NATIONAL TRANSPORTATION SAFETY BOARD
Investigative Hearing
Washington Metropolitan Area Transit Authority Metrorail train 302 that encountered heavy smoke in the tunnel between the L'Enfant Plaza Station and the Potomac River Bridge on January 12, 2015

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EXHIBIT	
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WMATA

Title

Outer B Route
Tunnel Ventilation Analysis
January 1998

Docket ID: **DCA 15 FR 004**

PROPERTY OF
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WMATA

WASHINGTON METROPOLITAN
AREA TRANSIT AUTHORITY

OUTER B ROUTE
TUNNEL VENTILATION ANALYSIS

JANUARY 1998

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EXECUTIVE SUMMARY

The Authority has deleted tunnel ventilation barriers from the Outer B Route ventilation system designs in the interests of operational safety. Barriers had been advocated as a means of selectively increasing airflow in individual tunnel segments in response to NFPA 130 emergency ventilation requirements. Therefore, an alternate increase in ventilation system capacity is required to compensate for the elimination of the barriers.

The magnitude of this capacity increase is dependent on the passenger evacuation path. In an uphill passenger evacuation scenario, the required ventilation flow must oppose buoyant effects produced by a fire. In contrast, if passengers evacuate in a downhill direction, the ventilation flow reinforces the natural tendency of smoke and hot air to rise. Consequently, an uphill evacuation path will result in a higher ventilation capacity requirement than a downhill path.

The existing ventilation system designs were analyzed with passenger evacuations occurring in both the uphill and downhill directions. Based on this analysis, the performance of the existing ventilation systems (without barriers or other augmentation) is summarized as follows:

- The existing ventilation capacities are not sufficient for any of the uphill passenger evacuation scenarios analyzed. Provision of uphill passenger evacuation capability would require either augmenting the existing ventilation system with tunnel ventilation barriers or extensive modifications to the existing designs.

- The existing ventilation capacities are sufficient to provide a safe exit path for downhill evacuation at all locations except for a burning train on the outbound side of Blueridge Avenue fan shaft. At this location, the relatively flat grade does not provide sufficient buoyancy to prevent backlayering toward Blueridge.

Alternative methods of achieving the required air flow rates were developed and evaluated. The available options include alterations to Mason Street and/or Blueridge Avenue fan shafts. Based on this evaluation, a solution involving modification of the Blueridge Avenue fan shaft provided the only practical alternative. An increase in fan capacity at Blueridge allows downhill evacuation in all locations. This alternative requires that emergency evacuation always occur in a downhill direction.

1.0 INTRODUCTION

1.1 Background

The current tunnel ventilation system serving **the Outer B Route is based on a 1970's design which preceded the development of NFPA 130.** This ventilation system was **designed to provide temperature control only, and not smoke control** as mandated in the new standards. The normal mode of fan operation is in exhaust to remove hot tunnel air while fresh air is drawn into the tunnel from gravity ventilation shafts. Tunnel ventilation fans are rated at 100% capacity in the exhaust mode and approximately 70% in the supply mode. Fan modes are remotely controlled to allow for passenger evacuation in the event of a disabled and burning train.

The WMATA standard for tunnel ventilation systems in new construction is to comply with NFPA 130 requirements. Per NFPA 130, tunnel ventilation systems must produce air flow rates which prevent backlayering of smoke in a path of egress away from a train fire. Analysis indicated that **increased tunnel air flow rates, beyond those provided by the original design, are necessary to ensure compliance with NFPA 130 smoke control requirements.** Alternative methods of achieving the required flow rates were developed and evaluated. These alternatives included the following:

- Installation of tunnel barriers which sufficiently seal selected tunnel segments such that the airflow produced by a fan shaft is directed into a single tunnel segment. Two devices were considered, inflatable parachutes and electrically operated roll-down doors.

- Increasing the capacity of the existing fan shafts to produce the required flow rates in an incident tunnel.

At the time, the Authority had elected to use barriers in order to ensure NFPA 130 compliance and to enable a safe evacuation path to be provided either downhill or uphill, depending upon the relative locations of the train and the selected exit shafts. The Authority has recently determined not to use barriers due to operational safety concerns. Since barriers are no longer an option, an alternative method of NFPA 130 compliance is required. The primary objective of this analysis involved a performance evaluation of the current ventilation system designs without barriers. **Ventilation system performance was evaluated** with passenger evacuations occurring in both the uphill and downhill directions. The results of this evaluation were used to identify the magnitude and the feasibility of tunnel ventilation system modifications required for NFPA 130 compliance.

1.2 System Description

The Outer B Route contains a tunnel segment which connects the existing Wheaton station to the new Glenmont station (Figure 1.1). Ventilation for this segment is provided by the existing Blueridge Avenue fan shaft and the new Mason Street fan shaft. The performance characteristics of these fan shafts are summarized as follow:

- Blueridge Avenue Fan Shaft (FB-8) at approximate STA 1148+00, design section B-10; four fans total producing 200,000 cubic feet per minute (cfm) in the exhaust mode and 140,000 cfm in the supply mode.
- Mason Street Fan Shaft (FB-9) at approximate STA 1191+67, design section B-11a; four fans total producing 200,000 cfm in the exhaust mode and 140,000 cfm in the supply mode.

The Blueridge Avenue fan shaft is currently within the operating system.

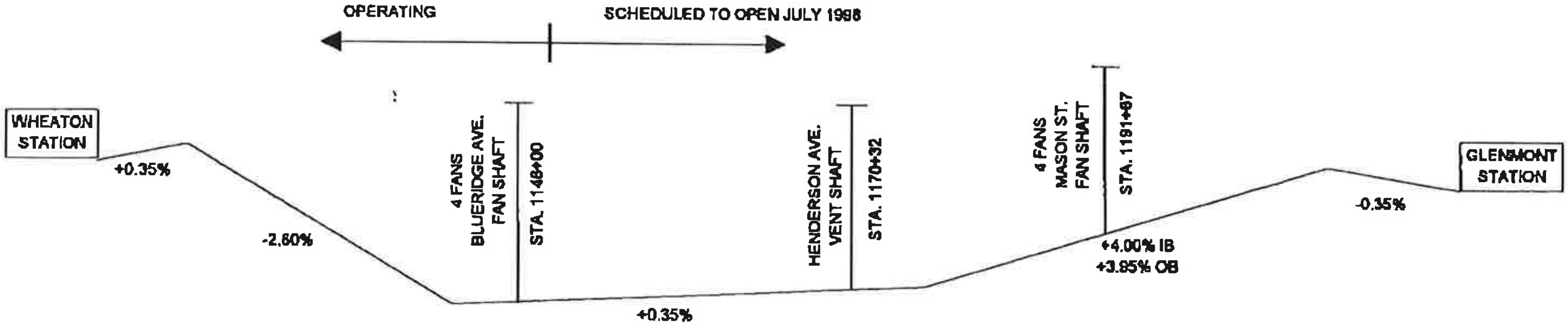
Underground stations are equipped with both an under platform exhaust system and a dome exhaust system. The combined capacities of both systems equal a nominal 150,000 cfm per station in the exhaust mode. These station systems are also intended for emergency use and can provide a nominal 105,000 cfm in the supply mode per station. Vent shafts are located at each end of underground stations and in mid-tunnel locations. In terms of ventilation, these shafts primarily provide a means of piston action relief during normal operations. In the event the tunnel ventilation system is operated in the emergency mode, vent shaft dampers close and effectively prevent air movement between the surface and the tunnel.

1.3 Analysis

This analysis involved the following tasks:

- Determine the passenger evacuation times from a burning train.
- Utilize the Subway Environment Simulation (SES) program to evaluate existing ventilation system performance without barriers and identify any ventilation deficiencies. This portion of the analysis considered uphill and downhill evacuation paths.
- Identify the modifications to the existing ventilation system to remedy any deficiencies. Verify the adequacy of the proposed modifications by additional SES program runs.

FIGURE 1.1
OUTER B ROUTE



- Utilize a Computational Fluid Dynamics (CFD) program to augment SES simulation results.
- Evaluate the feasibility of modifying the existing ventilation system to provide for uphill and downhill passenger evacuation in terms of constructability and cost.

2.0 PASSENGER EVACUATION

2.1 Objective

In conjunction with the fire simulations performed as part of this analysis, passenger exit times from a Metrorail train were also calculated by Parsons Brinckerhoff (PB) under a subcontract to the GEC. This calculation provides a means of comparing passenger exit times with the spread of smoke and evaluating the potential for passengers exiting a burning train before smoke engulfs the tunnel exit path. In addition, the computed exiting time also provides a useful comparison to the time required for an undercar fire to penetrate the vehicle floor. The calculations are provided in Appendix 1.

Passengers were assumed to leave the train in single file through the train doors located on each end of the cars. Other parameters used in this calculation are summarized as follows:

- Train Length - 600 feet (eight car train).
- Train Occupancy - 500 people (approximately 63 people per car).
- Walking Speed - 200 feet per minute.
- Safety Walk Capacity - 50 people per minute.

Based on information provided by the Authority, the expected train occupancy on the Outer B Route is 250 people. In these calculations, an occupancy of 500 people was utilized to account for abnormal train loading resulting from a missed headway.

2.2 Conclusions

Based on the calculation provided in Appendix 1, 10 minutes will elapse before the last person leaves the train. The first person off the train will have traveled 2000 feet through the tunnel when the last persons exits the train.

Since 10 minute exiting is less than the 30 minute rating of the vehicle floor, passenger will have the opportunity to evacuate a burning car before an under car fire can penetrate the floor.

3.0 CRITERIA

For the purpose of this analysis, ventilation systems must conform to the following NFPA 130, 1995 requirements:

- Paragraph 3-2.2.2(a) - provide a stream of non-contaminated air to passengers in a path of egress away from a train fire.
- Paragraph 3-2.2.2(b) - produce air flow rates to prevent backlayering of smoke in a path of egress away from a train fire.
- Paragraph 3-2.2.2(c) - limit the air temperature in a path of egress away from a train fire to 140° F or less.

