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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

Agency / Organization

WMATA

Title

Metrorail Ventilation System Analysis Report, Phase I
April 1988

Docket ID: **DCA 15 FR 004**

Metrorail

Ventilation System Analysis Report Phase I

April 1988

Parsons Brinckerhoff ® 100 YEARS

prepared by
Parsons Brinckerhoff Quade & Douglas, Inc.

prepared for

metro
Washington Metropolitan Area Transit Authority

TABLE OF CONTENTS

Page No.

LIST OF FIGURES AND TABLES

Figure — Following Page

Table

EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

Over the past several years, the Washington Metropolitan Area Transit Authority (WMATA) has commissioned various studies, field tests, and site investigations directed toward evaluating the ability of the Metrorail ventilation systems to control the movement of smoke during a fire emergency. This has led to the development of WMATA's three-phase program for the study, analysis, and implementation of systemwide modifications to the ventilation system.

Phase I, the current phase of the program, included a review of prior studies, the development of ventilation strategies (or concepts) and their anticipated effectiveness, and the designation of existing site locations where field testing of viable concepts could be accomplished. Phase II will include the design of the field test program and related system modifications, and the test program. Phase III will include design modifications to achieve desired ventilation performance objectives throughout the Metrorail predicated upon the findings of the Phase II program.

For this Phase I report, four ventilation strategies for improving smoke control in the running tunnels were considered on the basis of satisfying the following:

- No additional fan shafts
- Minimal civil/structural modifications
- Minimal construction impact on transit system operations
- Cost-effective solutions

The highlights of the findings and recommendations contained in this Phase I report include the following:

1. The required airflows to meet the ventilation criteria for controlling the movement of smoke and heat in a fire emergency were determined to be less than identified in earlier studies.

2. To achieve effective control of smoke and heat in a fire emergency, the deployment of blockage devices, which direct ventilation airflow to the fire site, appears to provide a cost-effective solution. As discussed in the body of this report, however, further consideration of the use of such blockage devices as it relates to their technical feasibility and compatability with overall operational safety and maintenance requirements, needs to be addressed before a firm commitment to the application of such devices can be made.

3. A jet fan alternative appears viable and approaches the capability of the blockage devices to control airflows in a fire situation. This system, however, may be more costly to apply than the blockage devices, as described in item 2 above.

4. Based on the various analyses performed during this study, it is recommended that the tunnel section between McPherson Square and Metro Center Stations serve as the location for performing both the single-track and double-track test program in Phase II. The prototype tests are primarily intended to accomplish two objectives:

- Demonstrate the viability of the recommended ventilation strategies and physical modifications.

- Provide a basis of comparison with the methodology of analyses to permit "fine-tuning calibration" of the analytical program. Through the full scale field review of the Subway Environment Simulation (SES) computer program results, this analytical tool can then be applied to all other existing, or future sections of the Metrorail, to determine the required modifications, if any, that may be necessary to achieve the emergency ventilation objectives.

5. The total cost of the Phase II program, including all engineering and construction costs, is estimated to be approximately $1,450,000, which is less than previously estimated.

INTRODUCTION

INTRODUCTION

HISTORY OF THE PROGRAM

Over the past several years, the Washington Metropolitan Area Transit Authority (WMATA) has commissioned various studies, field tests, and site investigations directed toward evaluating the ability of the Metrorail ventilation systems to control the movement of smoke during a fire emergency. These studies have led to a series of recommendations for improving fire life safety in the system. Various measures have since been implemented, including fire hardening of vehicles to reduce the magnitude of potential vehicle fires and repairing/maintaining the existing ventilation system to improve its effectiveness. Notwithstanding these and other measures, the performance of the ventilation system for smoke control continues to be of concern.

As a result of these previous studies and measures, WMATA has developed a three-phase program which will assist the Authority in implementing systemwide modifications to its ventilation system. Phase I, the current phase of the program, included a review of prior studies, the development of ventilation strategies (or concepts) and their anticipated effectiveness, and the designation of existing site locations where field testing of viable concepts could be accomplished. Phase II will include the design of the field test program and related system modifications, and the test program. Phase III will include design modifications to achieve desired ventilation performance objectives throughout the Metrorail predicated upon the findings of the Phase II program.

PHASE I OBJECTIVES

The overall objective of the study was to develop ventilation strategies to expand the existing ventilation system capabilities for smoke control and develop groundwork for their site testing at both a single track and double track location considered to be prototypical of the system. Specific objectives of the study include the following:

- Review and evaluate previous studies related to the ability of the ventilation system to control the movement of smoke and heat during a fire emergency.

- Review the Subway Environment Simulation (SES) Version 3.0 computer analysis of two single track tunnel configurations performed by DeLeuw Cather as addressed in their report "Tunnel Smoke Control Study, Phase I", August 1985 (Ref. 1). The review is to confirm the validity of the simulation approach, the results of the study, and the viability of these locations as prototype test sites.

- Review the double track portions of the Metrorail and propose locations for prototype testing. Select two sites, with the assistance of WMATA staff, and analyze ventilation strategies with the SES Version 3.0 computer program.

- Select one single and one double track location for prototype testing.

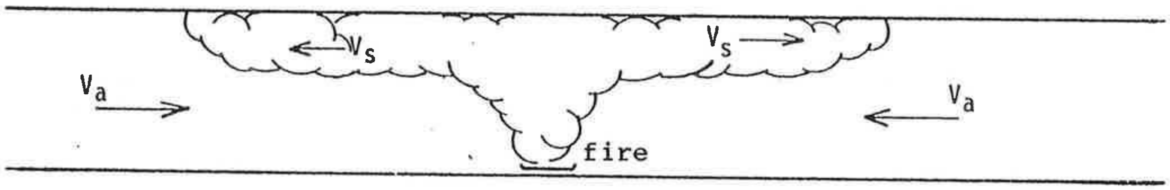
- Identify the modifications to the prototype test sites required to achieve the desired ventilation flow rates.

- Develop an outline of the prototype test program.
- Develop preliminary cost estimates covering:
  - a. Preparation of bid documents for prototype site design modifications and field test program.
  - b. Supervision of field test program and preparation of report.
  - c. Construction of design modifications and execution of field test program.

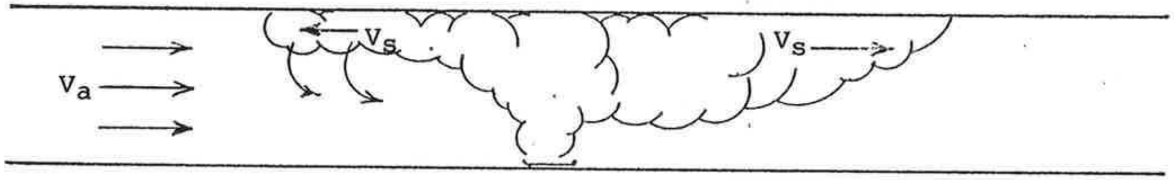
TUNNEL FIRE AND SMOKE CONTROL

The ventilation system should be designed to control the direction of smoke and heat movement - for a reasonable fire scenario - to provide a clear and safe path for evacuating people and to facilitate firefighting operations. The performance of the ventilation system, therefore, plays an important role in a transit system's overall fire life safety program.

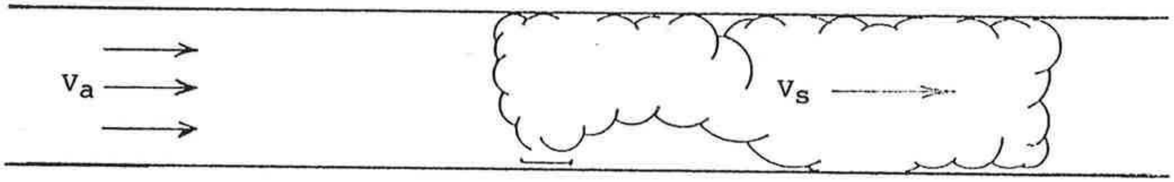
The fire and its associated airflows differ significantly from more familiar fire situations occurring outside the confines of a tunnel where smoke and heat can escape upwards into the atmosphere. The most noteworthy distinction is the tendency to create a layer of hot smoke and gases flowing away from the fire near the crown of the tunnel in both directions, while air supporting combustion moves toward the fire beneath the smoke layer. This phenomenon is called "back-layering". (See Figure 1). The method used to evaluate "back-layering" is discussed in APPENDIX A.1.



Flow Pattern Typical for an Unventilated Tunnel Fire



Back-Layering Occurs -- Insufficient Ventilation



Direction of Smoke-Flow Controlled

V_a = Air Velocity
V_s = Smoke Velocity

TUNNEL FIRE SMOKE PATTERNS

FIGURE 1

If the ventilation is of sufficient capacity, however, it can cause all of the heated air and smoke to flow towards one direction only.

To achieve these results and prevent back-layering, the following criteria were considered: fire size and critical velocity. Fire size is an important criterion since the magnitude of the bouyant effect is directly related to the size of the fire. Critical velocity describes the level of ventilation required to cause all of the heated air and smoke to flow in the direction of the ventilation airflow. The ventilation airflow against the smoke movement must be equal to or greater than this critical velocity. These criteria are discussed in detail in APPENDIX A.2. The ability of a ventilation system to prevent back-layering is the current state-of-the-art standard against which system performance for smoke control is measured.

