BN-97-6-4

The Memorial Tunnel Fire Ventilation Test Program: Test Plan and Test Operations

William D. Kennedy, P.E.
Member ASHRAE

Flor D. Hernandez

ABSTRACT

The Memorial Tunnel Fire Ventilation Test Program (MTFVTP) comprised three phases:

- *phase I, test program development;*
- *phase II, test program and test facility design; and*
- *phase III, test facility construction, testing, and final report preparation.*

This paper provides an overview of the testing and comprehensive test report preparation activities that were part of phase III.

The MTFVTP was conducted to obtain definitive fire test data to support ventilation design and operation concepts in road tunnels. More specifically, the objective of the testing was to determine, under full-scale conditions, the relative effectiveness of various ventilation systems and operating modes in the management of heat and smoke for tunnel fires of varying intensities.

THE TEST PLAN

At the time testing began in September 1993, 130 tests were anticipated. However, the dynamic nature of the program and the knowledge acquired during the early tests led to modifications to and deletion of some test sequences, such that at the completion of testing in March 1995, 98 fire tests had been conducted in all.

Ventilation Systems

The fire ventilation tests utilized the following ventilation schemes:

- full transverse
- partial transverse exhaust and supply,
- two-zone partial transverse,
- partial transverse with single-point extraction,
- partial transverse with oversized exhaust ports,
- point supply and point exhaust,
- natural ventilation, and
- longitudinal ventilation using jet fans.

The full transverse and partial transverse ventilation systems were included because of their extensive use in the United States. They also aided in gaining insight as to their tunnel fire capabilities and the most effective ways of operating them.

The basic partial transverse exhaust ventilation system was supplemented with oversized exhaust ports and single-point extraction openings to assess the effect of these features during a tunnel fire, specifically the ability to confine smoke and hot gases closer to the fire.

The objective of the point supply and point exhaust operation tests was to identify the minimum longitudinal air velocity required to control the direction of spread of smoke and hot gases given off by a fire with the tunnel ceiling in place. This air velocity is called the critical air velocity and is also referred to as that required to prevent backlayering (the movement of smoke contrary to the forced ventilation).

The natural ventilation tests were included to observe the length, depth, velocity, and stability of the stratified smoke layer produced by tunnel fires of various sizes with the tunnel ceiling removed and no fans operated.

The objective of the jet fan tests was to identify the minimum longitudinal air velocity required to prevent backlayering with the tunnel ceiling removed (providing a greater height and an arched crown). Prior to these tests, the use of longitudinal ventilation systems was not approved by the Federal Highway Administration (FHWA). Therefore, these tests were planned to answer questions concerning the performance of longitudinal ventilation systems with jet fans during fire emergencies.

Test Parameters

In addition to the type of ventilation system, the fire tests were varied by fire heat release rate, ventilation rate, ventilation

William D. Kennedy is vice president and **Flor D. Hernandez** is a mechanical engineer at PBQ&D, New York, N.Y.

system response time, portal opening adjustments, use of vehicle silhouettes, and foam suppression system use. Table 1 provides a complete listing of the 98 fire ventilation tests and their relevant parameters. During many tests, the ventilation rate was changed during the course of the test, but only the initial ventilation rate is listed here.

Fire Heat Release Rate Fire release rates of 10, 20, 50, and 100 megawatts (MW) were employed to evaluate ventilation systems at different fire heat release rates—an important parameter in tunnel design. A 20-MW fire is equivalent to a bus or truck fire, and a 100-MW fire is equivalent to a gas tanker fully engulfed in flames.

TABLE 1a
As-Conducted Fire Ventilation Tests

Test Number	Ventilation System	Fire Size (MW)	Ventilation Response Time	Ventilation Rate		Additional Comments
				Supply (cfm/lf)	Exhaust (cfm/lf)	
101CR	Full Transverse	10	2 min	65	60	commissioning test
102	Full Transverse	20	2 min	25	90	
102R	Full Transverse	20	2 min	25	90	
102R1	Full Transverse	20	2 min	25	90	
103	Full Transverse	20	2 min	65	60	
104	Full Transverse	20	Pre-fire	25	20	
				25	90	
105	Full Transverse	20	2 min	25	60	
106	Full Transverse	20	2 min	25	70	
107	Full Transverse	20	5 min	65	60	
108	Full Transverse	20	2 min	45	40	
109	Full Transverse	20	5 min	45	40	
110	Full Transverse	50	Pre-fire	25	20	
				65	60	
111	Full Transverse	50	0 min	25	90	
112A	Full Transverse	20	2 min	100	100	note 4
113A	Full Transverse	50	0 min	100	100	note 4
115A	Full Transverse	50	2 min	100	100	notes 2, 4
126B	Full Transverse	20	2 min	25	100	note 4
126BR1	Full Transverse	20	2 min	25	100	note 4
128B	Full Transverse	20	2 min	65	100	note 4
202	Partial Transverse Exhaust	20	2 min	—	80	
203	Partial Transverse Exhaust	20	2:00	—	70	
205	Partial Transverse Exhaust	20	5 min	—	80	
207A	Partial Transverse Exhaust	20	2 min	—	80	note 1
208A	Partial Transverse Exhaust	20	33 sec	—	80	
210	Partial Transverse Exhaust	20	2 min	—	80	note 3
212	Partial Transverse Exhaust	20	2 min	—	80	note 3
214A	Partial Transverse Exhaust	50	2 min	—	100	
215A	Partial Transverse Exhaust	50	2 min	—	80	
216A	Partial Transverse Exhaust	50	2 min	—	100	note 1
217A	Partial Transverse Exhaust	50	2 min	—	80	note 2