NFPA 130 Paragraph 3-2.2.2(a) is essentially an operational requirement. Tunnel ventilation fans must be operated in the appropriate modes in an emergency situation. Compliance with paragraphs 3-2.2.2(b) and (c) requires tunnel ventilation systems capable of producing sufficient air flow rates to preclude backlayering and maintain an exit path air temperature below NFPA mandated limits. The minimum required flow rate is a function of fire intensity, tunnel grade and tunnel geometry. If the ventilation system can not produce sufficient air flow in the incident tunnel, buoyant effects will cause smoke and hot gasses to flow in a direction counter to the forced ventilation.

In the case of an uphill passenger evacuation path, the buoyant effects produced by a fire restrict mechanically produced air flows and become more severe as the grade increases.

In the case of a downhill evacuation path, mechanical ventilation airflows augment the flows produced by buoyancy. Since buoyant effects no longer oppose the forced ventilation, the demands on the existing ventilation systems are less severe in this situation.

Per NFPA 130, paragraph 3-2.2.3, "The design heat release rate produced by a train fire shall be used to design the emergency ventilation system." The heat release rate used in this analysis was 69.7 million British Thermal Units per hour (Btu/hr) and was taken from the Phase II study performed in July 1991.

The following minimum airflow requirements have been determined using the Authority's design vehicle heat release rate:

	Uphill Evacuation	Downhill Evacuation
● Critical Airflow - Single Track Tunnel (cubic feet per minute)	57,048	49,662
● Critical Airflow - Double Box Tunnel (cubic feet per minute)	122,747	106,006
● Tunnel Grade (Percent)	4.0	0

NFPA 130 has recently been revised to provide for ventilation system approval on the basis of an engineering analysis of the environmental conditions in the passenger exit path. In lieu of completely eliminating backlayering, an exit path is acceptable provided that the following parameters are not exceeded in the passenger exit path:

- Light attenuation - 0.2 meters^{-1}.
- Temperature - 140°F.

4.0 SES PROGRAM RUNS

4.1 Objective

The SES program was utilized to evaluate the performance of both the existing Outer B Route tunnel ventilation system and the effectiveness of the proposed modifications to the existing system.

Version 3 of the SES program provides a fire simulation option. This option allows the user to simulate a fire and evaluate the smoke control capability of a particular ventilation system.

4.2 Initial SES Simulations

Vehicle fire scenarios and the corresponding ventilating system operating modes were developed using an approach consisting of the following:

- Vehicle fire locations were selected in each tunnel segment. Two simulations were performed for each fire location to evaluate ventilation system performance when either uphill or downhill evacuation paths are utilized.
- For each simulation, tunnel and station emergency fan operating modes were developed on the basis of producing air flow in a direction opposite to the selected passenger evacuation path. The existing fan capacities were used for each simulation.

The simulation scenarios and results are shown in Table 4.1. All uphill evacuation scenarios failed. The following downhill evacuation scenario failed to comply with criteria:

Run	Train Location
3	3

The run numbers and train locations given above are identified on the matrix provided in Table 4.1.

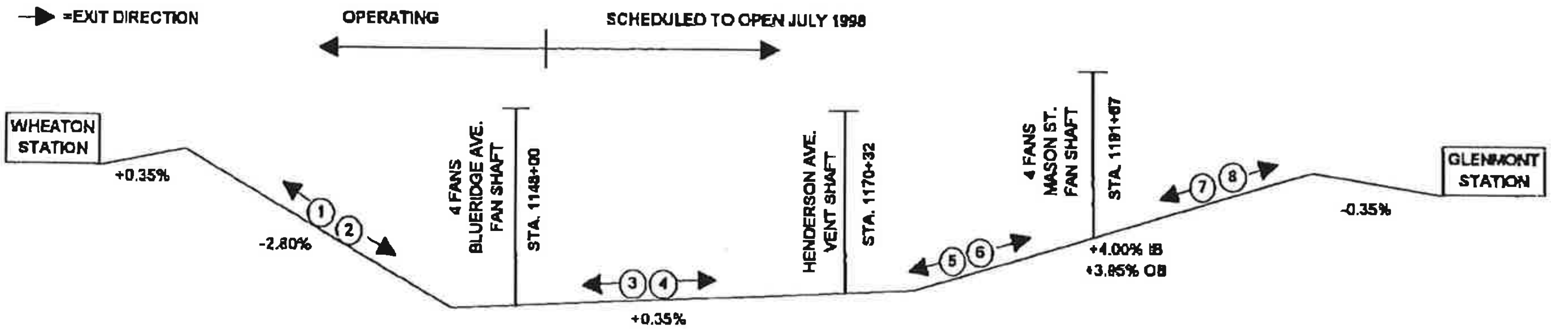
4.3 Final SES Simulations

A second series of simulations were performed to evaluate the remedial actions necessary to ensure criteria compliance for the downhill evacuation scenarios which failed during the initial simulations. The results of these simulations are summarized in Table 4.2. The required modification consists of increasing the supply mode capacity of Blueridge Avenue fan shaft from the current level of 140,000 cfm to 288,000 cfm. The actions required to provide the necessary capacity are summarized as follows:

TABLE 4.1

B-11a SES SIMULATION RESULTS

ORIGINAL SYSTEM WITHOUT MODIFICATION
MASON STREET FAN SHAFT WITH 4 FANS
BLUERIDGE AVE. FAN SHAFT WITH 4 FANS



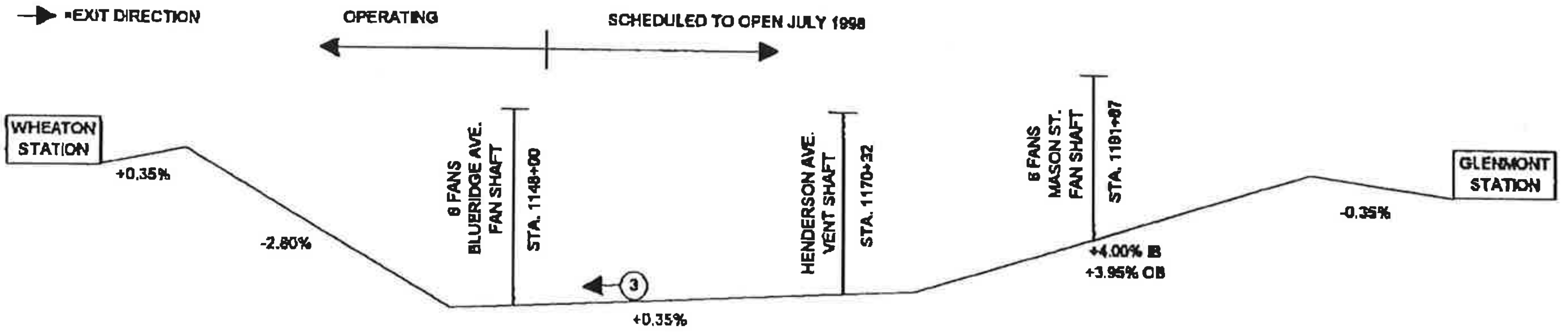
RUN	BLUERIDGE AVE. FAN SHAFT	MASON ST. FAN SHAFT	WHEATON STATION	GLENMONT STATION	EXIT TO	TRAIN/FIRE LOCATION	SES RESULTS (CFM)	CRITERIA (CFM)	PASS/FAIL	COMMENT
1	EXHAUST	EXHAUST	SUPPLY	EXHAUST	WHEATON STATION	1	53,466	57,048	FAIL	MEETS CRITERIA IN DOWNHILL DIRECTION ONLY
2	SUPPLY	SUPPLY	EXHAUST	SUPPLY	BLUERIDGE AVE. FAN SHAFT	2	65,481	49,662	PASS	
3	SUPPLY	EXHAUST	SUPPLY	EXHAUST	BLUERIDGE AVE. FAN SHAFT	3	37,701	49,662	FAIL	DOES NOT MEET CRITERIA IN EITHER DIRECTION, MODIFICATION REQUIRED
4	EXHAUST	SUPPLY	EXHAUST	SUPPLY	HENDERSON AVE. VENT SHAFT	4	25,449	57,048	FAIL	
5	SUPPLY	EXHAUST	SUPPLY	EXHAUST	HENDERSON AVE. VENT SHAFT	5	65,574	49,662	PASS	MEETS CRITERIA IN DOWNHILL DIRECTION ONLY
6	EXHAUST	SUPPLY	EXHAUST	SUPPLY	MASON ST. FAN SHAFT	6	-17,467*	57,048	FAIL	
7	SUPPLY	SUPPLY	SUPPLY	EXHAUST	MASON ST. FAN SHAFT	7	62,991	49,662	PASS	MEETS CRITERIA IN DOWNHILL DIRECTION ONLY
8	EXHAUST	EXHAUST	EXHAUST	SUPPLY	GLENMONT STATION	8	7,352	57,048	FAIL	

[redacted]

TABLE 4.2

B-11a SES SIMULATION RESULTS

MODIFIED TUNNEL VENTILATION DESIGN
ADDED 2 FANS TO MASON STREET FAN SHAFT (65,000 CFM EACH)
ADDED 2 FANS TO BLUERIDGE AVE. FAN SHAFT (60,000 CFM EACH)



RUN	BLUERIDGE AVE. FAN SHAFT	MASON ST. FAN SHAFT	WHEATON STATION	GLENMONT STATION	EXIT TO	TRAIN/FIRE LOCATION	SES RESULTS (CFM)	CRITERIA (CFM)	PASS/FAIL	COMMENT
3R	SUPPLY	EXHAUST	SUPPLY	EXHAUST	BLUERIDGE AVE. FAN SHAFT	3	53,754	49,662	PASS	MEETS CRITERIA IN DOWNHILL DIRECTION

5.0 CFD SIMULATIONS

5.1 Objective

The analysis involved an evaluation of the ventilation system's ability to either completely eliminate backlayering or limit backlayering to a degree which does not preclude passenger evacuation. The degree of backlayering was considered unacceptable whenever either of the following conditions occurred in the selected exit path while evacuation was taking place:

- Light attenuation greater than 0.2 meters^{-1}.
- Temperature greater than 140°F.