The solution to achieve the ventilation criterion has been developed which considered four alternative ventilation strategies.

VENTILATION STRATEGIES

Four ventilation strategies for improving smoke control in the running tunnels were considered on the basis of satisfying the following:

- No additional fan shafts
- Minimal civil/structural modifications
- Minimal construction impact on transit system operations
- Cost-effective solutions

With the above limitations, the following four strategies were considered in the event that the existing ventilation systems were found to be ineffective by themselves to satisfy emergency ventilation objectives:

- "Brute-force" emergency ventilation
- "Push-pull" emergency ventilation
- Tunnel blockage devices
- Wall-mounted jet (impulse) fans

"Brute-Force" Emergency Ventilation

Based on various studies and our own evaluations, most of the existing fan shaft installations lack sufficient capacity to effectively control the movement of smoke and heat in the event of a fire situation in an adjacent tunnel section. The concept of "brute-force" relates to increasing the capacity of the existing fan shaft system of ventilation in the Metrorail to the point where smoke control can be achieved.

To meet the desired objective, however, would necessitate an extraordinarily large increase in the existing fan shaft capacities. This could only be achieved by replacement of the existing fans with substantially larger capacity units driven by very large horsepower motors. In addition to the fan equipment, significant structural modifications to the existing fan shafts and a significant increase in the electrical power services would be required. This alternative was therefore determined not to be cost-effective and no further consideration was given to this "brute-force" approach.

"Push-Pull" Emergency Ventilation

In many recent rapid transit system designs, reversible operating fans are installed in fan shafts associated with each trainway at the ends of each underground station. By operating selected fans in a supply mode and fans in other shafts in an exhaust mode, sufficient airflow through the tunnel section containing a burning disabled train can usually be achieved to control back-layering of smoke.

The ventilation system for the Metrorail was designed for environmental comfort control, and not for fire emergency situations. Accordingly, while shafts at the ends of stations have generally been provided in the system, they are not equipped with fans.

Based on past experience, the magnitude and capacity of fans appropriate to a "push-pull" concept are significantly greater than could be reasonably added to the existing vent shafts at the ends of each station. Given the level of structural modifications required, along with the significant mechanical and electrical installations that would be necessary, a conclusion was reached that a "push-pull" system of emergency ventilation would not be cost-effective. Therefore, no further consideration was given to this approach.

Tunnel Blockage Devices

To make better use of existing fan shaft capacities, this strategy is designed to increase the percentage of airflow processed by the shaft through the tunnel section containing a burning disabled train. As the system is currently configured, the base of each fan shaft is connected to both inbound and outbound trainways without any means of aerodynamically isolating one trainway from the other. In the case of single track tunnels, four possible airflow paths formed by the connecting trainways exist at the base of the shaft. Because the presence of a train in a tunnel creates considerable resistance to airflow as compared to an empty tunnel, an overwhelming quantity of air processed by the fan shaft bypasses the tunnel containing the train and flows through the remaining empty tunnel sections. To minimize this effect, the blockage device strategy increases the resistance to airflow in the three empty tunnel sections by means of physical barriers.

This strategy had previously been proposed and studied by other consultants (Ref. 1, 2, 3). In one of the prior studies, (Ref. 1), ventilation system performance was evaluated on the basis of having tunnel blockage devices installed in all four tunnel sections at the base of all fan shafts. This allowed the opportunity to block as many as three of the four tunnel sections at each fan shaft.

In Ref. 1 an inflatable blockage device that could be locally or remotely activated and be self-sealing had been proposed. The inflatable portion of the proposed barrier was configured in the shape of a "toroid" whose outer diameter would be somewhat larger than the effective tunnel diameter. The barrier would be held in place by friction created by the oversized barrier in contact with the tunnel wall surfaces. The center portion of the barrier would be made of a reinforced fabric which could be opened to allow evacuating people or firefighting personnel to pass through. In their ventilation study, air leakage across the barrier was evaluated on the basis that approximately 80 percent of the tunnel cross-section would be blocked. It was pointed out that the proposed barrier would require further design development and prototype testing before such a device could be used in the Metrorail.

The basic assumptions used in the referenced study were also used in this study. Four tunnel blockage devices were assumed available at the base of each fan shaft and each device effectively blocked 80 percent of the tunnel cross-sectional area.

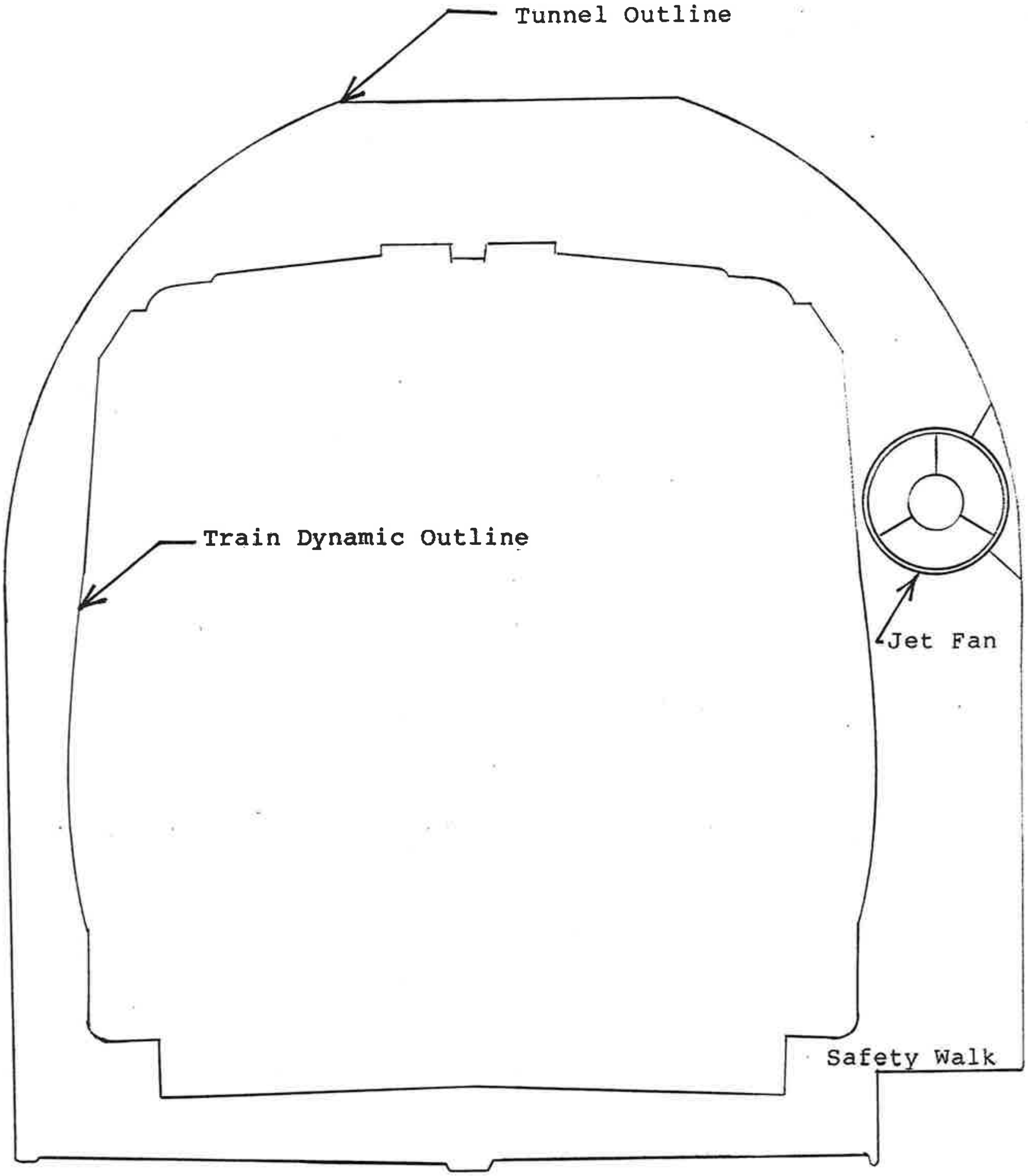
Since actual performance data for such devices is not available, sensitivity studies in the current study were performed. In some cases when tunnel ventilation criteria was not achieved, the analyses were repeated assuming the device effectively blocked 90 percent of the tunnel. The resulting level of improved ventilation performance determined the potential benefits that could be achieved with a more effective device.

With regard to the viability of the tunnel blockage device strategy, it is recognized that the implications of extensive use of such untried devices in an operating transit system are far reaching and go beyond just demonstrating functional operability. Questions relating to maintenance, long-term reliability, and in particular "operational safety" must still be addressed before such a strategy, other than its potential for benefitting fire safety ventilation, can be endorsed.

Wall-Mounted Jet (Impulse) Fans

The jet fan strategy is also designed to increase the resistance to airflow in the three empty tunnel sections connecting to the base of the fan shaft. This is accomplished through the dissipation of linear momentum created by the discharge of a low volume, high velocity, quantity of air in the direction opposing tunnel air movement.