TABLE 1a (Continued)
As-Conducted Fire Ventilation Tests

218B	Partial Transverse Exhaust	20	2 min	—	100	note 4
247B	Partial Transverse Exhaust	20	2 min	—	80	note 3
248B	Partial Transverse Exhaust	20	2 min	—	100	note 3
249B	Partial Transverse Exhaust	20	Pre-fire	— —	25 80	
252B	Partial Transverse Exhaust	20	2 min	—	140	
223	Partial Transverse Supply	20	2 min	65	—	supply at roadway
226	Partial Transverse Supply	20	2 min	65	—	supply from ceiling
227A	Partial Transverse Supply	20	2 min	90	—	supply from ceiling
244B	Partial Transverse Supply	20	2 min	45	—	supply from ceiling
229	Two-Zone Partial Transverse	20	2 min	140	120	note 3
230	Two-Zone Partial Transverse	20	2 min	100	85	note 3
231	Two-Zone Partial Transverse	20	2 min	70	60	note 3
233	Two-Zone Partial Transverse	20	5 min	95	85	note 3
235	Two-Zone Partial Transverse	50	2 min	110	110	note 3
236	Two-Zone Partial Transverse	50	2 min	150	150	
238A	Two-Zone Partial Transverse	50	2 min	150	150	note 1, 2
239	Two-Zone Partial Transverse	100	2 min	171	171	note 3
245B	Two-Zone Partial Transverse	20	2 min	135	115	
246B	Two-Zone Partial Transverse	20	2 min	135	115	note 1
250B	Two-Zone Partial Transverse	20	2 min	60	60	
251B	Two-Zone Partial Transverse	20	2 min	100	100	

Notes:
1. Vehicle silhouettes used.
2. Foam suppression system used.
3. North and/or south portal openings adjusted.
4. Tunnel in full transverse configuration with ventilated length of tunnel shortened to 2300 feet.

Ventilation Rate The ventilation rate was varied to determine the most effective operation for each ventilation system and to acquire data for the various fire heat release rates over a range of ventilation rates.

Ventilation System Response Time The ventilation system response times of 0, 2, and 5 minutes were used to assess the importance of quick response in a fire emergency. The issues are how far and how fast the smoke will spread prior to the operation of the fans, and how the response time affects the ultimate ventilation system capacity required to manage smoke.

Portal Opening Adjustments In some tests, the north and/or south portal openings were adjusted to vary the longitudinal airflow across the fire site. In this way, the longitudinal air velocity across the fire was varied while maintaining a given exhaust rate. This provided insight into the importance of longitudinal airflow in the management and control of smoke and hot gases produced by a tunnel fire.

Use of Vehicle Silhouettes Vehicle silhouettes consisted of rectangular steel plate structures that were placed in the airstream to simulate the blockage effect of vehicles stopped in the tunnel. Three silhouette sizes were used to represent each of the following vehicle types: passenger cars, vans, and tractor trailers. A total of 16 silhouettes were used: 9 representing passenger cars, 4 representing vans, and 3 representing tractor trailers. The silhouettes were placed along the tunnel roadway between the fire site and the midpoint of the tunnel, upgrade of the fire.

Foam Suppression System Use A foam suppression system was utilized in six tests. Ceiling and sidewall systems were tested with the ceiling in place and with the ceiling removed. Of interest was whether high longitudinal air velocities could alter the discharge path of the foam, deflecting the foam away from the fire. The foam suppression system effectiveness was observed for various physical configurations, longitudinal

TABLE 1b
As-Conducted Fire Ventilation Tests

Test Number	Ventilation System	SPE Opening		Fire Size (MW)	Ventilation Response Time	Ventilation Rate		Additional Comments
		Location[4]	Size (ft²)			Supply (cfm/lf)	Exhaust (cfm/lf)	
301A	Partial Transverse with SPE	1	300	20	2 min	—	110	
302A	Partial Transverse with SPE	1	100	20	2 min	—	100	note 3
303A	Partial Transverse with SPE	1	100	20	2 min	—	65	note 3
305A	Partial Transverse with SPE	1	100	20	2 min	—	85	note 1, 3
306A	Partial Transverse with SPE	2 and 4	300 and 300	20	2 min	—	110	
309A	Partial Transverse with SPE	1	200	50	2 min	—	100	
312A	Partial Transverse with SPE	2	300	50	2 min	—	110	
313A	Partial Transverse with SPE	2	200	50	2 min	—	100	
338B	Partial Transverse with SPE	2	300	20	2 min		110	
339B	Partial Transverse with SPE	2	300	20	5 min	—	110	
340B	Partial Transverse with SPE	2	100	20	2 min	—	110	
341B	Partial Transverse with SPE	2	100	20	2 min	—	65	
342B	Partial Transverse with SPE	2	100	20	2 min	—	85	
343B	Partial Transverse with SPE	2	100	20	2 min	—	100	
344B	Partial Transverse with SPE	1	200	20	2 min	—	65	note 3
345B	Partial Transverse with SPE	2	200	20	2 min	—	65	
346B	Partial Transverse with SPE	2	200	20	2 min	—	100	

Test Number	Ventilation System	Oversized Exhaust Port Type	Fire Size (MW)	Ventilation Response Time	Ventilation Rate		Additional Comments
					Supply (cfm/lf)	Exhaust (cfm/lf)	
403A	Partial Transverse with OEP	Fusible Panel	20	2 min	—	85	
407B	Partial Transverse with OEP	Fusible Panel	20	Pre-fire	—	35	
					—	85	
408B	Partial Transverse with OEP	Fusible Panel	20	2 min	—	85	
401A	Partial Transverse with OEP	Fusible Panel	50	2 min	—	100	
404A	Partial Transverse with OEP	Fusible Link Damper	20	2 min	—	85	

Test Number	Ventilation System	Single Point Opening		Fire Size (MW)	Ventilation Response Time	Ventilation Rate Supply or Exhaust (cfm)	Additional Comments
		Location[4]	Size (ft²)				
314	Point Supply	3 and 4	300 and 300	10	2 min	115,000	note 3
316	Point Supply	3 and 4	300 and 300	20	2 min	140,000	note 3
321A	Point Supply	4	300	50	2 min	190,000	note 3
315A	Point Exhaust	1	100	20	2 min	430,000	note 3
317A	Point Exhaust	2	100	20	2 min	295,000	
318A	Point Exhaust	1	100	50	2 min	440,000	note 3
319A	Point Exhaust	2	100	50	2 min	364,000	
320A	Point Exhaust	4	300	50	2 min	670,000	note 2, 3