This portion of the analysis was performed by PB under a subcontract to the GEC.

5.2 Approach and Methodology

The simulations were performed using Version 4.44 of the Fluent CFD computer program. The CFD simulations provided output which visually depicted the light attenuation produced by smoke and the air temperature in the vicinity of a fire. CFD program input was taken from the following sources:

- Geometry data were taken from the Contract Drawings.
- Train Fire Heat Release Rates developed by as part of the barrier development studies performed during 1988-1991. Simulations were performed using a fire heat release rate of 42.4 Million BTU per hour.
- Tunnel airflows generated by SES computer program runs.
- Tunnel wall temperatures extracted from field measurements.
- Evacuation times calculated on the basis of a train occupancy of 500 people. The evacuation time for the last person to exit the train is 10 minutes assuming that passengers evacuate through the doors on the vehicle ends only.

5.3 Simulation Scenarios

The fire scenarios simulated to date were selected to produce a worst case situation for both downhill and uphill passenger evacuation. Per NFPA requirements, emergency ventilation must produce flow in a direction opposite to passenger exit. In the case of an uphill evacuation path, the ventilation flow must counter the buoyant effects produced by a fire. Since the buoyant force increases with tunnel grade, the worst case occurs at the steepest grade encountered. For a downhill evacuation path the required airflow reinforces the buoyant effect. The worst case therefore occurs at the flattest grade encountered.

The scenarios simulated are as follow:

- Scenario 1 - The burning vehicle was located on a relatively flat grade (0.35%) between Blueridge Avenue Fan Shaft and the Henderson Avenue Vent Shaft. Passengers were evacuated in a downhill direction toward the Blueridge Avenue Fan Shaft. To produce airflow opposite to the direction of passenger evacuation, the Blueridge Avenue fan shaft operated in the supply mode while the Mason Street Fan Shaft operated in the exhaust mode. The existing fan shaft capacities were used. The resulting airflow rate in the incident tunnel was 39,800 cfm.

- Scenario 2 - This scenario is identical to Scenario 1 in terms of train location, passenger exit path and fan shaft operating modes. However, in this case, Blueridge Avenue fan shaft was modified to produce an air flow rate of 288,000 cfm in the supply mode, resulting in an incident tunnel flow rate of 51,960 cfm.

- Scenario 3 - The burning vehicle was located on a 4.00% grade between the Henderson Avenue Vent Shaft and the Mason Street Fan Shaft. Passengers were evacuated in an uphill direction toward the Mason Street Fan Shaft. To produce airflow opposite to the direction of passenger evacuation, the Blueridge Avenue fan shaft operated in the exhaust mode while the Mason Street Fan Shaft operated in the supply mode. The resulting airflow rate in the incident tunnel was minimal at approximately 3,000 cfm.

- Scenario 4 - This scenario is identical to Scenario 3 in terms of train location, passenger exit path and fan shaft operating modes. However, in this case the airflow rate within the incident tunnel was increased in increments to determine a flow rate which would limit backlayering to an acceptable degree.

5.4 Results

Results are summarized as follow:

- CFD results indicate that smoke and heat rapidly spread through the tunnel. As a result, in cases where backlayering occurs, the exit path will become engulfed before passengers can clear the area.

- Scenario 1 - CFD results indicate that the current ventilation system will allow back-layering to occur in the passenger evacuation path. The light attenuation and air temperature will exceed the criteria for a distance of 75 to 150 feet upstream of the fire (Figures 5.1, Temperature and 5.2, Light Attenuation).

- Scenario 2 - CFD results indicate that modifications to the current Blueridge Avenue fan shaft will eliminate back-layering in the passenger evacuation path. These results are illustrated in Figures 5.3, Temperature and 5.4, Light Attenuation.

- Scenario 3 - CFD results indicate that the current ventilation system will allow an unacceptable degree of back-layering to occur in the passenger evacuation path. These results are illustrated in Figures 5.5, Temperature and 5.6, Light Attenuation.

- Scenario 4 - CFD results indicate that an air flow rate of approximately 45,000 cfm is required to reduce back layering to an acceptable degree. These results are illustrated in Figures 5.7, Temperature and 5.8, Light Attenuation.

In reference to Figures 5.1 through 5.8, guidelines for interpretation of the figures are as follow:

- Air flows from the left hand side to the right hand side of the sheet.

- Passengers exit toward the left hand side of the sheet,

- The longitudinal section denoted as K = 10 was cut through the centerline of the trackway.

- The longitudinal section denoted as K = 18 was cut through the safety walk.

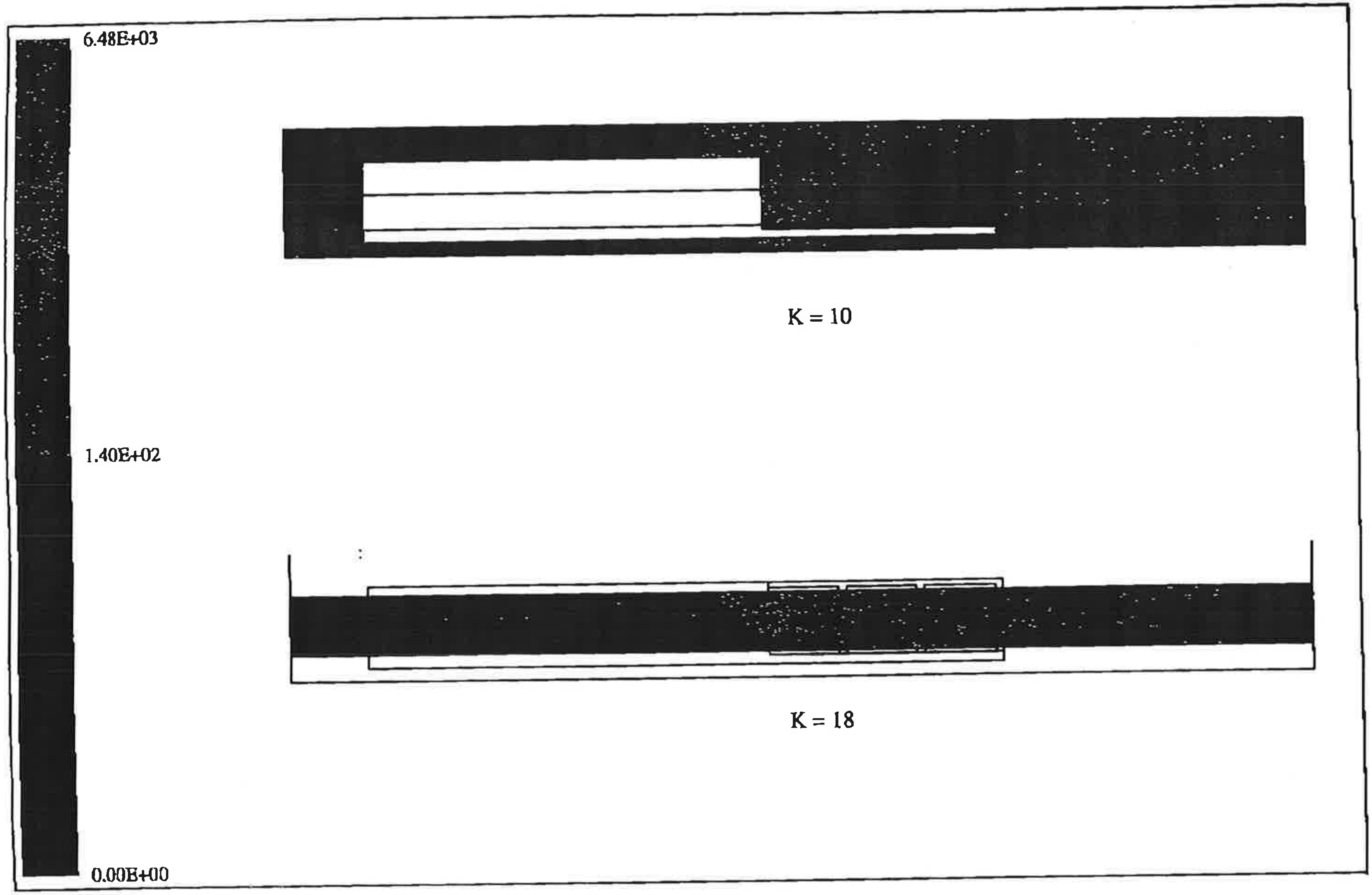
- Regions shown in red exceed criteria.

- Regions shown in blue comply with criteria.

