was 25 cfm/ln-ft (0.04 m^3/s per ln-m) or 100 cfm/ln-ft (0.155 m^3/s per ln-m). The system was able to mitigate, but unable to manage or control, smoke spread. Due to the system's limited effectiveness with 20- and 50-megawatt fires, full-transverse tests with 100-megawatt fire size were deleted from the test plan.
3. Most of the tests indicated a predominant flow of heat and smoke in the northerly direction. This was especially evident prior to fan start, shortly after fire ignition, and was obviously due to the buoyant effect, since the tunnel had a 3.2% upgrade toward the north. After fans were started, the buoyancy helped to keep the southern tunnel section relatively smokefree at the expense of conditions north of the fire.

   The exception to this observation was test 18, where temperatures at the checkpoint south of the fire had increased to 300°F (150°C) at the ceiling and a stratified smoke layer near the ceiling could not be dislodged by the ventilation system during the entire test. This was attributed to an apparent downdraft coming from the north, resulting from differences in atmospheric conditions between the two portals.
4. Comparisons of test results with different fan delay times (0, 2, and 5 minutes) demonstrated some benefit in quick fan response. For example, in test 4 with a two-minute system response, it took two minutes longer for the smoke to travel the 2,100-ft (640-m) distance to the north portal than in test 5, which had a five-minute system response time. A similar observation was made in comparing tests 2 and 3 with an identical difference in system response.
5. Given the physical constraints of a full-transverse system, it became apparent that operation of the system in the unbalanced mode was somewhat more effective than in the balanced mode. These contrasts are revealed when comparing test results with a balanced flow of 100 cfm/ln-ft (0.155 m^3/s per ln-m) with those of unbalanced flow with 90 cfm/ln-ft (0.10 m^3/s per ln-m) exhaust and 25 cfm/ln-ft (0.04 m^3/s per ln-m) supply, especially in managing smoke. On the other hand, increased supply flow provided some benefit in controlling temperatures. Little difference was detected, however, when comparing exhaust/supply ratios of 90/25with an imbalance ratio of 70/25.

If any of these test results were to be used in designing a new or modifying an existing tunnel ventilation system, several other factors must be considered before ruling out application of full-transverse ventilation. One is the fact that transverse systems offer more effective and uniform control of the tunnel environment during normal operation. Air is supplied and extracted at essentially the same uniform rate as vehicle pollutants are emitted. Central fans, housed in separate structures or rooms, are readily accessible and easily maintained without interrupting traffic. Urban tunnels on level grade may not provide the same degree of difficulty in controlling the buoyant flow of heat and smoke as mountain tunnels with steep inclines. Transverse systems have built-in operational flexibility in that the balance between supply and exhaust, and the rate of flow for both, can quickly be changed. Overhead plenums provide an opportunity for special devices to be installed with which smoke-removal capability can be enhanced. Finally, for tunnels with bidirectional traffic (such as the abandoned Memorial Tunnel), longitudinal flow, as opposed to transverse flow, presents no viable alternative because it can at best only aid stranded motorists in one lane, but not in both. These, and the reduced impact of emissions from the exit portals, are some of the reasons why full-transverse ventilation systems have found such widespread application in the past and to this date.

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