TABLE 1b (Continued)
As-Conducted Fire Ventilation Tests

Test Number	Ventilation System	Fire Size (MW)	Ventilation Response Time	Initial Number of Jet Fans in Operation	Additional Comments
501	Natural	20	—	—	
502	Natural	50	—	—	
605	Longitudinal (15 Jet Fans)	10	0 min	15	
606A	Longitudinal (15 Jet Fans)	10	5 min	2	
607	Longitudinal (15 Jet Fans)	20	0 min	3	
608	Longitudinal (15 Jet Fans)	20	2 min	3	
610	Longitudinal (15 Jet Fans)	50	0 min	5	
611	Longitudinal (15 Jet Fans)	50	2 min	5	
612B	Longitudinal (15 Jet Fans)	50	5 min	5	
615B	Longitudinal (15 Jet Fans)	100	2 min	6	
617A	Longitudinal (15 Jet Fans)	10	0 min	5	note 1
618A	Longitudinal (15 Jet Fans)	20	2 min	2	note1
621A	Longitudinal (15 Jet Fans)	100	0 min	8	
622B	Longitudinal (15 Jet Fans)	50	0 min	5	
623B	Longitudinal (24 Jet Fans)	20	0 min	3	
624B	Longitudinal (24 Jet Fans)	50	2 min	6	note 2
625B	Longitudinal (24 Jet Fans)	100	0 min	9	note 2

Notes:
1. Vehicle silhouettes used.
2. Foam suppression system used.
3. North and/or south portal openings adjusted.
4. Point opening location designation: (1) 142 feet south of fire; (2) 143 feet north of fire; (3) 293 feet north of fire; (4) 43 feet north of fire.

air velocities, and fire heat release rates. Secondarily, the foam suppression system was installed as a safety precaution.

Ventilation System Tunnel Configuration

For each ventilation system, a specific tunnel configuration was required to allow for correct implementation and operation of the ventilation concept. When necessary, modifications to the overhead air duct were made to configure the tunnel for the desired concept. Figure 1 illustrates the original Memorial Tunnel duct and ceiling configuration, and Figure 2 depicts a Memorial Tunnel cross section. In addition, a duct bulkhead located at the midpoint of the tunnel could be opened or closed to allow for single-zone or two-zone ventilation. The duct and ceiling configurations for the ventilation systems for the various ventilation schemes are described below.

Full Transverse Ventilation The mid-tunnel duct bulkhead was not in place, and openings in the duct dividing wall were covered to allow for separate supply and exhaust air ducts.