5.5 Conclusions

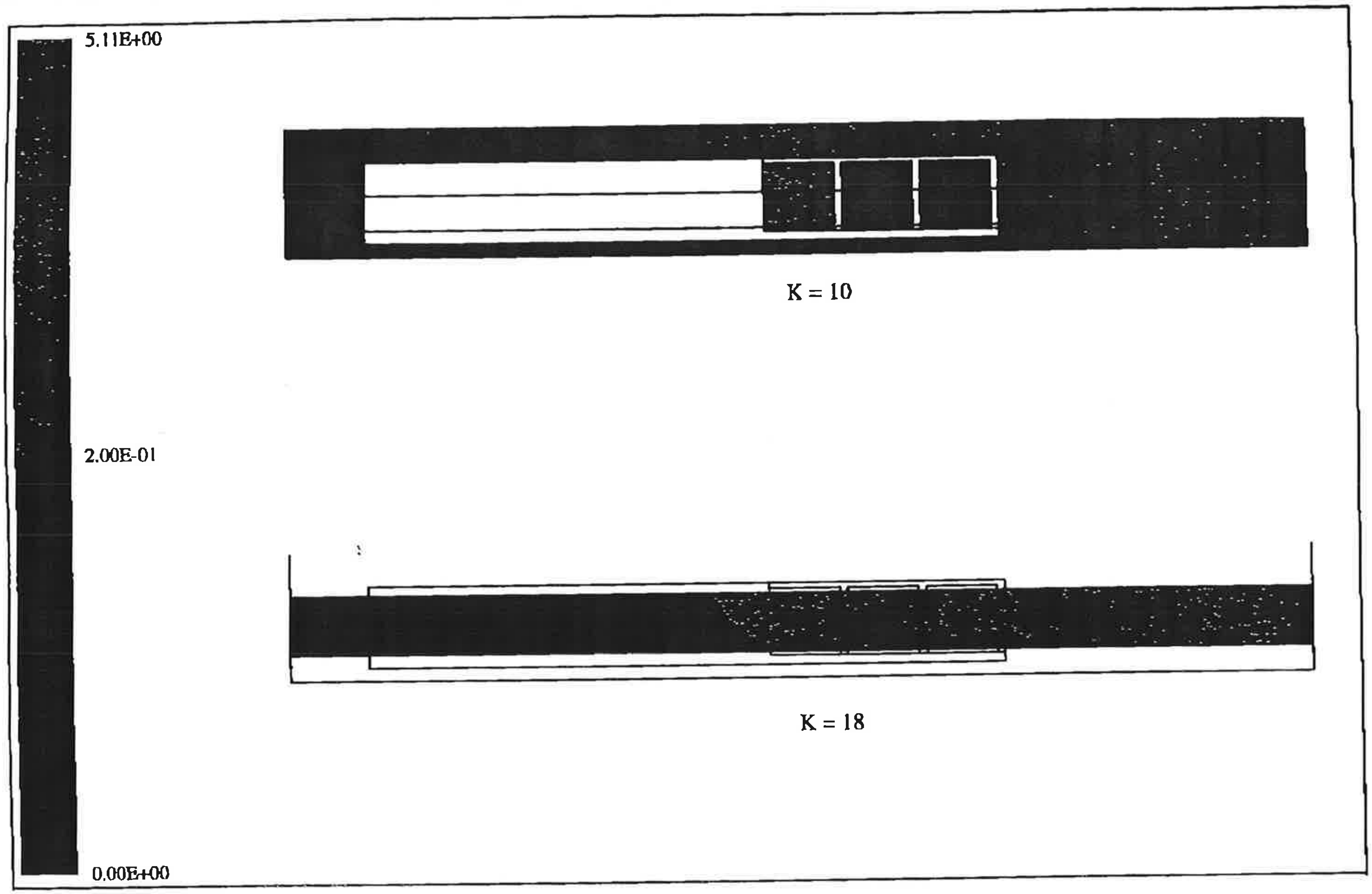
Conclusions based on the CFD simulations are summarized as follow:

- In the case of a downhill evacuation path, the existing ventilation system does not entirely eliminate backlayering. However, the extent of the backlayering is limited. A downhill evacuation path is possible provided that the fire is not located on the two vehicles closest to the source of airflow.



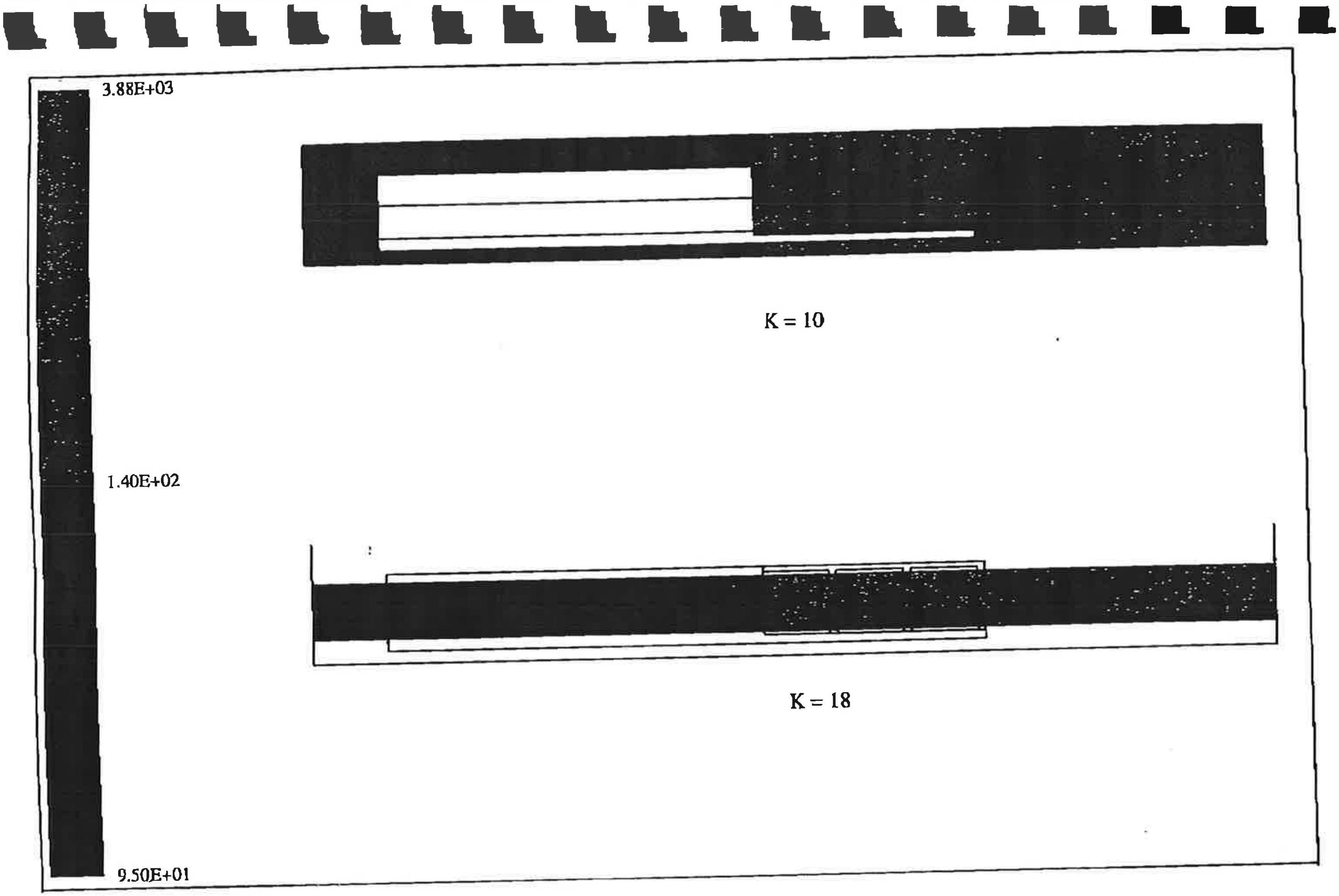
SCENARIO 1 - TEMPERATURE
FIGURE 5.1

Parsons
Brinckerhoff



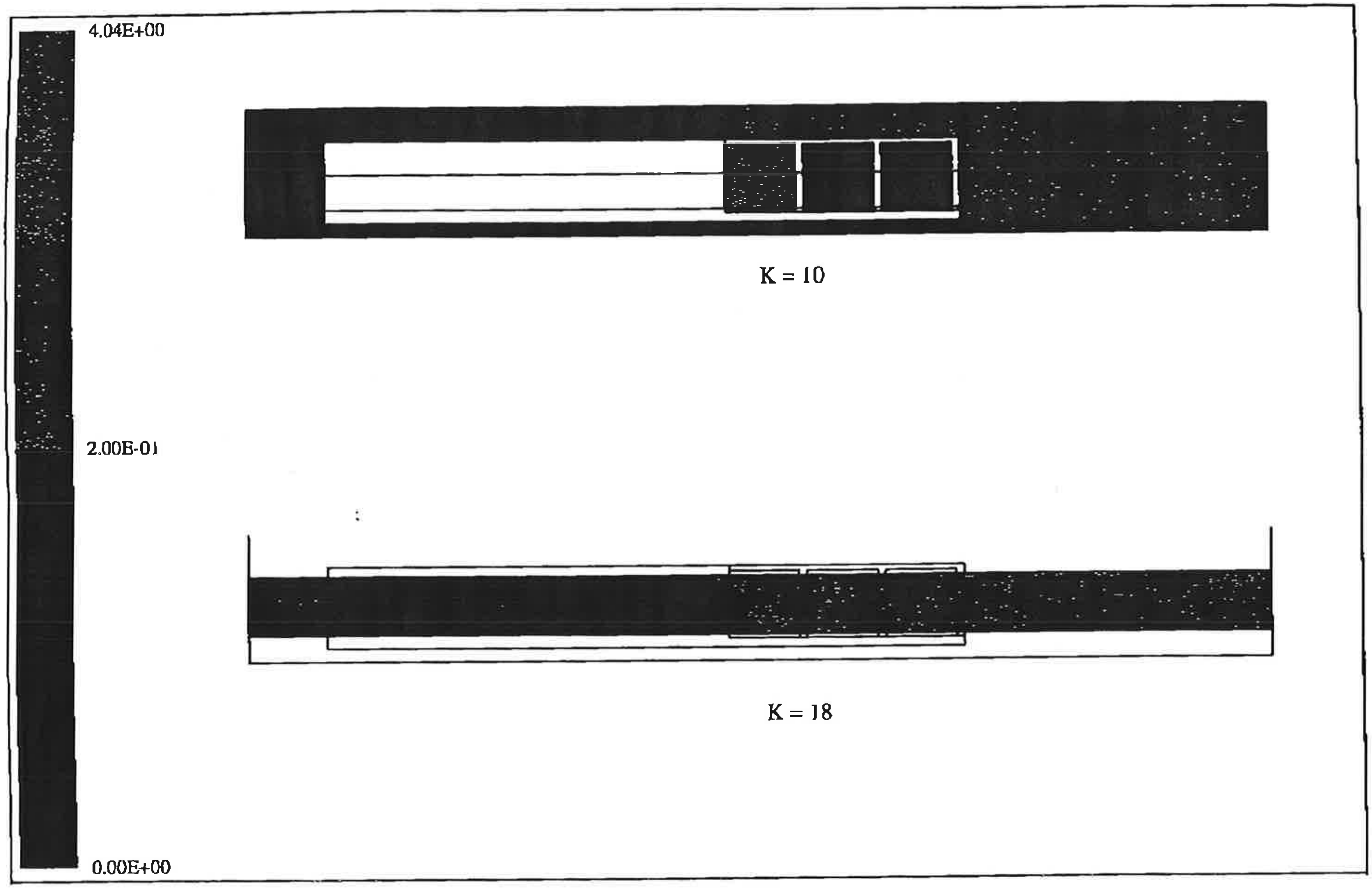
SCENARIO 1 - LIGHT ATTENUATION
FIGURE 5.2