In this strategy, reversible jet fans would be mounted along the walls (See Figure 2) of the four tunnel sections extending away from the base of a fan shaft. Having established the tunnel section in which the train fire is located and the intended evacuation path, the fan shaft would be activated



SCHEMATIC JET FAN ARRANGEMENT

FIGURE 2

to supply or exhaust air accordingly. The jet fans in the three open tunnel sections would be operated in the direction which would retard the movement of airflow generated by the fan shaft. The fans in the tunnel section containing the train would not be operated because of the danger of subjecting evacuating passengers to high velocity air and high noise levels. The total thrust capacity of the fans in each tunnel section was selected such that it would have the same effect as a tunnel blockage device in reducing airflow. The resulting more conventional jet fan system is essentially equivalent to the one which uses blockage devices.

The maximum size jet fan that could be used in the tunnel is limited. A review of the dynamic outline of the train superimposed on tunnel structural drawings indicated that a maximum space of 22 inches was available above the safety walk. Preliminary fan selections were based on this dimension. Tunnel services will have to be taken into account when making final selections.

Based on the above discussions, only the strategies of tunnel blockage devices and wall mounted jet (impulse) fans were selected for further evaluation. Either of these two viable strategies is most compatible with the existing structural, mechanical, and electrical installations of the Metrorail.

ANALYSIS AND RESULTS

ANALYSIS AND RESULTS

REVIEW OF PREVIOUS STUDIES

At the outset of this study, seven previous study reports were identified by WMATA as perhaps being pertinent to our study objectives. After a preliminary review, three reports (Ref. 1, 2, 3) were identified as key studies related to Metrorail ventilation systems. These three reports were thoroughly reviewed, with our findings documented in an interim report. (Ref. 5). The findings served in part as a basis for the analysis performed and are consistent with the recommendations appearing in this report.

STUDY APPROACH FOR B-ROUTE AND DOWNTOWN NETWORKS

The B-Route SES analysis, presented in Ref. 1, was selected to be reviewed in the current study. The approaches used to evaluate the SES analysis of the B-Route and to select and analyze the prototype test sites in the downtown network are discussed in APPENDIX A.3.

DESCRIPTION OF B-ROUTE NETWORK AND SIMULATIONS

The portion of the B-Route that was simulated is shown in Fig. 3. The network extends from the portal west of Forest Glen Station to the portal east of Glenmont Station. The network includes three stations, their interconnecting tunnels, and five fan shafts. Station and tunnel sections are comprised for the most part of single track tunnels. The capacities of the fan shafts and station systems are presented in Table 1. The analysis of the route and the results of the simulations have led to the conclusions and recommendations appearing in this report. Detailed information describing the B-Route is presented in APPENDIX E. The simulations and their results are presented in APPENDIX B.

PROFILE-B RTE. STA. 480+30 TO 1230+60

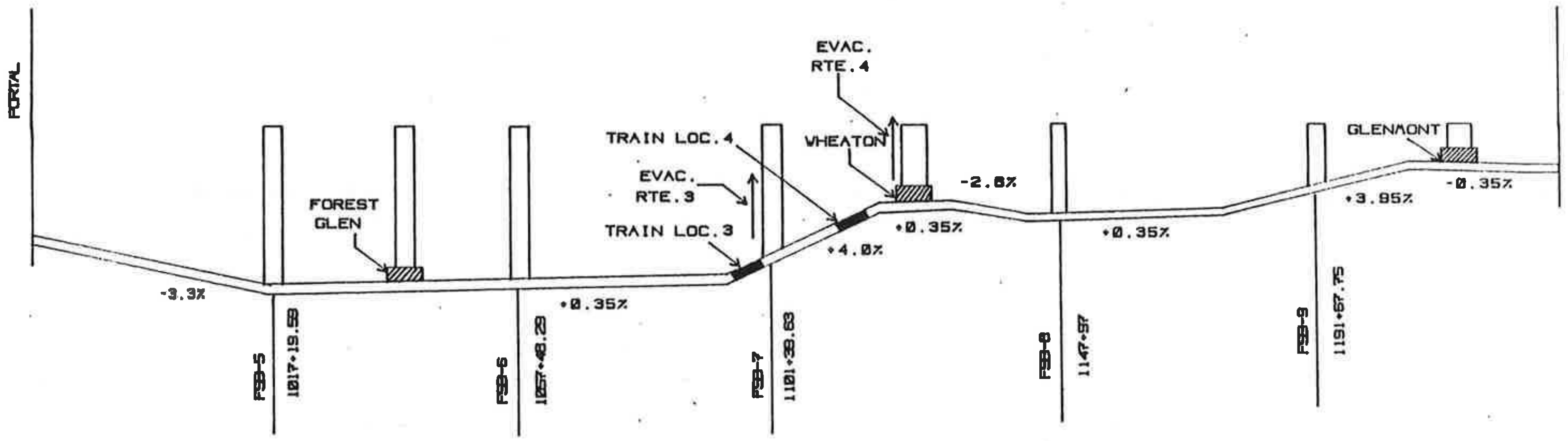
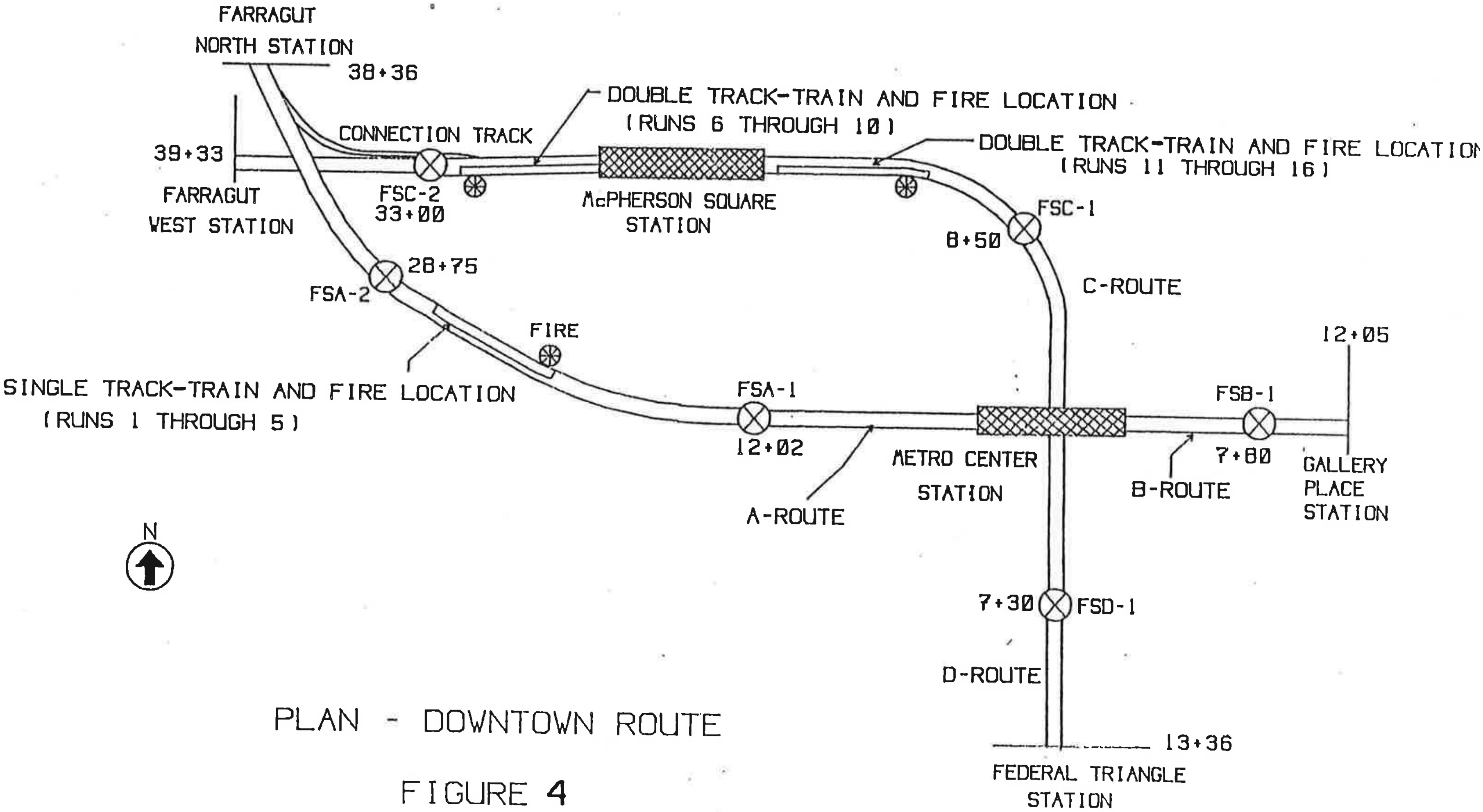


FIGURE 3

DESCRIPTION OF DOWNTOWN NETWORK AND SIMULATIONS

The portions of the downtown routes included in the SES network are shown in Fig. 4. The SES network includes two stations, their interconnecting tunnels, and six fan shafts. The stations are double track sections having large cross-sectional areas. The tunnels between the stations are comprised of combinations of single track and double track sections. In the double track sections, the dividing wall between trainways is either a line of columns or a continuous concrete wall with openings between trainways. The capacities of the fan shafts and the station exhaust systems are presented in Table 2. The analysis of the route and the results of the simulations have led to the conclusions and recommendations appearing in this report. Detailed information describing the Downtown Route is presented in APPENDIX E. The simulations performed and their results are presented in APPENDIX C.