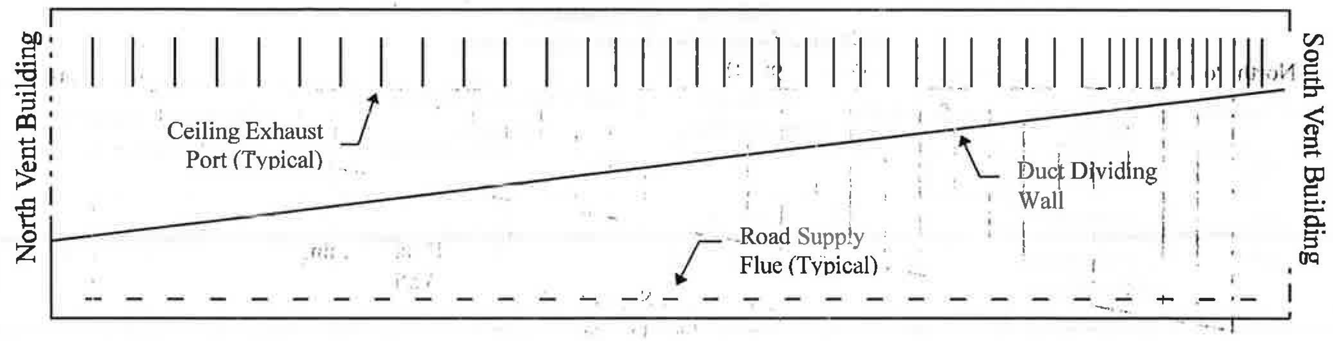

Figure 1 *Plan view of the original Memorial Tunnel duct and ceiling.*

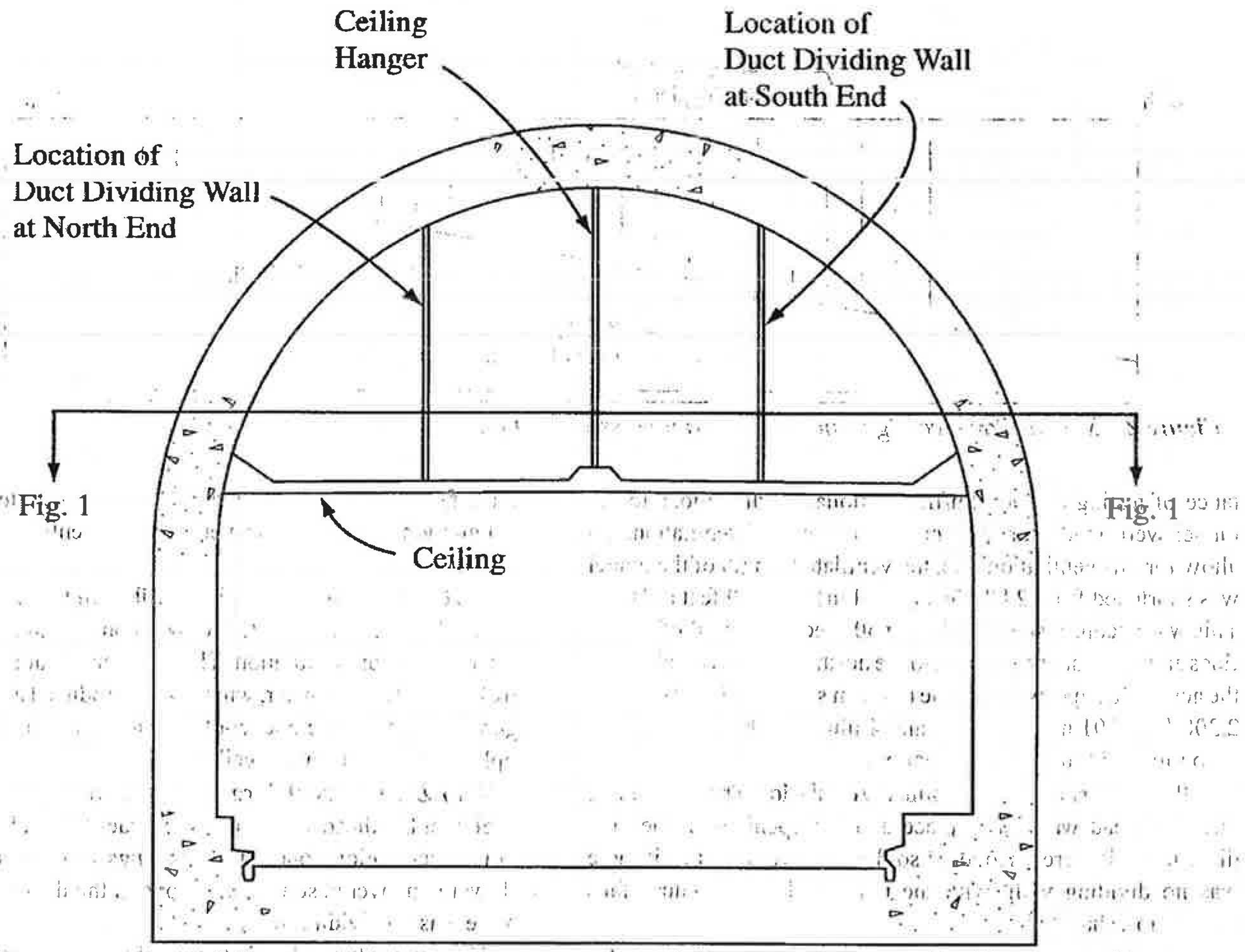

Figure 1 *Memorial Tunnel cross section, section looking north.*

The ports in the ceiling in the exhaust duct were balanced to provide for uniform exhaust over the full length of the tunnel. The north portal central fans were dedicated to the exhaust duct. The ports in the ceiling in the supply duct were closed and the supply flues along the west wall were balanced to provide for uniform supply over the full length of the tunnel. The supply flues dropped down within the wall to introduce supply air at the roadway. The south portal central fans were dedicated to the supply duct.

After the tunnel was configured for full transverse ventilation, however, the central fans were unable to achieve the recommended minimum 100 cubic feet per minute of air per lane-foot of tunnel (cfm/lf) for both supply and exhaust. This was due to the large resistance to airflow in the ducts created by insulation that had to be added during construction. Because of the impor-

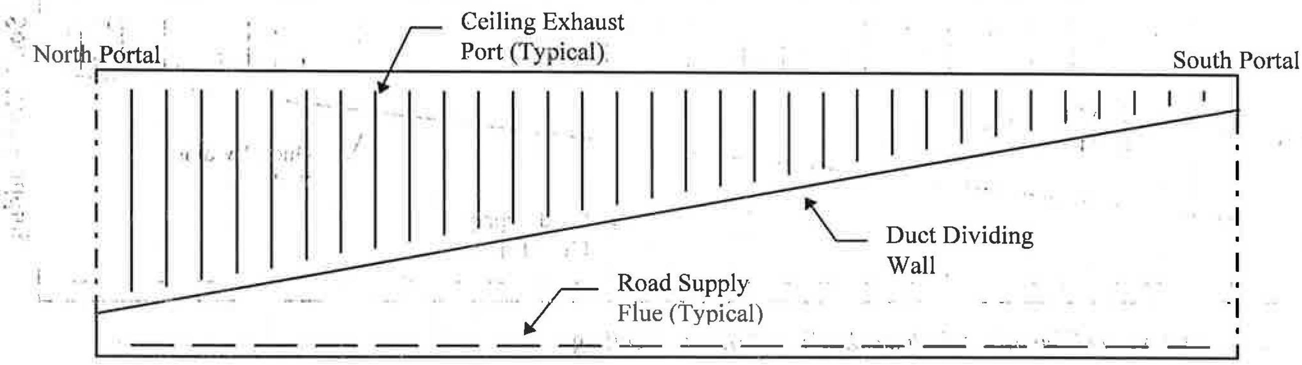

Figure 2 *Duct configuration for full transverse ventilation.*

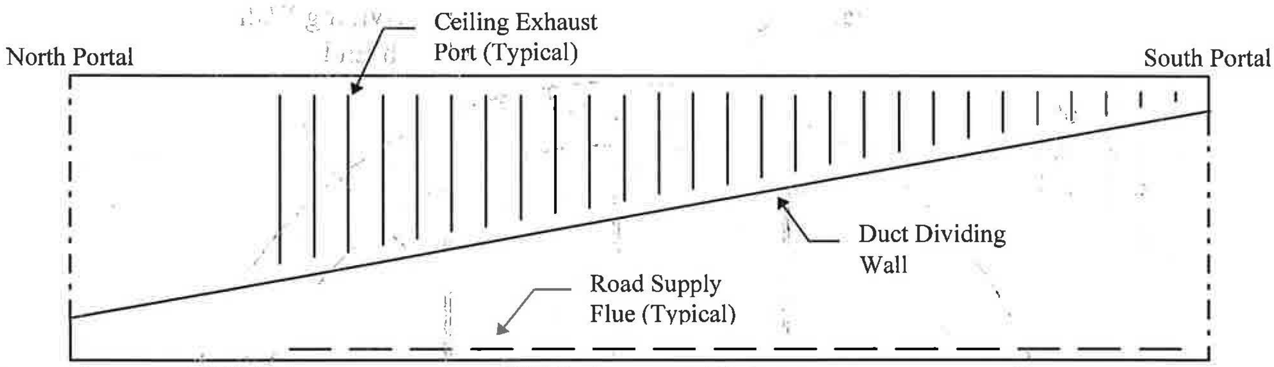

Figure 2 *Modified duct configuration for full transverse ventilation.*

tance of testing at 100 cfm/lf, additional modifications to the tunnel were made for tests having 100 cfm/lf ventilation. To allow for this ventilation rate, the ventilated length of the tunnel was shortened from 2,800 feet (853.4 m) to 2,300 feet (701 m). This was accomplished by closing 500 feet (152.4 m) of supply flues and exhaust ports closest to the north portal and rebalancing the active flues/ports to provide uniform supply/exhaust over the 2,300 feet (701 m). Figures 3 and 4 illustrate the duct configuration for full transverse ventilation.