Parsons
Brinckerhoff



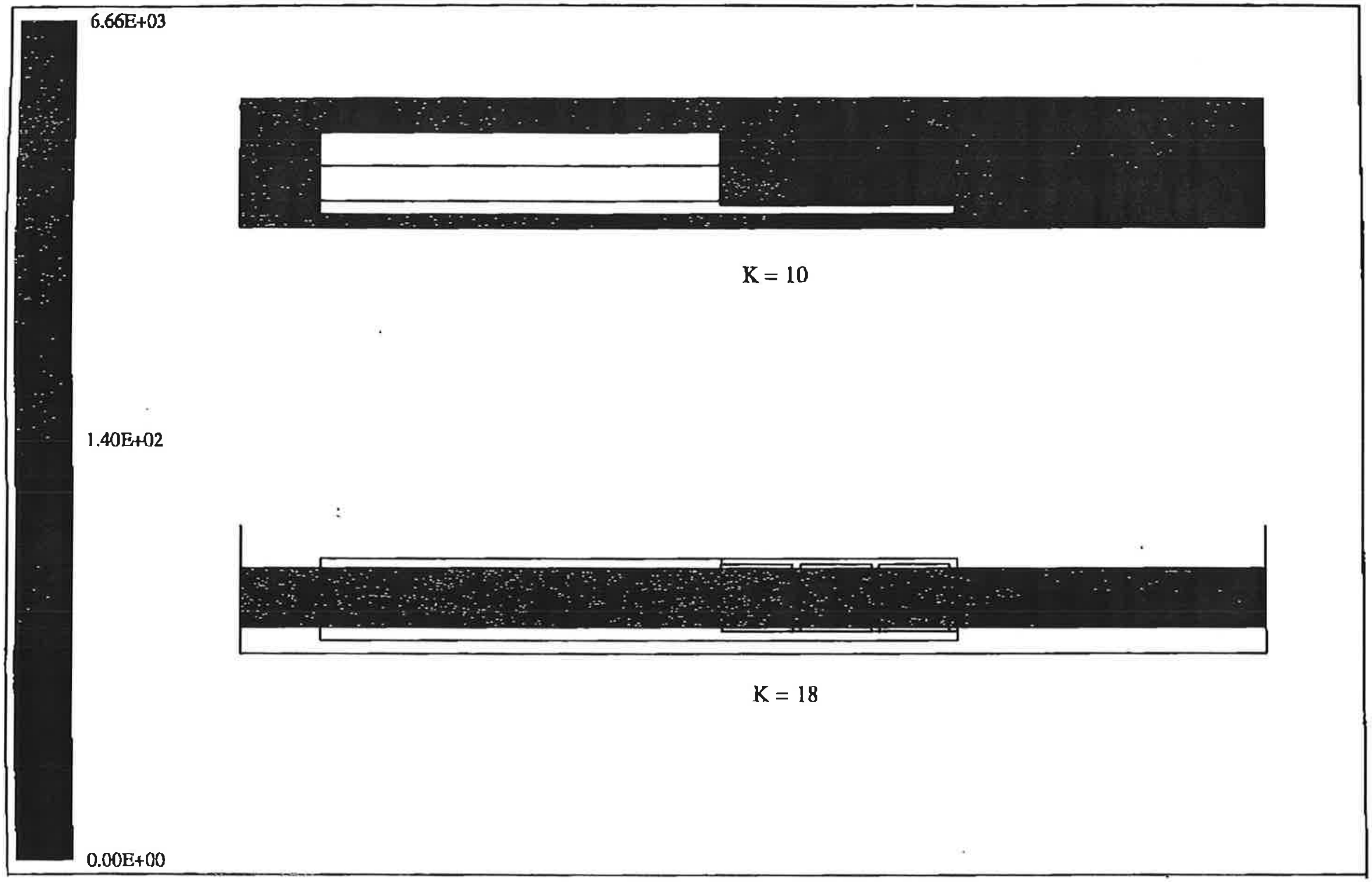
SCENARIO 2 - TEMPERATURE
FIGURE 5.3

Parsons
Brinckerhoff



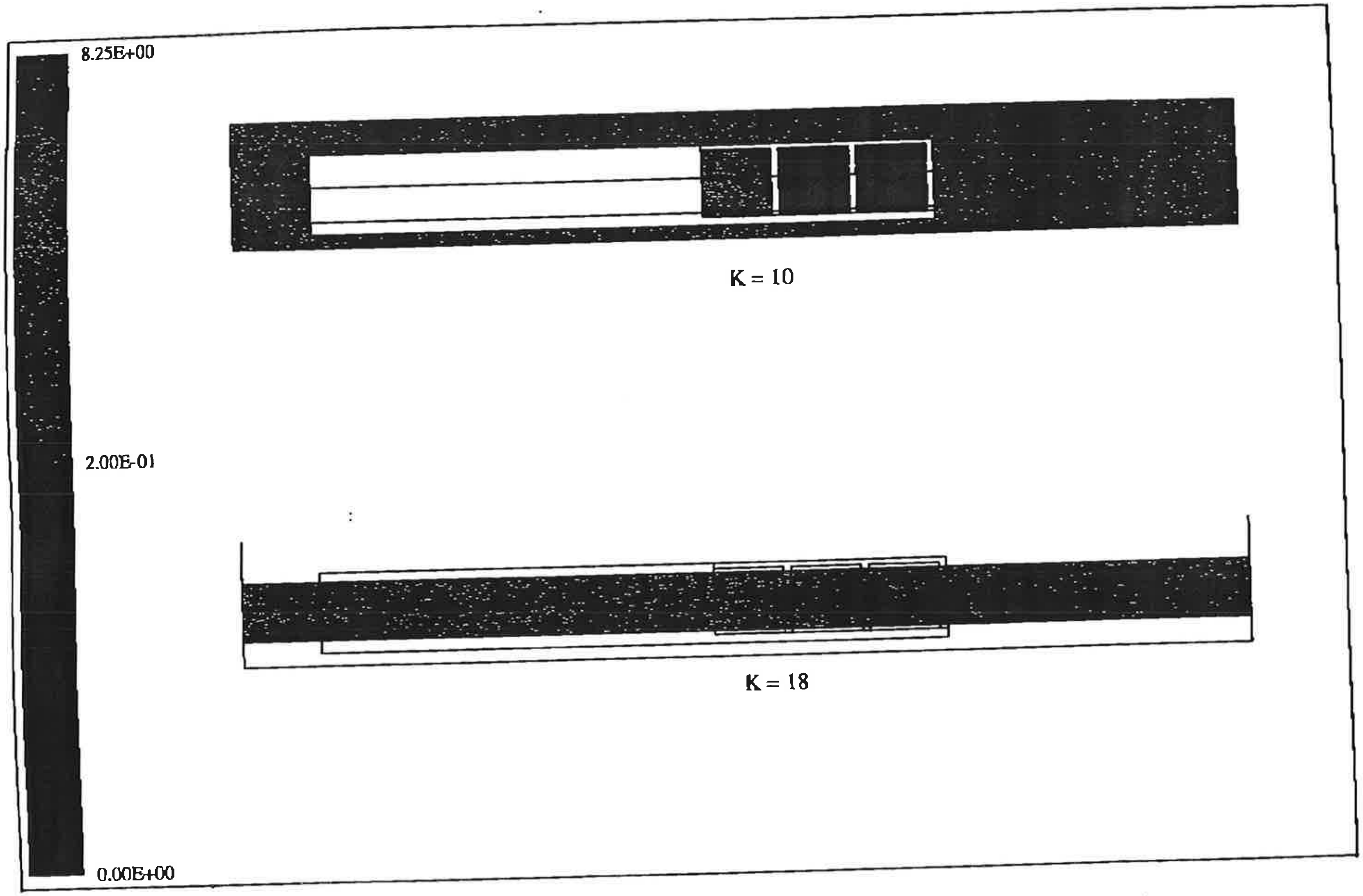
SCENARIO 2 - LIGHT ATTENUATION
FIGURE 5.4