PLAN - DOWNTOWN ROUTE

FIGURE 4

FAN SHAFT	TOTAL CAPACITY(kcfm)	
	SUPPLY	EXHAUST
FSA–1	98	150
FSA–2	65	100
FSB–1	65	100
FSC–1	163	250
FSC–2	130	200
FSD–1	130	200
McPHERSON STA. UPE	38	60

FAN CAPACITIES DOWNTOWN ROUTE

TABLE 2

CONCLUSION

CONCLUSIONS

The conclusions in this section are based on our SES analyses of the B-Route and Downtown-Route networks as well as our review of prior SES studies.

B-Route Network

1. The approach used in the prior analysis of the B-Route was both reasonable and thorough.

2. For the train locations studied, the changes made to the B-Route SES network and data sets that had been provided had little effect on the resulting airflows. This conclusion was reached as a result of aerodynamic sensitivity studies. The referenced changes are described in APPENDIX A.3.

3. The SES predicted airflow by the train at one location was about the same as predicted in the prior referenced study. For the second train location, the airflow predicted in the current study was somewhat greater (25 percent) than previously predicted. The discrepancy in magnitude of the airflow at this location cannot be explained without reviewing the actual computer runs of the previous study, which were not available. These conclusions are based on comparative runs which simulated a 20 million Btuh train fire and 80 percent effective blockage devices.

4. The critical velocity criteria used in the two studies result in different recommendations, even though the simulation results are similar. The

critical velocity criteria used in the current study is based on the effect of tunnel grade, fire size and annular area at the train location. Although the critical velocities were larger for the current study, they were easier to meet at the train location since the annular tunnel cross-sectional area is smaller and higher velocities, therefore, can be achieved with lower airflows.

5. The recommendations of the prior and current studies would be consistent if similar critical velocity criteria were used. Even though the airflows predicted for one of the train locations is different, the recommendations would be similar when the same critical velocity criteria are used.

6. Blockage devices are not required at the train locations evaluated to direct sufficient airflow by the train. This is in contrast to the recommendations of the previous study because different critical velocity criteria were used.

7. Train fire heat release rates up to 40 million Btuh are able to be controlled at the two train locations studied.

8. From a ventilation standpoint, the B-Route has relatively few flow paths and is therefore considered a "tight" system. The effects of operating tunnel ventilation fans and station systems were readily apparent on the predicted airflows. This characteristic of the system is beneficial in that the airflows past a train can be augmented by the operation of fans removed from the train location.

9. There were no required increases in tunnel fan capacity to satisfy the critical velocity criteria for the two locations simulated. Although the three remaining sites studied on the B-Route were not simulated, it is unlikely that the tunnel fan capacity increases previously recommended would be required to satisfy these locations. Further analyses should be performed to confirm this conclusion.

Downtown Route

1. Blockage devices or jet fans are required to direct sufficient airflow by a train to satisfy critical velocity criteria. Blockage devices are more desirable than jet fans from a ventilation standpoint, since their performance is less subject to varying tunnel airflow conditions.

2. The "brute-force" approach, i.e., increasing the existing tunnel ventilation fan shaft capacity until the critical velocity criteria in the tunnel is satisfied, is not a practical solution. Required fan capacities using this method would be many times greater than what is currently installed.

3. From a ventilation standpoint, the Downtown Route has many flow paths, large open stations, and multiple entranceways. Consequently, the system is "full of holes". Therefore, when the tunnel ventilation fans and station systems remote from the train location are operated, they have little effect on increasing the airflow by the train.

4. It is envisioned that only minimal civil and structural modifications to the tunnels may be

required to implement blockage devices or jet fans at the sites studied. When using blockage devices to control airflow in the tunnel sections having continuous concrete dividing walls with openings, it was found necessary to close these openings in order to achieve sufficient airflows to prevent back-layering of smoke. The effect of closing these openings on passenger comfort (sensed air pressure changes during train operation) must be evaluated.

5. Train fire heat release rates up to 40 million Btuh can be controlled using blockage devices and existing tunnel ventilation fan capacities at the sites studied.

6. The existing tunnel ventilation fan capacities were sufficient to meet the critical velocity criteria by the train at the sites studied when the fans are used in concert with blockage devices or jet fans and with modifications to certain dividing walls as previously identified.

7. The three sites examined were typical of the downtown area. Some of the information gained from this study is applicable to other sties throughout the system. Because of the many different site configurations existing in this system, each should be examined to determine the extent of required modification.

RECOMMENDATIONS

RECOMMENDATIONS

As previously described, the primary objectives of the Phase I program were to develop ventilation strategies and to identify both a single track and a double track location for testing the recommended concept(s). Our recommendations relevant to each of these objectives are as follows:

VENTILATION STRATEGIES

In addition to reviewing the existing ventilation system's capability to achieve desired emergency ventilation objectives, four other alternative ventilation strategies viable for implementation in the Metrorail were considered. The four alternatives previously described were:

- "Brute-Force" Emergency Ventilation
- "Push-Pull" Emergency Ventilation
- Tunnel Blockage Devices
- Wall Mounted Jet (Impulse) Fans

Based on the required airflows to control the movement of smoke and heat during a fire emergency as determined by SES analyses, it was concluded that the application of either of the first two alternatives identified above (i.e., "brute-force" and "push-pull") would be extremely costly to implement, due to the extensive installation and equipment modifications, and therefore neither one of these would provide a practical solution. Consequently, our attention was focused on the remaining two ventilation alternatives.

To achieve the most effective control of smoke and heat in a fire emergency, the deployment of blockage devices appears to provide the better cost-effective solution. However, as discussed in the body of this report, further consideration of the use of such blockage devices needs to be addressed before a commitment to them can be made. We would propose this as a concurrent two-pronged process in the early part of the Phase II program. One of these actions would consist of our review with the manufacturers of such devices, and the subsequent establishment of operational requirements and design criteria. The other concurrent action would be a review by the WMATA maintenance/operations/safety personnel regarding the use of such devices in a transit system. The time required to complete this two-pronged process, and its findings, will bear significantly on the definitive scope and completion schedule for the balance of the Phase II program. At this time there is no transit system precedent for the use of such blockage devices, although similar devices have been used for many years in mines, and other very substantial barriers are used on large mainline railroad tunnels in the United States and Canada.

The jet fan alternative appears viable and approaches the capability of the blockage devices to control airflows in a fire situation. We recommend that a design for its subsequent testing be developed concurrently with the investigation of the barrier devices during the Phase II program. Thus, in the event -- for whatever reason -- the blockage devices are eventually deemed to be inappropriate for the Metrorail, the jet fan alternative will provide a technically viable, although significantly more costly, alternative.

SINGLE TRACK AND DOUBLE TRACK TEST SITE LOCATIONS

Based on the various SES analyses performed during this study, it is recommended that the tunnel section between McPherson Square and Metro Center Stations serve as the location for performing both the single track and double track test program to be accomplished in Phase II:

The prototype tests are primarily intended to accomplish two objectives as follows:

- Demonstrate the viability of the recommended concept(s) and physical modifications.
- Provide a basis of comparison with the SES analyses to permit "fine tuning calibration" of the SES program. Through the full-scale verification of the findings from the SES computer analyses, this analytical tool can then be applied to any and all other existing, or future sections of the Metrorail, to determine the required modifications, if any, that may be necessary to achieve the emergency ventilation objectives and eliminate further full-scale testing. The basis for final prototype site selection, the required system modifications and an outline of the proposed prototype testing programs is presented in APPENDIX A.4.

COST ESTIMATE

The testing portion of the entire Phase II program for both single and double track tunnels will be conducted at a common site as described in the RECOMMENDATIONS section. The testing will be done to evaluate both blockage device and jet fan ventilation strategies. Order-of-magnitude costs for the planning and execution of the Phase II program are as follows:

I.	Preparation of Bid Documents for Design Modifications, Equipment Procurement, and Field Tests			$240,000
II.	Construction and Impact Studies			
	A.	Jet Fans and Electrical Service	$350,000	
	B.	Blockage Devices*	$300,000	
	C.	Closure of Refuge Openings between Trainways	$ 20,000	
	D.	Operations Safety Control Systems Investigations and Maintenance Impact Studies	$150,000	
				$820,000
III.	Performance of Field Tests			
	A.	Testing Contractor	$100,000	
	B.	Engineering & Supervision	$ 40,000	
				$140,000
IV.	Analysis and Recommendations for Ventilation Strategies and System Modifications			$230,000
		Phase II Program Total:		$1,430,000
			Say	$1,450,000

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* Estimate based on letter from A.J. Wendt (Sheldahl) to John Bumanis (DeLeuw Cather), dated July 31, 1985, (Ref. 1), and subsequent discussions relevant to additional features which might be required for the blockage devices.