Partial Transverse Exhaust Ventilation The mid-tunnel duct bulkhead was not in place and the openings in the duct dividing wall were uncovered so the duct would act as if there was no dividing wall, with the north and south central fans utilized to exhaust air.

The ports in the ceiling were balanced to provide for uniform exhaust over the full length of the tunnel, with the north and south central fans operating to exhaust equal amounts of air. For ease of balancing, only the ports in the ceiling located above the east lane north of the tunnel's midpoint and above the west lane south of the tunnel's midpoint were utilized; the others were closed. Figure 5 illustrates the duct configuration for partial transverse exhaust ventilation.

Partial Transverse Supply Ventilation from Roadway For this ventilation system, the tunnel was configured as for full transverse ventilation. The south central fans were operated to supply air, which was introduced at the roadway. The north central fans were not operated. Figure 6 illustrates the duct configuration for partial transverse supply ventilation from the roadway.

Partial Transverse Supply Ventilation from Ceiling For this ventilation system, the tunnel was configured as for partial transverse exhaust ventilation. The north and south central fans were operated to supply air, which was introduced at the ceiling. Figure 7 illustrates the duct configuration for partial transverse supply ventilation from the ceiling.

Two-Zone Partial Transverse Ventilation The mid-tunnel duct bulkhead was in place in order to divide the tunnel into two ventilation zones. The openings in the duct dividing wall were uncovered so that each zone in the duct would act as if there was no dividing wall.

The ports in the ceiling in the supply zone, the zone north of the bulkhead, were balanced to provide for uniform supply over the length of this zone. The ports in the ceiling in the exhaust zone, the zone south of the bulkhead, were balanced to provide for uniform exhaust over the length of this zone. The supply flues were closed. Figure 8 illustrates the duct configuration for two-zone partial transverse ventilation.

Partial Transverse Exhaust Ventilation with Single-Point Extraction For this ventilation system, the tunnel was configured as for partial transverse exhaust ventilation. In addition, large, normally closed openings in the ceiling were utilized. The ports in the ceiling were balanced with the single-point