Parsons
Brinckerhoff



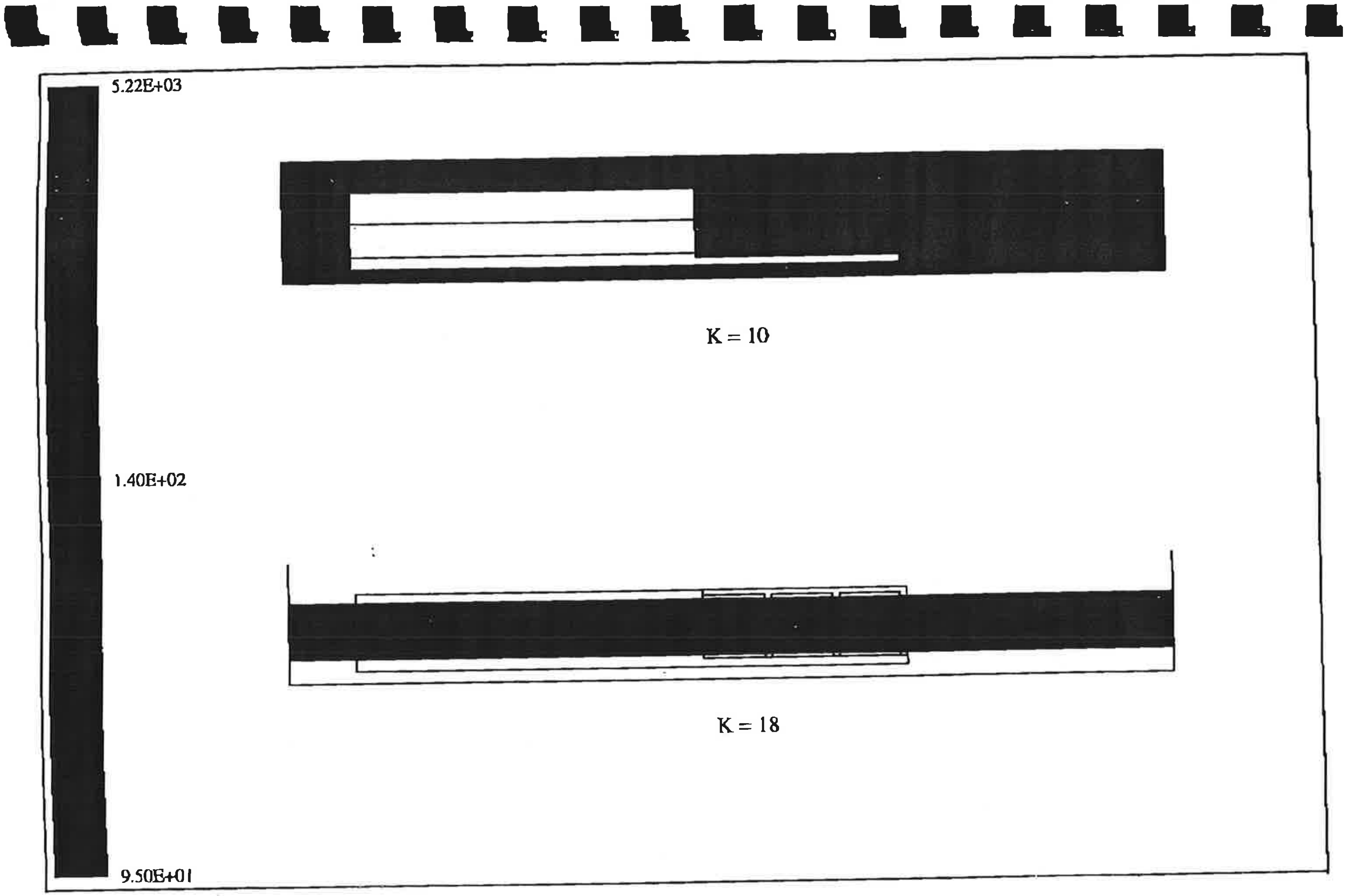
SCENARIO 3 - TEMPERATURE
FIGURE 5.5

Parsons
Brinckerhoff



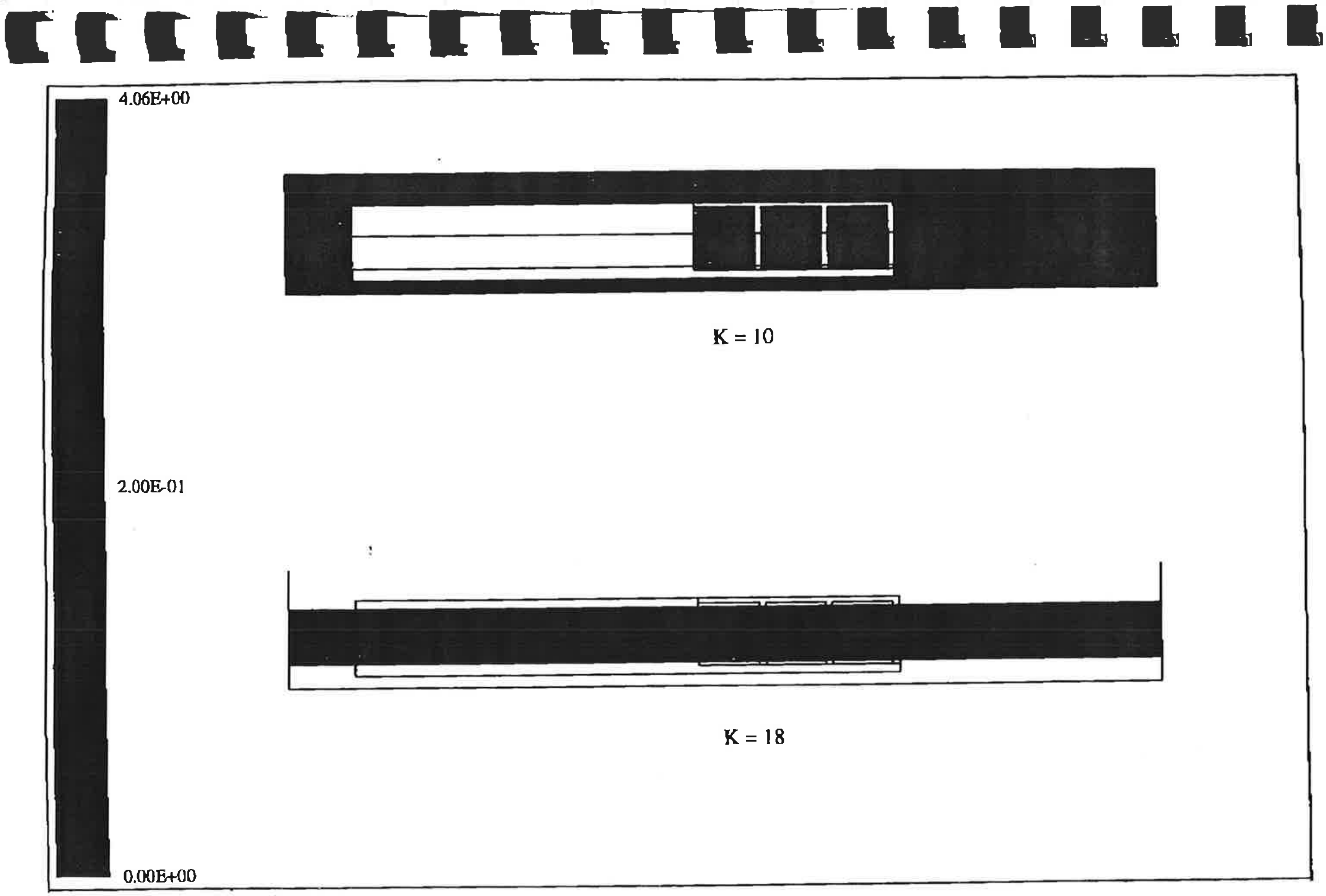
SCENARIO 3 - LIGHT ATTENUATION
FIGURE 5.6

Parsons
Brinckerhoff



SCENARIO 4 - TEMPERATURE
FIGURE 5.7

Parsons
Brinckerhoff



SCENARIO 4 - LIGHT ATTENUATION
FIGURE 5.8

Parsons
Brinckerhoff

- In the case of a downhill evacuation path, and a modified Blueridge Avenue fan shaft, backlayering is eliminated.
- The current ventilation system will not support an uphill evacuation path.
- Modification of the ventilation system to support safe uphill passenger evacuation is not feasible. Doing so would require major modifications to fan shafts and exit stairways, order of magnitude increases and horse power and fan capacity and addition of a new substation and associated electrical cabling.

6.0 BLUERIDGE AVENUE FAN SHAFT RETROFIT

6.1 Objective

The current capacity of the Blueridge Avenue fan shaft is not sufficient to completely eliminate backlayering in all downhill passenger evacuation paths. **A capacity increase from the current 140,000 cfm to 288,000 cfm is necessary to ensure downhill passenger evacuation capability in all cases.** Evaluating the feasibility of this option involved identifying the extent of the modifications required to sufficiently increase the capacity of the Blueridge Avenue fan shaft.

6.2 Scope

A detailed description of the required Blueridge Avenue fan shaft modifications is as follows:

- Install main circuit breaker, motor circuit protector and NEMA size 3 reversing starter in existing motor control center MCC-4.
- Install new automatic voltage regulator and new automatic transfer switch.
- Install new wiring and conduit as required.
- Install new fans rated at 30 HP, 72,500 cfm each.
- Ground new fans and electrical equipment enclosures to existing ground bus bars.
- Install power and control cables to new fan motors.
- Test new circuit breakers, motor circuit protectors, reversing starters, automatic voltage regulator and automatic transfer switch for proper operation.
- Install fan and control/electrical equipment identification tags.
- Test and adjust new fans.

6.3 Conclusions

This option was considered feasible for the following reasons:

- The required modifications are limited to relatively straightforward replacement of existing electrical and mechanical equipment.

- Since adequate space is available within the shaft, major modifications to the structure are not required.

On the basis of this evaluation, the Authority decided to proceed with the modifications described above. This work is currently under construction (Contract 1Z4195) at a cost of $264.336. This work is scheduled for completion prior to the Outer B Route operational date of mid 1998.

7.0 MASON STREET FAN SHAFT RETROFIT

7.1. Objective

The current capacity of the Mason Street fan shaft is not sufficient to allow passenger evacuation in an uphill path. The objective of this portion of the analysis involved identification of the consequences of increasing the capacity of the Mason Street fan shaft to provide uphill passenger evacuation capability.