REFERENCES

1. DeLeuw, Cather and Company, "Tunnel Smoke Control Study Phase I", August 1985.

2. Raymond Kaiser Engineers, "Assessment of Metrorail Ventilation System", Volume I and Appendix, Contract No. Y91012, Report No. 83-017-R-MD, May 1983.

3. Raymond Kaiser Engineers, "Metrorail Ventilation System Improvements and Vehicle Fire Hardening", Contract No. X91012, December 1983.

4. Parsons Brinckerhoff, Quade & Douglas, Inc. "Subway Environmental Design Handbook Volume II, Subway Environment Simulation (SES) Computer Program Version 3, Part 1: User's Manual", prepared for U.S. Department of Transportation, Urban Mass Transportation Administration, Draft Final Report, November 1980.

5. Parsons Brinckerhoff Quade & Douglas, Inc. , "Metrorail Ventilation System, Phase I, Interim Report - Review of Previous Studies", September 22, 1987.

6. Washington Metropolitan Area Transit Authority, "Metrorail System Maps", October 1984.

7. LTI Consultants, Inc., "Tunnel Ventilation Modifications, Tunnel Assessment and Recommendations", September 23, 1987.

8. Ebasco Services Inc., "System Ventilation Fan Test Program", November 1987.

APPENDIX

APPENDIX A.1

TUNNEL FIRE AND SMOKE CONTROL

In a horizontal (zero percent grade) unventilated tunnel with a fire near the midpoint, the buoyant effect will establish a symmetrical circulation pattern with the hot, smokey air leaving both ends of the tunnel and air outside the tunnel drawn in beneath it.

A longitudinal ventilation system forcing air to flow through the tunnel will shift the balance of heated air and smoke in the direction of the forced flow. Whether back-layering occurs depends upon a number of factors which include the intensity of the fire, the grade and geometry of the tunnel, and the velocity of the ventilating air by the fire site.

The basic analytical tool used in this study to evaluate ventilation strategies for smoke control is the Subway Environmental Simulation (SES), Version 3.0, computer program (Ref. 4). Unlike earlier versions, Version 3.0 includes an option to make use of a "fire model" which has the ability to simulate the overall interactive effects of a tunnel fire on the air flow induced by the ventilation system. After simulating a fire together with the intended operation and capacity of the ventilation system, the resulting air velocity approaching the fire site is compared to a certain "critical velocity". When the resulting air velocity exceeds the critical velocity, back-layering is precluded and the ventilation system is considered adequate for smoke control. The expression used to evaluate the critical velocity is an integral part of the SES fire model. Details of the fire model, including the expression for the critical velocity, are presented in APPENDIX D.

APPENDIX A.2

CRITERIA

Fire Size

The ability of the ventilation system to control the movement of smoke and heat resulting from a vehicle fire is dependent upon many variables including, and in particular, the size of the fire. This variable, represented in the analysis as the "fire heat release rate", is evaluated in consideration of such variables as the amount and type of combustibles comprising the vehicle, their respective burning rates, their distribution and relative isolation from one another, and the source of ignition.

Previous studies (Ref. 2) addressed emergency ventilation using fire heat release rates ranging from 8 to 40 million Btu/hr (Btuh). A subsequent study (Ref. 3) focused on refining the heat release rate and included performing a fuel load inventory for the Rohr vehicle and mathematically modeling fire propagation. Results of these studies led to recommendations for fire hardening the vehicles which would limit the burning rate to 20 million Btuh. WMATA has subsequently undertaken a fire hardening program to implement the recommendations.

As part of the current scope of work, a review of the relevant prior studies (Ref. 5) led to recommendations identifying further work required to confirm the appropriate fire heat release rate to be used in the emergency ventilation analysis. This additional work will be accomplished in a subsequent phase in the overall program. To bridge this gap with the current study, the ventilation analyses were performed for two fire heat release rates: 20 and 40 million Btuh.

Critical Velocity

The simultaneous solution of Equations 1 and 2 in APPENDIX D determines the critical velocity. This criterion determines the minimum steady-state velocity of the ventilating air moving toward the fire that would prevent back-layering. Note that this criterion determines the required velocity during the fire and not the air velocity in the absence of the fire which can be substantially different.

The critical velocity corresponds to the average tunnel air velocity across the fire incident area; i.e., the annular space between the train and the tunnel wall surfaces. The appropriate annular area depends on the type of tunnel in which the train, at the fire site, is located. In this study tunnel sections were analyzed as being either single track or double track depending on the type of dividing wall that is present between trainways. Trainways without a dividing wall or those separated by one that offers little aerodynamic separation between trainways, such as a line of columns, were considered double track. In this case the annular area corresponds to the sum of the areas of each trainway less the train area. Trainways separated by a solid dividing wall or one having a porosity level less than 15 percent were considered single track. In this case the annular area corresponds to the area of the trainway containing the train less the train area. With this in mind, critical velocities in ft/min (fpm) for these categories are shown below. The range corresponds to differences in tunnel grade and tunnel area at the particular sites studied.

CRITICAL VELOCITY (fpm)

Fire Size	Single Track	Double Track
20 million Btuh	430-480	330-360
40 million Btuh	470-540	400-430

APPENDIX A.3

STUDY APPROACH FOR B-ROUTE

For this study, it was assumed that computer printouts of the SES simulations underlying the prior study (Ref. 1) would be available for review. Instead, only completed input data coding forms and simulation network diagrams were provided for the sections of the B- and F-Routes that were simulated. After reviewing this data together with the results presented in the report, it was decided to simulate the B-Route network. Subsequently, a "list-off" for B-Route which updated and supplemented the previous coding forms was received.

In the process of reviewing the resulting data set, inconsistencies between the information presented on the input forms and the network diagram were observed. Consequently, the contract drawings of the simulated sections had to be reviewed to insure both geometric compliance and appropriate simulation representation. All pertinent aerodynamic and thermodynamic characteristic data along with simulation controls were also reviewed and changes were made where deemed appropriate.

After reviewing the various train locations previously simulated, two locations considered to be candidates for prototype site testing were selected for simulation. For each location a matrix of simulations was performed to test the sensitivity of results to modifications made to the input data, to fire size, and to effectiveness of tunnel blockage devices.

CHANGES TO THE SIMULATED B-ROUTE NETWORK

- **Network Geometry**

  A detailed review of the simulated network was performed. Using contract drawings provided by WMATA, pertinent data such as lengths, cross sections, and perimeters associated with the station and tunnel sections were evaluated. The geometric changes resulting from this review were considered to be minor. The SES network diagram used in a prior study (Ref. 1) to represent the physical configuration of the system was also revised at the base of some fan shafts to reflect a more accurate representation of the actual flow patterns.

- **Tunnel Surface Roughness Length**

  The tunnel wall surface roughness lengths were adjusted to reflect a resulting tunnel surface friction factor which is typical for transit tunnels of this type. In general, the tunnel friction factor was reduced from about 0.033 to 0.026.

- **Train Aerodynamic Resistance**

  The train skin friction coefficient was changed from 0.012 to 0.023. The train drag coefficient weighted total truck area was changed from 75.0 to zero square feet. These values are considered to be more typical of the Rohr and Breta cars. A sensitivity analysis of these changes was performed and is discussed in APPENDIX B.

- **Radiation Component-Fire Heat Release Rate**

  The radiation component of the fire heat release rate depends on the effective flame temperature and the effective surface area of the fire. In the DeLeuw Cather study, the values entered for these variables results in approximately 86 percent of the 20 million Btuh fire being radiated directly to the tunnel walls. The airflow across the fire site is therefore subjected to only 14 percent of the fire load. Although the walls transfer a portion of the radiant heat received back to the airstream via convection, the process is relatively slow and would require a long simulation time for the air temperature and resulting buoyancy effects to reach steady-state.

  In our analysis, 20 percent of the 20 million Btuh fire and 10 percent of the 40 million Btuh fire were assumed to be radiated to the tunnel walls. The effect of this assumption is that the airflow by the train is subjected to a significantly higher heat release rate. This, in turn, increases the buoyancy effect and results in a more conservative analysis.

- **Fire Simulation Time**

  Fire simulation time was increased from 500 to 900 seconds to insure that adverse buoyancy effects were better established further downstream of the fire site.

SELECTION AND ANALYSIS OF PROTOTYPE TEST SITES

At the suggestion of WMATA staff, the search for potential prototype test sites focused on the downtown area. Using Metrorail System Maps (Ref. 6) to initially determine locations and lengths of double track sections between stations, potential double track prototype test sites were identified based on a guideline that a continuous double track section should be at least as long as an eight-car train. The number of potential sites was further reduced to the general area of Metro Center Station and adjoining stations where more information on the performance of the ventilation systems is known as a result of previous studies and testing. A schematic diagram of this area was developed identifying the portion of the system which had to be simulated to study the potential test sites. Contract drawings covering this area were used to develop the tunnel configurations. Fan shaft capacities were identified from WMATA systemwide drawings and verified through recent field inspections and tests (Ref. 7, 8). Specific single and double track test sites were then proposed to WMATA staff for their review. The final sites proposed were selected as a consequence of being prototypical of the system and also for their proximity to relatively high capacity ventilation shafts which minimizes the potential increase in fan capacity required for the tests.