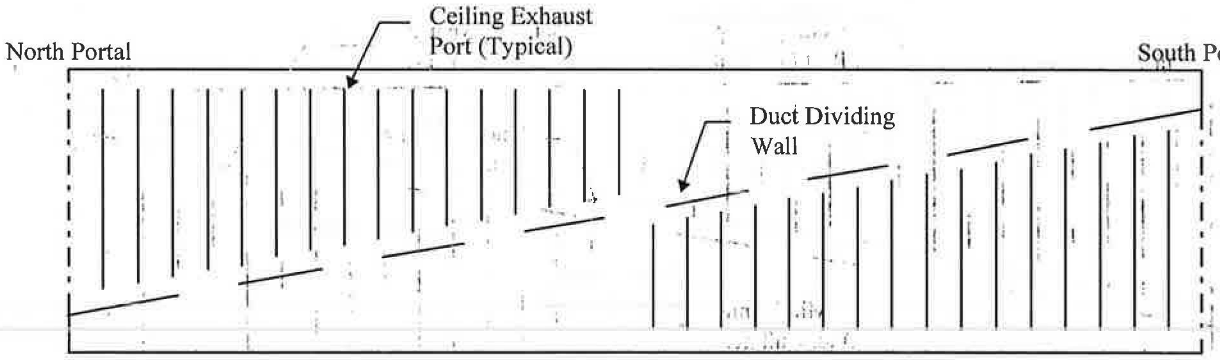

***Figure 5** Duct configuration for partial transverse exhaust ventilation.*

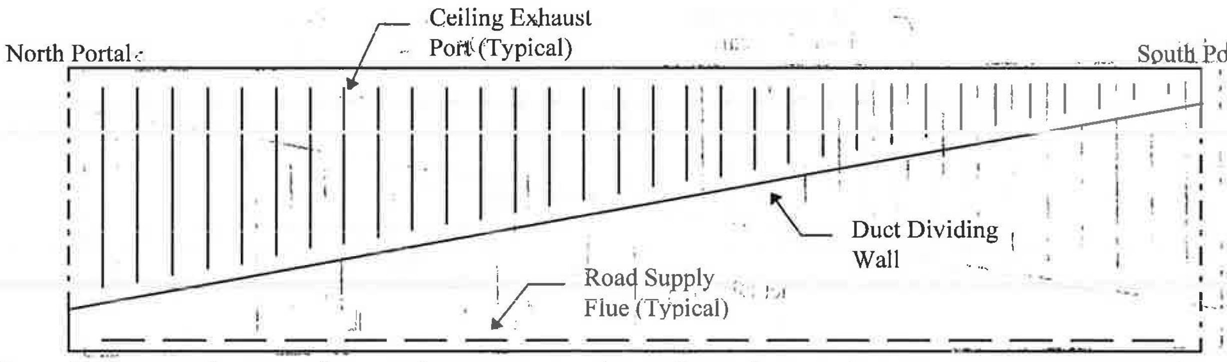

***Figure 6** Duct configuration for partial transverse supply ventilation from roadway.*

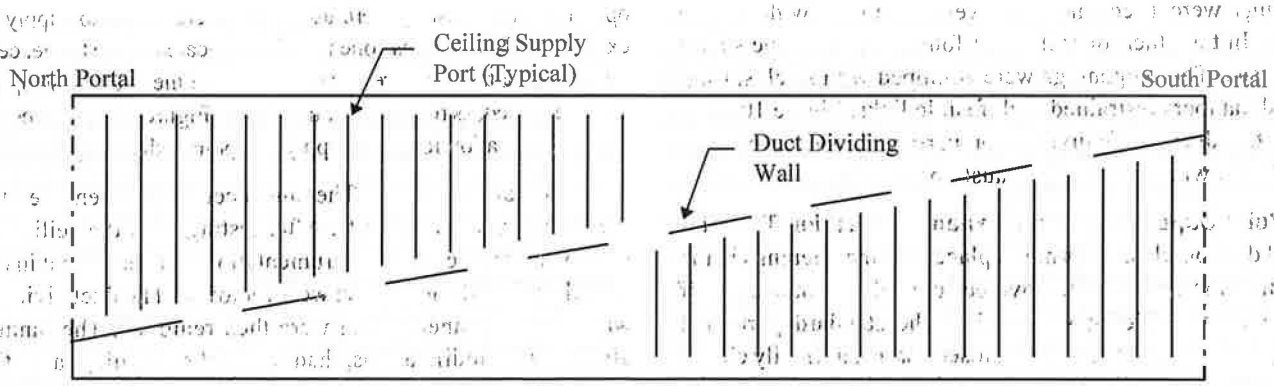

***Figure 7** Duct configuration for partial transverse supply ventilation from ceiling.*

extraction openings (SPE) closed to provide for uniform exhaust over the full length of the tunnel.

Four SPEs were located in the tunnel ceiling—one south of the fire and three north of the fire. One or more of these openings were utilized, as required, for each fire test conducted in this sequence. Each SPE could be adjusted from 0 to 300 ft^2 (27.8 m^2). Figure 9 illustrates the duct configuration for partial transverse exhaust ventilation with single-point extraction.

Partial Transverse Ventilation with Oversized Exhaust Ports For this ventilation system, the tunnel was configured as for partial transverse exhaust ventilation. In addition, 30 ft^2 (2.7 m^2) of oversized exhaust ports (OEP) in the ceiling were utilized. The ports in the ceiling were balanced with the OEPs closed to provide for uniform exhaust over the full length of the tunnel.

Nine pairs of oversized openings were located in the tunnel ceiling. Seven pairs were spaced 30 feet (9.1 m) apart beginning 30 feet (9.1 m) south of the fire site and extending north. The other two pairs were located 295 feet (89.9 m) north of the fire and 620 feet (188.9 m) north of the fire (mid-tunnel).

In this ventilation concept, two different system configurations were employed. In one, all nine pairs of oversized

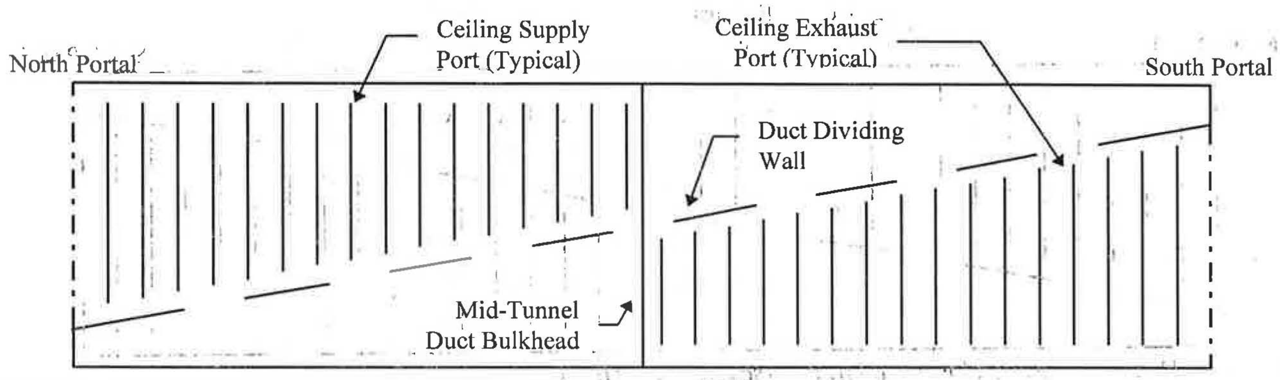

Figure 8 *Duct configuration for two-zone partial transverse ventilation.*

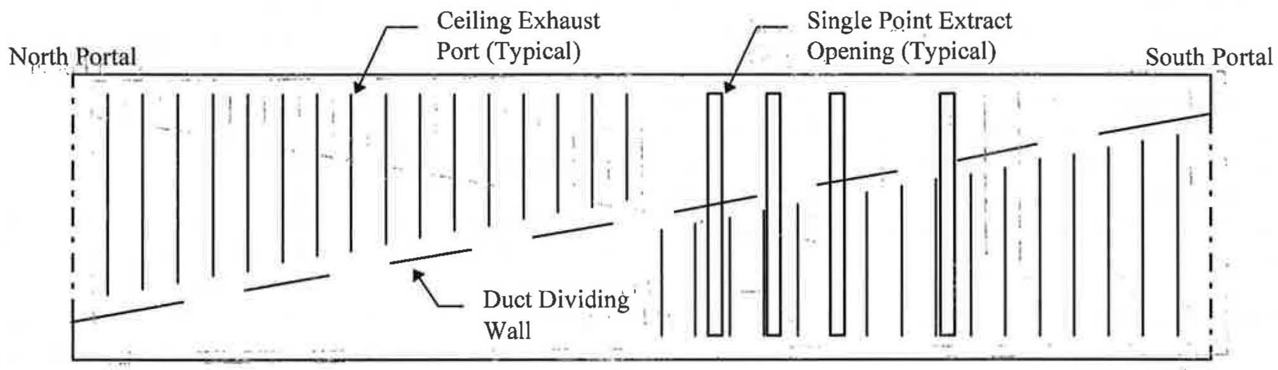

Figure 9 *Duct configuration for partial transverse exhaust ventilation with single-point extraction.*

openings were used and they were equipped with fusible panels. In the other, only the first four pairs (from the south) were used. These openings were equipped with steel, spring-loaded dampers restrained with fusible links. Figure 10 illustrates the duct configuration for partial transverse exhaust ventilation with oversized exhaust ports.