7.2 Existing Conditions

The current performance characteristics of the Mason Street fan shaft are summarized as follows:

- Four fans total, each fan rated at 25 horsepower and producing 50,000 cfm in the supply mode, 35,000 cfm in the exhaust mode.
- 200,000 cfm total in exhaust.
- 140,000 cfm total in supply.
- 100 horsepower total.

The Mason Street fan shaft was designed in accordance with Authority criteria which limits air velocity to 1000 feet per minute. The resulting fan shaft structure has the following characteristics:

- Grating dimensions - 10 feet by 20 feet, 200 square feet gross area. The free area of a grating is approximately 70 percent.
- Shaft diameter - 16 feet diameter, 201 square feet gross area. This shaft also contains emergency egress stairs which reduce the usable area and increase the pressure drop in this portion of the shaft.
- Shaft depth - Approximately 89 feet from lower fan level to top of rail.
- Measured air flow resistance - 1.6 inches wg. This figure is the sum of the individual losses resulting from the grating, sound attenuator, dampers, elbows, the emergency egress stair and shaft friction.

7.3 Performance Criteria for Uphill Evacuation

To prevent back-layering during a train fire and allow for passengers to evacuate in an uphill direction, the required flow rate in an incident tunnel is 57,048 cfm.

In order to produce the required flow rate in the incident tunnel, the fan shaft must have sufficient capacity to account for airflow which will by-pass the incident. In the case of the Mason Street fan shaft, operation of the fans will produce air flow in four tunnel segments, two segments extending outbound and two extending inbound from the shaft. Air flow is distributed through these segments according to the relative resistance of each flow path. In the case of a train fire, the normal airflow distribution is altered. The flow through the affected tunnel segment is reduced due to additional resistance caused by the stationary train while flow through the unaffected segments is increased proportionately. The buoyant effects produced by the fire may also force air flow in the direction counter to the desired flow direction.

Two scenarios were tested as shown on Figure 1. The capacities of the Mason Street fan shaft were increased to the degree necessary to produce the required airflow in the incident tunnel. A fire intensity of 69.7 million Btu/hr was utilized.

Scenario 1 involved a train located on a four percent grade on the inbound side of the Mason Street fan shaft. Passengers were assumed to evacuate uphill toward the Mason Street shaft. To provide airflow counter to the passenger exit direction, Mason Street fan shaft operated in the supply mode.

Scenario 2 involved a train located on a four percent grade on the outbound side of the Mason Street fan shaft. Passengers were assumed to evacuate uphill toward Glenmont station. Consequently, Mason Street fan shaft operated in the exhaust mode.

For scenario 1, the estimated total flow requirement for the Mason Street fan shaft is 550,000 cfm with fans operating in supply.

For Scenario 2, the estimated flow rate requirement for mason street fan shaft 600,000 cfm with the fans operating in exhaust.

Since the exhaust and supply mode flow requirements are similar, a 90% reversible fan would provide a better match between fan performance characteristics and the actual performance required. Use of a 90% reversible fan represents a change to the standard specifications. The efficiency of this type of fan is approximately 60%.

7.4 Increased Capacity without Increase in Fan Shaft Size

For this analysis, it is assumed that the existing sound attenuators will be replaced with a suitably sized models having a pressure drop of 0.3 inches wg at the new flow rate. The pressure drop at the new flow rate is estimated from the existing pressure drop of 1.6 inches wg minus the pressure drop contributed by the existing sound attenuator (0.31 inches wg per the standard specifications).

At a flow rate of 550,000 cfm, the pressure drop increases to approximately 10.1 inches wg (i.e. $1.3[550{,}000/200{,}000]^2+0.3$).

At a flow rate of 600,000 cfm, the pressure drop increases to approximately 12.0 inches wg (i.e. $1.3[600{,}000/200{,}000]^2+0.3$).

Assuming that a 60% efficient 90% reversible fans are utilized, the resulting power requirement is 1888 HP (i.e. [600,000 x 12.0]/[6356 x 0.6]. This reflects the most severe requirement which occurs when the fan operates in the exhaust mode.

Due to size constraints in the Mason Avenue fan shaft, the number of fans and sound attenuators which can be added without extensive structural modifications is limited. Utilizing a total of two fans, the performance of each fan is as follows:

- Fan air flow rate: 275,000 cfm minimum at 10.1 inches wg in supply and 300,000 cfm minimum at 12.0 inches wg in exhaust.
- Brake horsepower 944 hp.

Structural modifications will be necessary to accommodate the new sound attenuators, transitions, dampers and fans.

In this performance range, custom manufactured fans are typically required. The final power requirement is dependent on the fan efficiencies the manufacturer can achieve while meeting performance requirements for both the exhaust and supply modes.

7.5 Increased Capacity with Increase In Shaft Size

A reduction in the estimated fan horsepower requires a corresponding reduction in the flow resistance of the shaft. Possible modifications include the following:

- Increasing the size of the grating and the portion of the fan shaft between the fan level and the surface.
- Increasing the size of the vertical shaft which leads from the fan level to the trackway.

An increase in grating size to 600 square feet would reduce the pressure drop as follows:

- Current pressure drop with 200 square foot grating at 70% free area-

$$PD = 1.75[(600{,}000/200 \times .7)/4005]^2 = 2.0\text{" wg}$$

- Pressure drop with 600 square foot grating at 70% free area-

  $$PD = 1.75[(600{,}000/600 \times .7)/4005]^2 = 0.22 \text{ " wg}$$

- Horsepower requirement with modified grating-

  $$HP = [600{,}000 \times (12.0-2.0+0.22)]/[6356 \times 0.6] = 1608 \text{ hp}$$

- The estimated horsepower reduction from increasing grating size is 280 hp.

An increase in vertical shaft size to 600 square feet would reduce the pressure drop as follows:

- The pressure drop at 200,000 cfm is 0.77 inches wg per the balancing report. The shaft velocity in this case is 1000 feet per minute. Increasing the shaft diameter to maintain a 1000 fpm velocity at the new flow rate would also maintain a pressure drop of approximately 0.77 inches wg.

- At 600,000 cfm, the pressure drop is estimated as 6.93 inches wg.

- Horsepower requirement with modified grating-

  $$HP = [600{,}000 \times (12.0-6.93+0.77)]/[6356 \times 0.6] = 918 \text{ hp}$$

- The estimated horsepower reduction from increasing the shaft size is 970 hp.

7.6 Conclusions

Conclusions are summarized as follows:

- Increasing the capacity of the Mason Street fan shaft without a corresponding enlargement of the shaft substantially increases the horsepower requirement. **Approximately 1900 horsepower is required versus the existing 100 horsepower.** In addition, some structural modifications would still be required to accommodate the new fans, electrical equipment such as motor control centers, transitions, sound attenuators and dampers.

- **Provision of electrical power to serve the new fans would require construction of a new substation in the vicinity of the Mason Street fan shaft. A new PEPCO feeder would be required. Per Authority criteria and NFPA 130, two independent feeders are necessary.** Substation construction may require acquisition of additional real estate.

- **At a flow rate of 600,000 cfm, the air velocity in the emergency exit stairway will exceed 3000 feet per minute** if the stairway is not enlarged. According to the 1995 version of NFPA 130 (Appendix B, paragraph B-2.3.1), **air velocities should not exceed 2200 feet per minute.** Above 2200 feet per minute, some people will have difficulty walking. Compliance with the 2500 foot maximum exit spacing requirement contained in both Authority criteria and NFPA 130 requires provision of exit stairs at the Mason Street fan shaft.

- Significant reductions in horsepower are possible if the fan shaft structure is enlarged. If both the grating structure and the shaft are enlarged, the resulting horsepower requirement is 650. Since shaft construction is complete, structural modifications to the extent required are not feasible. In addition to the structural issues involved, enlargement of the shaft could also affect utilities in the area and require additional real estate. In any event, a substation in the vicinity of Mason Street fan shaft remains a requirement since the horsepower requirement of 650 still greatly exceeds the existing 100 horsepower.

- **The Mason Street fan shaft was designed to accommodate fans with a total capacity of 200,000 cfm. An increase to a capacity of 600,000 cfm requires either a drastic increase in horsepower and electrical service, or extensive structural changes to reduce horsepower requirements to a manageable level.** Due to the complexity and expense involved, neither alternative provides a feasible means of achieving the required airflow rates.

8.0 CONCLUSIONS

The performance of the existing ventilation system was analyzed by computer simulations with the SES program and a CFD program. Conclusions based on this analysis are as follow:

- SES results indicate that **backlayering is generally prevented when a downhill passenger evacuation path is used.** Air is supplied from Blueridge Avenue fan shaft and exhausted from Mason Street fan shaft taking advantage of the uphill gradient of the tunnel and the natural buoyancy of the hot smoke.
- **An exception occurs only in the vicinity of the Blueridge Avenue fan shaft** where the tunnel gradient is relatively flat. A CFD computer run simulating downhill evacuation to the south toward Blueridge in this area shows however that the extent of the backlayering is limited to a range of 75 to 150 feet.
- Both SES and CFD computer runs simulating downhill evacuation in the vicinity of Blueridge Avenue fan shaft show that **all backlayering is eliminated if the capacity of Blueridge Avenue fan shaft is increased.**
- SES results indicate that the current ventilation system cannot eliminate backlayering when passenger evacuation takes place in an uphill direction. This is the case at all points on the Outer B Route, with the worst case occurring in the vicinity of the Mason Street Fan Shaft.

A study has been done of the feasibility of providing sufficient ventilation capacity to completely eliminate back-layering and provide the capability of evacuating passengers in both the uphill and downhill directions. Additional SES simulations were performed to estimate the required increases in fan shaft capacity. The approximate total flow requirement for the Mason Street fan shaft is 550,000 cfm with fans operating in supply and 600,000 cfm with the fans operating in exhaust. This alternative requires a 393 percent increase in the supply capacity and a 300 percent increase in the exhaust capacity of the existing fan shaft. Since the shaft is existing and space is limited, the necessary increase in capacity is not feasible.