After reviewing the proposed site location with WMATA staff, one single track location (A-Route between Metro Center and Farragut North) and two double track locations (C-Route between Farragut West and McPherson Square, C-Route between McPherson Square and Metro Center) were selected for SES analysis.

Initial simulations of a particular ventilation strategy focused on determining airflow rates and air velocities corresponding to a "no fire" condition. When the resulting average air velocity in the annulus between the train and tunnel surfaces was considered high enough, only then was a fire simulation performed. The latter simulation predicts the resulting airflow rates taking into account the retarding effects of the fire. When the resulting annular velocity exceeds the "critical velocity", back-layering of smoke is considered to be controlled.

The method used to simulate the double track tunnel sections at the proposed test sites was arrived at by performing sensitivity studies with the SES program, coupled with comparisons to field test results. A review of the contract drawings at the proposed test sites and throughout the simulated portions of the system indicates the double track dividing wall to be either a continuous line of columns or a continuous concrete dividing wall having openings between trainways. The mathematical model in the SES program which describes the airflow in a tunnel section is effectively one-dimensional. Consequently, the double track tunnel can be practically treated as either one large tunnel or two smaller tunnels, depending on the porosity level (the ratio of open area to total area) of the dividing wall. The tunnel sections having a line of columns between trainways can be accurately simulated as one large single tunnel because the porosity level (80 percent) is sufficiently high such that air essentially flows uniformly over its entire cross section. On the other hand, the much lower porosity level (10 to 15 percent) of the continuous concrete dividing wall with openings has a substantially greater isolating effect on the trainways. Furthermore, the openings are located in the lower half of the dividing wall, which in the event of a fire effectively confines the hotter stratified smoke layers to the crown of the trainway containing the fire. This type of double track section was simulated as a pair of non-interconnecting parallel tunnels.

To examine the reasonableness of this approach, separate airflow simulations were performed treating the tunnel section each way for comparison. In both cases, the sum of the airflows in each trainway was about the same. However, the flow split between trainways was considerably greater when treated as separate tunnels. The resulting flow splits were compared to field test results of similar situations presented in Ref. 2. This comparison confirmed the appropriateness of the more conservative approach of simulating each trainway as a separate tunnel.

APPENDIX A.4

BASIS FOR FINAL PROTOTYPE SITE SELECTION

The tunnel section between McPherson Square and Metro Center Stations was selected as the prototype site for testing ventilation strategies for both single track and double track tunnel configurations on the basis of the following:

- **Installed Fan Capacity**

  Ventilation for this section is provided by fan shaft FSC-1. Installed fan capacity is 250 kcfm in exhaust and approximately 163 kcfm in supply. Additional fan capacity would not be required for the testing. The effect of less available fan capacity, which is typical of other fan shafts throughout the system, can be tested by operating fewer fans.

- **Tunnel Configuration**

  This tunnel is comprised of three basic types of sections which, from the standpoint of ventilation, are typical of the Metrorail. Starting from McPherson Square Station, these three types are: trainways separated by a line of columns (309 ft), trainways separated by a continuous concrete dividing wall with intermittent openings between trainways (366 ft), single track tunnels with no access between trainways (525 ft to fan shaft FSC-1, 625 ft to Metro Center Station). The double track section (access between trainways) is sufficiently long to accommodate an eight-car train. The single track tunnels in the section between McPherson Square Station and the fan shaft can be effectively extended to accommodate an eight-car train when the openings in the dividing wall are closed. Closing these openings at some time during the testing is required in any event as part of the ventilation strategy for the double track configuration.

Given the above physical and geometrical features of this tunnel section and the ability to locate the train as required, tests for both single and double track tunnel configurations can be accomplished most cost-effectively in this one tunnel section.

APPENDIX A.5

SYSTEM MODIFICATIONS

This section discusses the modifications to the existing system that are likely to be required to implement the field test program for evaluation of both recommended ventilation strategies.

One important reason for recommending the designated test site was that there would be no need to increase the existing fan shaft capacity. The modifications to the system, therefore, involve the installation of the elements associated with each strategy; such as blockage devices, jet fans and electrical service, and a means of closing the openings in the dividing wall during the program.

- **Install Tunnel Blockage Devices**

  A minimum of three tunnel blockage devices located at the base of the fan shaft are required for the tests. The devices provided for the testing need not be complete with all required controls, safety features, and self-inflating systems, although the final design of the basic blockage element of the system must be used to accurately assess their airflow control capabilities (sealing effectiveness).

- **Install Wall-Mounted Jet Fans and Electrical Services**

  Approximately eighteen jet fans are required for the tests. Six fans will be wall mounted at about

100 foot intervals in each of the three unoccupied tunnel sections adjoining the base of the fan shaft. The jet fans will be bracket mounted over the safety walk and supported by means of anchor bolts. Each fan would be driven by a 10 hp, 3 phase, 460 volt motor. The fans will have 100 percent reversible flow capability. The fans might also be equipped with silencers if deemed necessary.

It is assumed that sufficient power is available at the fan shaft to drive the jet fans and that adequate space in the fan shaft ancillary areas is available to locate the necessary switchgear and motor starters. Power to the jet fans would be fed through wall-mounted cable. With the assistance of WMATA staff, a review of the electrical services in this portion of the system will be performed to determine the most cost-effective way to power the jet fans.

- **Close Wall Openings**

The results of the analysis indicate that in order for the blockage devices or jet fans in the trainway adjacent to the train to be effective, the openings in the dividing wall must be closed. Therefore, the ability to close some or all of these openings during the tests is required. It is envisioned that this could be achieved for the tests by construction of non-combustible frames in each of the openings. The frames would be securely fastened to the concrete. The openings would then be closed as required by means of non-combustible panels on one side of the frame. To close all of the openings, about fifteen of these temporary walls would have to be constructed.

APPENDIX A.6

PROTOTYPE TESTING OUTLINE

The purpose of the tests is to determine the effectiveness of the ventilation strategies to direct the airflow from the fan shaft past the train. This information would then be used to "fine tune" the SES program and its application approach for subsequent evaluation of the required ventilation modifications throughout the Metrorail. The prototype tests will be performed by a testing contractor under the supervision of WMATA staff and their consultants.

The prototype tests will involve a series of airflow measurements carefully sequenced to evaluate the ventilation strategies in a cost-effective manner. Specific air measurement tests, to be developed and detailed in Phase II, include the following:

- o Determine the net airflow processed through the fan shaft in both exhaust and supply modes.
- o Determine the leakage characteristics of the blockage devices.
- o Determine the airflow splits at the base of the fan shaft.
- o Determine the airflow moving by the train at the assumed fire site.

Tests will first be performed to establish the airflow processed through the fan shaft in both supply and exhaust modes. The resulting airflows will be compared to the rated capacity of the fans and serve as a benchmark for subsequent tunnel airflow measurements.

Tests will then be performed to develop the leakage characteristics of the blockage devices. The airflow across one isolated blockage device will be varied while airflow and static pressure readings (across the device) are measured. The resulting airflow vs. static pressure characteristic curve allows the leakage across the blockage devices to be determined in subsequent tunnel tests by taking relatively simple static pressure measurements only. The remaining tests will focus on airflow measurements past an eight-car train in the tunnel.

For the single track tests, the train will be located in the tunnel adjacent to the solid dividing wall (or made solid by closing the openings). Blockage devices will be located at the base of the fan shaft across the three empty tunnel sections. With the fans operating, static pressure readings will be taken across each of the three blockage devices and airflow will be measured in the trainway containing the train, either upstream or downstream of the train. An airflow "continuity" check will then be made by comparing the measured airflow to the difference between the fan shaft flow rate (which was previously established) and the sum of the leakage rates across the blockage devices (determined by the static pressure readings and the blockage device characteristic curve previously developed).

For the double track tests, the train will be located in the portion of the tunnel adjacent to the dividing wall comprised of a continuous line of columns and solid dividing wall with openings between trainways. A series of tests would be performed similar to those described for the single track but will also include airflow measurements in the unoccupied trainway adjacent to the train. These tests will be repeated, closing different percentages of the openings.

The tunnel airflow measurements for both the single and double track tunnel train locations will then be repeated, with jet fans in lieu of blockage devices.

The matrix of tests and the airflow measurement techniques will be further developed in Phase II.

APPENDIX B

B-ROUTE SES SIMULATIONS

This section describes the SES simulations that were performed to verify the conclusions reached in the analysis of ventilation requirements for train locations 3 and 4, as identified in the prior study (Ref. 1). These locations are shown in Fig. 3. Both locations are on a four percent grade, the steepest of the B-Route network.

For each of the two train situations simulated, train location, fire location, and direction of ventilation were as before. In each case, the fire was located in the vicinity of the downgrade end of the train thereby requiring the ventilation system to force air downgrade in the direction opposing buoyancy. The mode of operation of the tunnel ventilation fans and station systems, the capacities of which are shown in Table 1, and the resulting air velocity in the annulus by the train are presented in Table 3 for each of the simulations. The resulting airflows in the tunnel sections and fan shafts in the vicinity of the train for each simulation are shown schematically in figures presented in this appendix.

For Runs 1 through 7, the train was at location 3.