Point Supply and Point Exhaust Operation The mid-tunnel duct bulkhead was not in place, and the openings in the duct dividing wall were uncovered so the duct would act as if there was no dividing wall. All of the standard ports and supply flues in the ceiling were closed. Large, normally closed openings in the ceiling were used as discrete points to supply or exhaust air. Four of these openings were located in the tunnel ceiling—one south of the fire and three north of the fire. These openings were used, as required, for these tests. Figure 11 illustrates the duct configuration for point supply and point exhaust operation.

Natural Ventilation The tunnel ceiling was removed for the natural ventilation tests. After testing with the ceiling in place was completed, all instrumentation and equipment in the tunnel and overhead air duct were removed. The duct dividing wall and the tunnel ceiling were then removed. The tunnel, after these modifications, had an arched ceiling and the

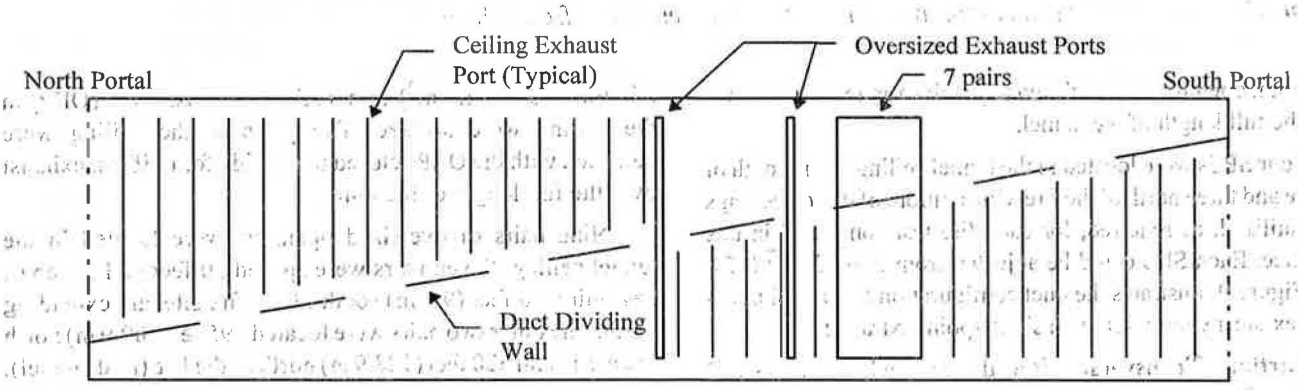

Figure 10 *Duct configuration for partial transverse exhaust ventilation with oversized exhaust ports.*

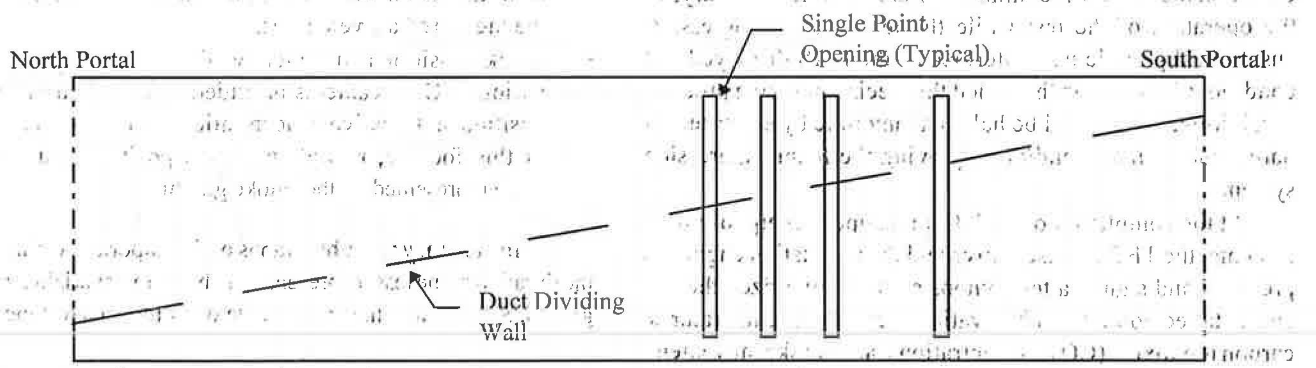

Figure 11 Duct configuration for point supply and point exhaust operation.

distance from roadway to crown was approximately 26 feet (7.9 m). Before conducting the natural ventilation tests, all the instrumentation and equipment was replaced in the tunnel.

Longitudinal Ventilation with Jet Fans The jet fan tests were performed after the natural ventilation tests. Prior to the start of jet fan testing, 15 jet fans were installed, in groups of 3, north of the fire. After the conduct of 12 tests, 9 additional jet fans were installed, also in groups of 3. One of these groups was installed north of the fire, and the other two groups were installed south of the fire.

CONDUCTING A FIRE VENTILATION TEST

Personnel

The individuals responsible for the day-to-day activities of the project, as well as the tasks necessary for the conduct of each fire test, were an important part of the test program. Only authorized personnel with specific assignments and trained in emergency procedures were permitted to remain on site during a test, and they were confined to the control trailer. Project personnel included

- test supervisor/resident engineer,
- lead field engineer,
- lead start-up engineer,
- field engineer,
- data acquisition system (DAS) technician,
- joint test group (JTG) chair,
- technical evaluation committee (TEC) representative,
- senior ventilation engineer, and
- ventilation engineer.

Preparing the Facility

Once the tunnel was configured for a given ventilation system, additional preparations (specific to individual tests) were required. These additional preparations included

- modifying the fuel delivery system to deliver fuel to the desired fuel pan(s);
- opening the large, normally closed openings in the tunnel ceiling, as required (applicable to partial transverse ventilation with single-point extraction and point supply and point exhaust operation);
- adjusting the north and south portal openings, as required; and
- erecting vehicle silhouettes, as required.