A feasible alternative consists of providing sufficient ventilation capacity to completely eliminate back-layering and provide the capability of evacuating passengers in the downhill direction only. For this alternative, the worst case, as mentioned, occurs when passengers evacuate in a downhill direction on the 0.35% grade adjacent to Blueridge Avenue fan shaft. To produce the required flow rate, SES simulations indicate that the new flow requirement for the Blueridge Avenue fan shaft is 288,000 cfm in lieu of the present 140,000 cfm with fans operating in supply and remains 200,000 cfm with the fans operating in exhaust. **This required capacity increase is feasible at Blueridge Avenue fan shaft by replacing the existing fans and motors.**

This alternative is based on the concept that passenger evacuation will always occur in a downhill direction. This concept is acceptable for the following reasons:

- WMATA operating procedures require that a burning train be brought into a station when possible. This action simplifies passenger exiting and eliminates the need for evacuation through the tunnels. As a matter of record, we have found no record in the last 21 years of WMATA operation of any train ever being disabled by smoke or fire to a degree which required evacuation of passengers in a tunnel.
- Vehicle fires in the past had started below the train floor due to overheating of cable insulation near the braking resistors. WMATA has reported that this problem has been virtually eliminated in WMATA cars. WMATA vehicle floors are fire rated for one half hour whereas the estimated time for passenger evacuation is ten minutes in this rail segment. Therefore, in all cases of underfloor fires, ample time for passenger evacuation exists.
- If evacuation in a tunnel is necessary, this concept prevents backlayering in a path of egress away from a train fire and therefore conforms to NFPA 130.
- Because central control or train operators may not know the exact location of a fire on a train if evacuation in a tunnel is required, downhill evacuation in all cases will reduce response time and tend to eliminate errors.

In summary, **by increasing the fan capacity at Blueridge Avenue fan shaft in supply mode to 288,000 cfm, backlayering of smoke toward Blueridge will be eliminated, creating a safe evacuation path for passengers.**

APPENDIX 1

PARSONS BRINCKERHOFF
COMPUTATION SHEET

GLENMONT TUNNEL EGRESS CALCULATIONS

I. NFPA 130 Emergency Exit Details

Since the two tunnel bores are not connected by way of cross passageways, the NFPA 130 requirement that **"[e]mergency exit stairways shall be provided throughout the tunnels, spaced so that the distance to an emergency exit shall not be greater than 1,250 ft (381 m) ..." (NFPA 130, 3-2.4.2)** applies.

Since the Glenmont Route is bound by stations offering egress on both sides, the maximum distance to an exit is encountered at the mid-point between two egress locations (i.e., stations or emergency exits), from where the distance to either egress location is one-half of the total spacing between the egress locations. Thus, where the spacing between two emergency exits is less than or equal to 2,500 feet, the maximum distance to an exit is equal to or less than 1,250 feet and the NFPA 130 exit spacing requirement is satisfied.

Each of the fan and ventilation shafts along the Glenmont Route is equipped with emergency stairways which are accessible from both tunnels. The approximate distances between stations and emergency exits along the Glenmont Route are as follows:

Egress Location	Station	Distance to previous egress location
Wheaton Station	1,126+70	–
Blueridge Ave. Fan Shaft	1,148+00	2,130 ft
Henderson Ave. Fan Shaft	1,170+32	2,232 ft
Mason St. Fan Shaft	1,191+67	2,135 ft
Glenmont Station	1,212+00	2,033 ft

The NFPA emergency exit requirement is met as there exists no tunnel segment where the distance between exit stairways exceeds 2,500 feet.

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Date: 7/15/97

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II. Simulation of Egress from Trainway (see Figure 1 on page 4)

Egress element capacities and walking speeds prescribed in NFPA 130 as part of the time-based egress criteria for transit stations (Section 2-5.3.4.1) were used to describe the evacuation of passengers from trains along the tunnel safety walk.

Assumptions

Egress Demand:	500 persons (p)
Train Length:	8 cars @ 75 feet = 600 feet (f)
Tunnel Safety Walk:	Minimum floor width = 2.0 feet (f)

The 2-foot safety walk accommodates single-file egress only. It is assumed to offer a passenger flow capacity equal to that of a corridor with an effective width of one 22-inch exit lane. Although the curvature of the tunnel wall creates a somewhat larger shoulder-level clearance than the 2-foot floor width, the assignment of a full exit lane for the safety walk is nonetheless optimistic since wall deductions and minimum ramp widths per 2-5.3.4.1 were not considered for the purpose of estimating tunnel egress times. According to Section 2-5.3.4.1, a corridor of 4 percent slope or less offers a capacity of 50 persons per minutes (ppm) per 22-inch exit lane and permits passengers to walk at speeds of 200 feet per minute (fpm).

Range of Egress Times

Figure 1 illustrates the range of egress times for persons evacuating a train in the tunnel. At a given distance from the train, approximately 10 minutes will elapse between the arrival of the first and last person. The stream of 500 passengers moving along the safety walk will proceed at a rate of 200 feet per minute and be approximately 2,000 feet in length (see Figure 1).

Egress of the First Person

The first passenger stepping onto the safety walk at the end of the train will proceed along the safety walk at a fixed speed of 200 feet per minute. The time required for the first person to travel a given distance along the safety walk is a function only of this fixed walking speed.

Walk Time (m) = Distance along Safety Walk (f) / 200 fpm; or
Distance (f) = 200 fpm x Walk Time (m)

Egress of the Last Person

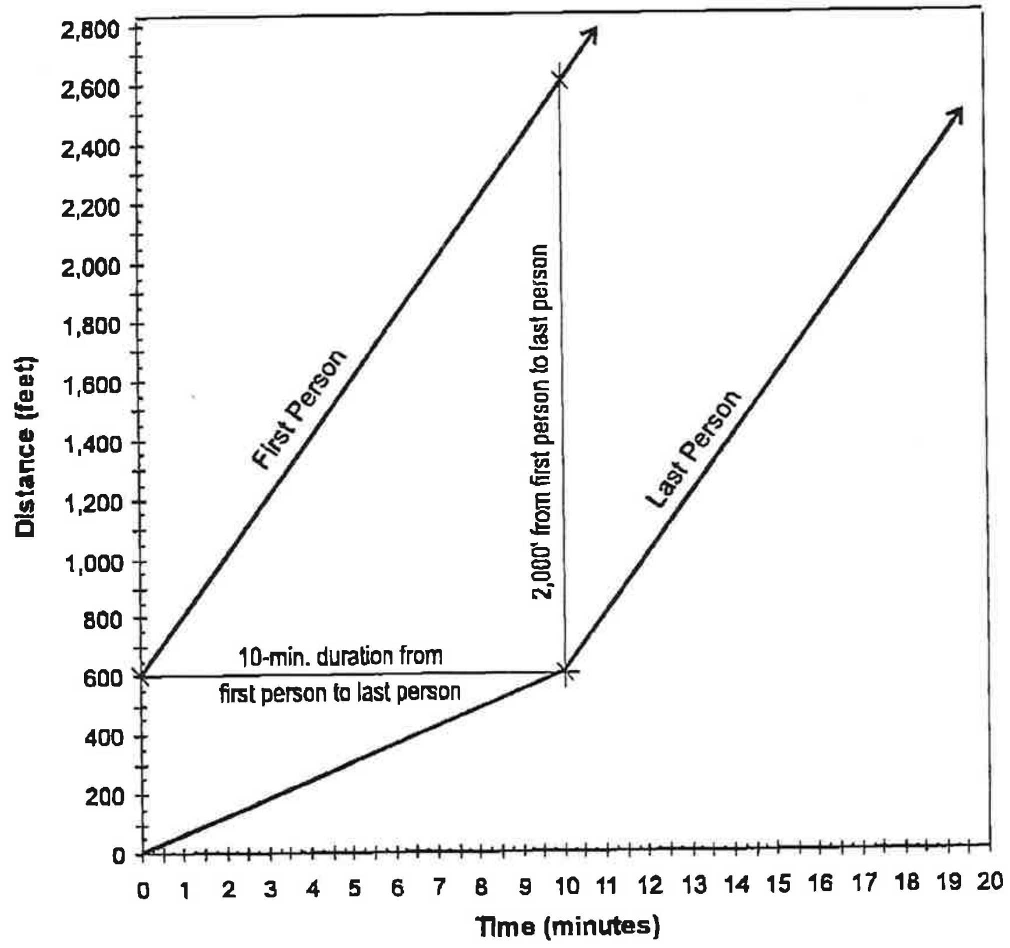
Given the limited absorption rate of the safety walk (50 passengers per minute) and the size of the overall egress demand (500 passenger), a sizable queue will form inside the train during the evacuation. The time for the last passenger aboard the train to reach a given location along the safety walk is therefore computed as the sum of the time required for the last passenger to be processed by the safety walk (i.e., wait time) and the time required to walk along the safety walk (i.e., walk time).

For purposes of these calculations, the safety walk is treated as a single egress element as prescribed in the NFPA 130 station egress computations in Section 2.5. The wait time for the last passenger to be processed is a function of the total train load and the carrying capacity of the safety walk:

Wait Time (m) = Egress Demand (p) / Capacity (ppm)
= 500 p / 50 ppm = 10 minutes

While waiting to be processed by the safety walk, passengers are assumed to be moving in the direction of egress onboard the train. Thus, during the 10-minute wait time, the last person has traversed the entire length of the train (600 feet) before stepping onto the safety walk.

Egress Time (m) = 10 m + [Distance along Safety Walk (f) / 200 fpm]



PARAMETERS
Train Load: 500 persons
Train Length: 600 feet
Walking Speed: 200 feet per minute
Safety Walk Capacity: 50 persons per minute

Glenmont Tunnel Egress Calculations
Figure 1
Time - Distance Diagram

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