Run 1 (Figure 1B)

The objective of this run was to provide a base case of airflows against which airflows in subsequent runs simulating blockage devices and heat sources are compared. The tunnel ventilation fans, station underplatform exhaust fans (UPE),

RUN	FIRE	BLOCK.	TUNNEL VENTILATION FANS FSB–5	FSB–6	FSB–7	FSB–8	FSB–9	STA.SYST. FG	WH	GL	VELOCITY BY TRAIN (fpm)	CRITICAL VELOCITY (fpm)	CRITERIA SATISFIED
RUN1	——	NONE	E	E	S	S	S	E	S	S	912	———	———
RUN2	——	80%	E	E	S	S	S	E	S	S	1254	———	———
RUN3	——	90%	E	E	S	S	S	E	S	S	1395	———	———
RUN4	20M	80%	E	E	S	S	S	E	S	S	1114	474	YES
RUN5	40M	80%	E	E	S	S	S	E	S	S	1021	538	YES
RUN6	40M	NONE	E	E	S	S	S	E	S	S	636	538	YES
RUN7	——	80%	E	E	S	S	S	E	S	S	1162	———	———
RUN8	——	NONE	E	E	E	S	S	E	S	S	1144	———	———
RUN9	20M	NONE	E	E	E	S	S	E	OFF	S	913	474	YES

BLOCK. = Tunnel Blockage
STA.SYST. = Station Systems
E = EXHAUST
S = SUPPLY

B — ROUTE SES SIMULATIONS
TABLE 3

and dome exhaust fans (DE) were operated according to the schedule outlined in the previous study and shown in Table 2. This "aero" run shows the airflows established by the fans in the absence of both blockage devices and heat sources.

The total simulation time for this and all other "aero" runs was 120 seconds, which is sufficient time for the airflows to reach steady-state. This run simulated the DeLeuw Cather network as modified by our review.

The simulation showed that the airflow by the train was approximately 72.4 kcfm. This resulted in an annular air velocity (Va) by the train equal to 912 fpm as shown in Figure 1B. The airflow in the inbound parallel tunnel was 205.8 kcfm or 2.8 times greater than the airflow by the train. The airflow difference is due to the increased resistance resulting from the presence of the train in the tunnel.

Run 2 (Figure 2B)

This was the first run to simulate the airflow control capabilities of tunnel blockage devices. For this simulation each blockage devices was assumed to block 80 percent of the tunnel cross-sectional area where it was located.

All conditions remained as in Run 1 except for the addition of 80 percent blockage devices at the locations shown in Figure 2B.

For these conditions, the airflow by the train increased to 99.5 kcfm. This is 38 percent greater than the airflow at the same location for the previous simulation.

Run 3 (Figure 3B)

This was a sensitivity run to simulate more "effective" blockage devices. Each of these devices was assumed to block 90 percent of the tunnel cross-sectional area.

All conditions remained as in Run 2 with the exception of the increased efficiency of the blockage devices.

This simulation showed that the airflow by the train was 110.8 kcfm, an 11 percent increase over the flow predicted using the less effective blockage devices.

Summary of Run 1, through Run 3

By adding blockage devices for airflow control, the available fan capacity can be directed to the location where it is most needed. Strategic placement of blockage devices closing off 80 percent of the cross-sectional area increases the airflow by the train by 38 percent. Increasing the "effectiveness" of the blockage devices to 90 percent increases airflow by another 11 percent. With more effective blockage devices, the airflow is 53 percent greater than the base case without blockage devices.

Run 4 (Figure 4B)

This run simulated a 20 million Btuh train fire and its effect in reducing the airflow by the train.

The location and effectiveness (80 percent) of the blockage devices, and fan operation remained as simulated in Run 2. The total simulation time for this and all other "fire" runs was 900 seconds, which is sufficient time for the system to achieve steady-state behavior.

The simulation showed an 11 percent reduction in airflow by the train as compared to the Run 2 without a fire. The air velocity by the train was 1114 fpm. The critical velocity (Vc) is 474 fpm. Since the critical velocity is exceeded, the airflow by the train is sufficient to prevent back-layering.

Run 5 (Figure 5B)

This run simulated a more severe 40 million Btuh train fire and its effect in reducing the airflow by the train.

All conditions remained as in Run 4 with the exception of the increase in heat release rate. By increasing the heat release rate, the "choking" effect of the fire is more severe and therefore the effect of retarding airflow is more pronounced.

The simulation showed an 8 percent reduction in airflow by the train as compared to Run 4, which simulated a 20 million Btuh fire. The air velocity by the train is 1021 fpm, exceeding the critical velocity of 538 fpm. Despite the larger fire heat release rate, the airflow by the train is still sufficient to prevent back-layering.

Run 6 (Figure 6B)

This run simulated the more severe fire rate of 40 million Btuh without using blockage devices to control airflow direction. As a result of the high airflow predictions of Runs 4 and 5, this simulation was performed to predict whether back-layering could be controlled without using any blockage devices.

All conditions remained as in Run 5 except the five blockage devices were removed.

The airflow by the train in this simulation was reduced by 38 percent as compared with Run 5. The air velocity by the train was 636 fpm which still exceeded the critical velocity of 538 fpm.

Summary of Run 4 through Run 6

Runs 4 and 5 showed that the resulting airflows greatly exceed those required to prevent back-layering. Even without using blockage devices, back-layering can be controlled.

Run 7 (Figure 7B)

This run examined the effect of changing the values used for the train skin friction coefficient, the train drag coefficient weighted total truck area, the roughness length in the incident tunnel and the perimeter of the incident tunnel on the airflow by the train. The values used in the current study were changed to those used by DeLeuw Cather as follows:

- o tunnel roughness length from 0.040 ft to 0.0760 ft
- o tunnel perimeter from 50.9 ft to 59.9 ft
- o train skin friction coefficient from 0.023 to 0.012
- o train drag coefficient weighted total truck area from 0.0 to 75.0 sq. ft

This was an aerodynamic simulation identical to Run 2 (80 percent blockage devices) with the exception of the above four changes.

This simulation showed that the combined effect of the above changes reduces the airflow by the train from 99.5 kcfm, predicted in Run 2, to 92.2 kcfm. This result could therefore partially explain the consistently lower airflows predicted by the previous study for this train location.

For Runs 8 and 9, the train was positioned at location 4.

Run 8 (Figure 8B)

The objective of this run was to provide a base case of airflows without using blockage devices. The tunnel ventilation fans and station systems (underplatform exhaust fans and dome exhaust fans) were operated according to the schedule outlined in the previous study and as shown in Table 2.

The simulation showed that the airflow by the train was about 90.9 kcfm. This resulted in an annular air velocity by the train of 1144 fpm. The airflow in the inbound parallel tunnel was 276.3 kcfm or approximately three times greater than the airflow by the train. The airflow difference is due to the increased resistance resulting from the presence of the train in the tunnel.

Run 9 (Figure 9B)

This run simulated a 20 million Btuh train fire and its effect in reducing the airflow by the train.

Previous runs for train position 3 indicated an 11 percent decrease in airflow by the train due to the presence of a 20 million Btuh fire. These results were projected to those of Run 8, resulting in a predicted air velocity of 1018 fpm by the train. Since this value exceeded the critical velocity, the simulation was executed without the addition of blockage devices.

The simulation showed a reduction in airflow of 20 percent from that predicted in Run 8. The greater reduction in airflow from Run 2 to Run 4 compared to Run 8 to Run 9 is due to the lower initial airflows by the train in the later runs. With lower airflow, the air at the fire site reaches a higher temperature thereby retarding the flow more. The airflow along the train for Run 9 is 72.4 kcfm. The corresponding air velocity by the train of 913 fpm, however, far exceeds the critical velocity of 474 fpm.

The extent to which the airflow by the train allows the critical velocity to be met makes it reasonable to predict that the available airflow will also satisfy the critical velocity for the more severe 40 million Btuh train fire without performing any additional simulations. Assuming that a 20 percent further reduction in airflow would occur due to an increased fire rate to 40 million Btuh, the estimated available airflow by the train would be 57.9 kcfm. The corresponding velocity of 726 fpm by the train would still exceed the critical velocity of 538 fpm. For these airflow predictions and those previously identified in Run 6, the airflows required to satisfy the more severe 40 million Btuh train fire can be generated by the "existing" fan capacities without using blockage devices to direct the flow.

Summary of Runs 8 and 9

The high airflows by the train can be generated by the "existing" fan capacities without using blockage devices. The simulations showed that a 20 percent reduction in airflow by the train occurs with a 20 million Btuh fire. Based on an assumed similar airflow reduction, the effect of a 40 million Btuh train fire was predicted without the need to perform additional simulations. The airflow predicted by this assumption still exceeds the critical velocity criteria.

Discussion of B-Route Simulations

The results of the B-Route simulations indicate that for train locations 3 and 4, the existing fan capacities shown in Table 1 provide sufficient airflow to control back-layering.

The more severe 40 million Btuh train fire was twice as large as that considered in the prior study but was still within the control capabilities of the ventilation system.

The use of blockage devices was considered in this study as in the previous study. The simulations for this study showed that although airflows by the train could be significantly increased by using blockage devices, the predicted airflows by the train exceeded the critical velocity criteria without the use of blockage devices.