Testing Procedures

The fire tests were conducted in strict conformity to approved protocol and safety procedures and in accordance with the Environmental Impact Statement required by the State of West Virginia.

Operational work procedures (OWP) were developed to control various aspects of the test program. Thirteen OWPs were established. While most of these OWPs dealt with phases of the test program not directly related to the conduct of the fire ventilation tests, OWP-03, "Test Performance and Control," related specifically to testing. OWP-03 consisted of a series of configuration checklists designed to make certain all support systems were configured to conduct the scheduled fire ventilation test. Checklists were established for the following support systems: fire pan, closed-circuit television (CCTV), chilled water, compressed air, data acquisition, fire protection, fuel oil, instrumentation, central fan, jet fan, liquid propane (LP) gas, and meteorological. All the support systems relevant to the scheduled test were verified according to the configuration checklists prior to the start of each and every test.

Operational test procedures (OTP) were also established as part of the test program. An OTP was prepared for every fire test before the start of the test. OTPs were prepared by the lead field engineer and reviewed for accuracy by the JTG chair or designated TEC representative. Customized graphics, trends, and tables that presented test data while each test was in progress were used to aid test monitoring. An OTP defined the test objectives and outlined the specific procedures to be followed for the successful performance of the test.

After the OTP was prepared and reviewed, and after all support systems were configured properly, testing commenced. During a test, all systems were monitored and controlled by the lead start-up engineer using the DAS and CCTV cameras. The JTG chair or designated TEC representative and the senior ventilation engineer monitored the test using DAS computers and the

CCTV cameras and recommended changes, if necessary, to the operation of the test while the test was in progress. A customized graphic user interface of the DAS displayed test conditions in real time that aided this decisionmaking process. In addition, a test could be halted at any time by either terminating fuel delivery and/or employing the foam suppression system.

At the completion of each test and upon receipt of initial test data, the TEC representative and the ventilation engineers prepared and signed a test synopsis that summarized the test and detailed some test observations regarding temperatures, carbon monoxide (CO) concentrations, and smoke movement. Graphs were also prepared that focused primarily on fan airflows, fire heat release rate, temperatures, and CO concentrations.

After each test, in the interest of obtaining maximum benefit from the tests, the JTG performed some preliminary data analysis on the test to determine the operational procedures for the next scheduled test.

USING THE TEST DATA

On average, each fire ventilation test yielded approximately three million points of data and seven videotapes containing footage of the test. Because of this large volume of information, the test data were reduced to a graphical format to facilitate and support the efforts of examining and analyzing the data. These graphics were included as part of the comprehensive test report of the Memorial Tunnel fire ventilation test program.

Test Data Reduction

The data from each test were documented by the following reports.

Test Summary The test summary lists the test number, test date, nominal fire size, sequence of test events, and other pertinent information specific to each test.

Point-in-Time Graphics Each page of these graphics shows the instantaneous value ("snapshot in time") of important variables at pretest conditions, every minute from 0 to 6 minutes, and thereafter every 2 minutes. Specifically, each point-in-time graphic depicts the following:

- Test number.
- Nominal ventilation rate (for tests using the central fans).
- Jet fan operation (for tests using the jet fans).
- Actual fire heat release rate.
- Air temperature distribution in the tunnel—temperature measurements taken at various elevations at 15 locations in the tunnel were used to develop the temperature contours.
- Air velocity at the instrumented cross sections—air velocity measurements taken at various elevations at 10 locations in the tunnel were used to create air velocity profiles.
- Bulk tunnel airflow—bulk airflow was calculated using the measured air velocities.
- Smoke position and camera visibility—footage from the various CCTV cameras provided information on smoke position and relative concentrations. Visual observations of this footage, regarding smoke position and density, were represented on the smoke graphics.

Time History Graphs Graphs of the important variables for the duration of the test are presented in the form of variable vs. time graphs. Specifically, the graphs developed for each test include

- central fan airflow (for tests using the central fans);
- air temperature through the central fans (for tests using the central fans);
- fire heat release rate—including a calculated value, which is based on fuel consumption, and a corrected value, which is the calculated value corrected by an efficiency factor calculated using carbon monoxide and carbon dioxide concentrations;
- bulk tunnel airflow at the instrumented cross sections;
- air temperature for the various elevations at the instrumented tunnel cross sections;
- air velocity for the various elevations at the instrumented tunnel cross sections; and
- carbon monoxide concentrations at the various sensing points throughout the tunnel.

Test Data Analysis

The primary objective of the data analysis was to determine the effectiveness of the various tunnel ventilation systems and configurations on temperature and smoke management during a fire in the Memorial Tunnel. The point-in-time graphics and the time history graphs were the tools used to accomplish this objective. These graphics facilitated test-to-test comparisons that were essential in identifying the capabilities of each ventilation system.

Comprehensive Test Report

The comprehensive test report is composed of nine volumes. Volume 1 contains background information on the test program, a description of the test facility, results of the data analyses, and findings and conclusions of the test program. Volumes 2 through 8 are a compilation of the reduced data for all the tests. Volume 9 contains the field test synopses for all fire tests, as well as the phase I report. A synopsis that summarized preliminary test observations was prepared at the conclusion of each test. The volumes containing reduced data are as follows:

- Volume 2: Natural Ventilation and Longitudinal Ventilation with Jet Fans
- Volume 3: Full Transverse Ventilation
- Volume 4: Partial Transverse Supply and Exhaust Ventilation
- Volume 5: Two-Zone Partial Transverse Ventilation

- Volume 6: Partial Transverse Ventilation with Single-Point Extraction
- Volume 7: Partial Transverse Ventilation with Oversized Exhaust Ports
- Volume 8: Point Supply and Point Exhaust Operation

REFERENCES

Massachusetts Highway Department and Federal Highway Administration. 1995. Memorial Tunnel fire ventilation test program, comprehensive test report, November 1995.