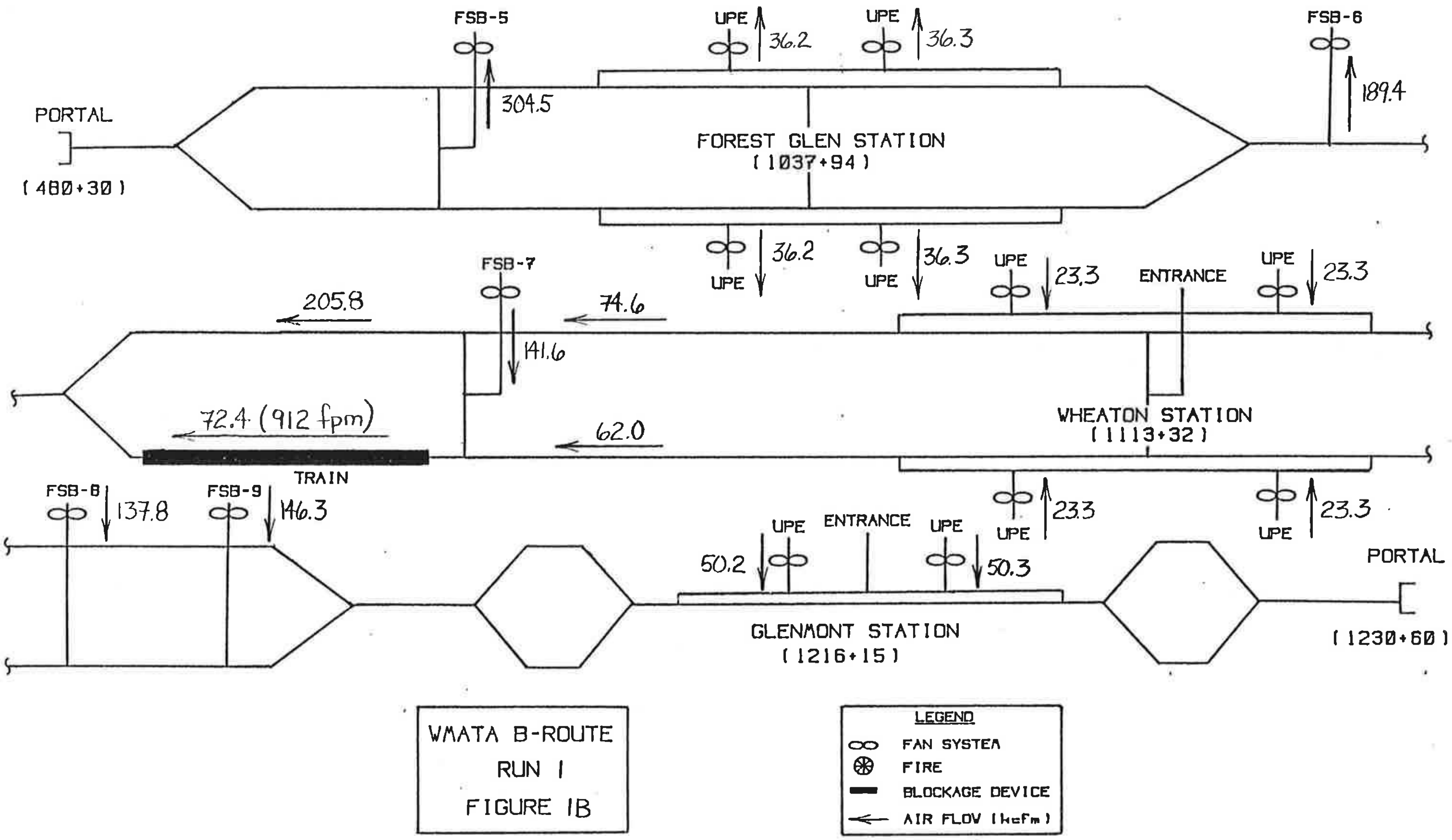
Some additional points should be considered when comparing the results of this study with previous studies:

1. The proposed corrective action in the previous study to increase tunnel fan shaft capacities is the result of analyzing five train locations. Changes in system capacity required for one train location were considered base capacities for subsequent analyses of other locations. The present study investigated only two of the five locations. Although no increases in fan capacities were identified for the two train locations studied, additional fan capacities may be required to satisfy all locations. As a future work item, a study of the remaining three sites would determine if any increases in fan capacities are required.

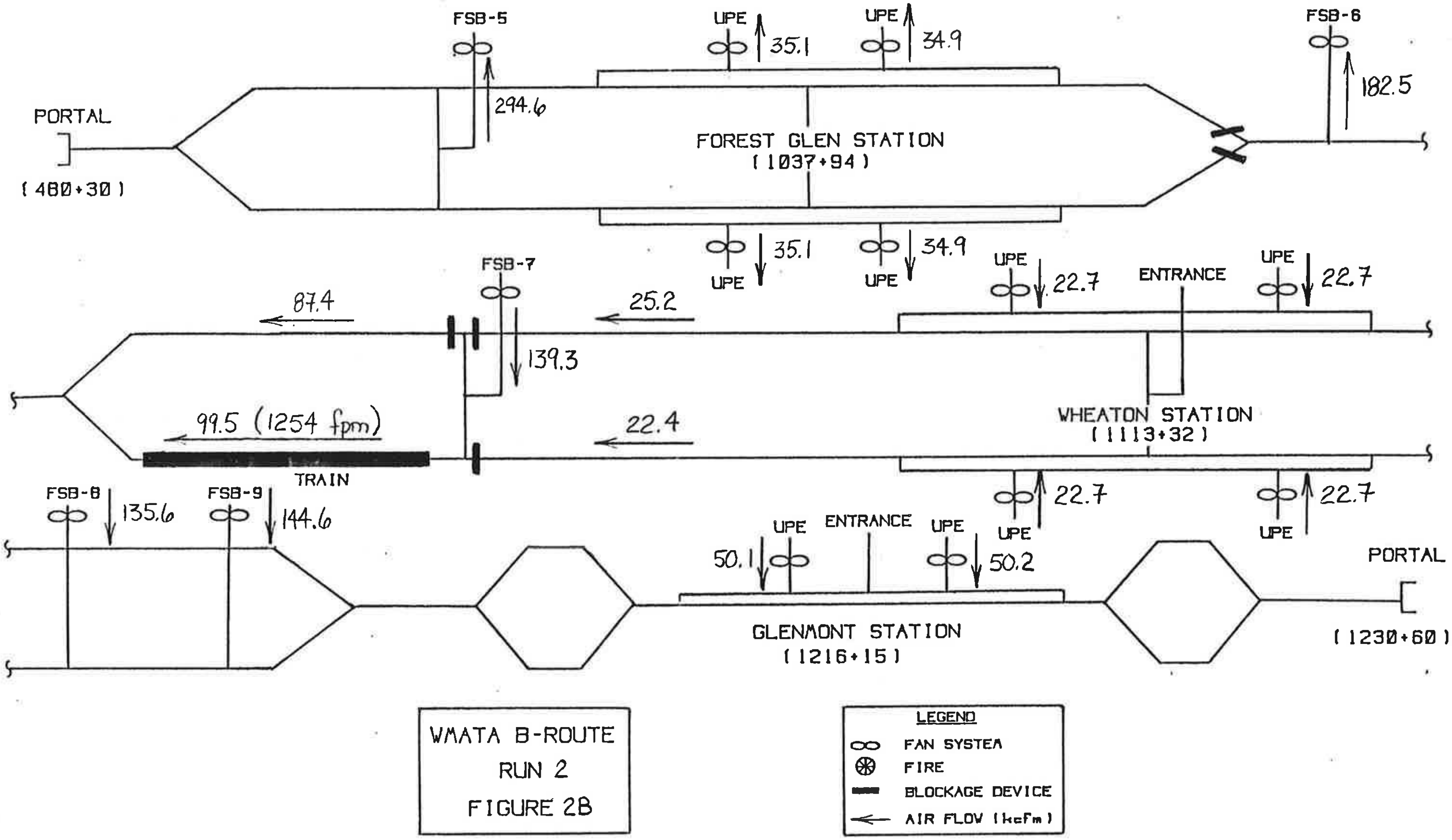
2. The proposed corrective action in the previous study was the use of blockage devices at fan shafts FSB-5, FSB-6, FSB-7, FSB-8 and FSB-9. Although blockage devices for train locations 3 and 4, the available airflow at the remaining three train locations are unknown and therefore the requirement for using blockage devices is not certain. As with fan capacity increases, future study of the remaining three sites is required to determine whether blockage devices are required.

3. Whether or not the airflow by the train predicted in the previous study complies with the critical velocity criteria requires clarification. The critical velocity criteria previously used required comparison with open tunnel air velocity, rather than with air velocity by the train. This resulted in fewer cases satisfying criteria and the need for system modification. The airflows predicted in the present study are slightly higher for train location 3 and about the same for train location 4 as compared with those predicted by the previous study. Increasing fan capacity and the use of blockage devices was required in the previous study, however, to meet the more difficult critical velocity criteria. As stated above, neither fan capacity increases nor blockage devices are required in order for the critical velocity criteria to be satisfied at train locations 3 and 4.

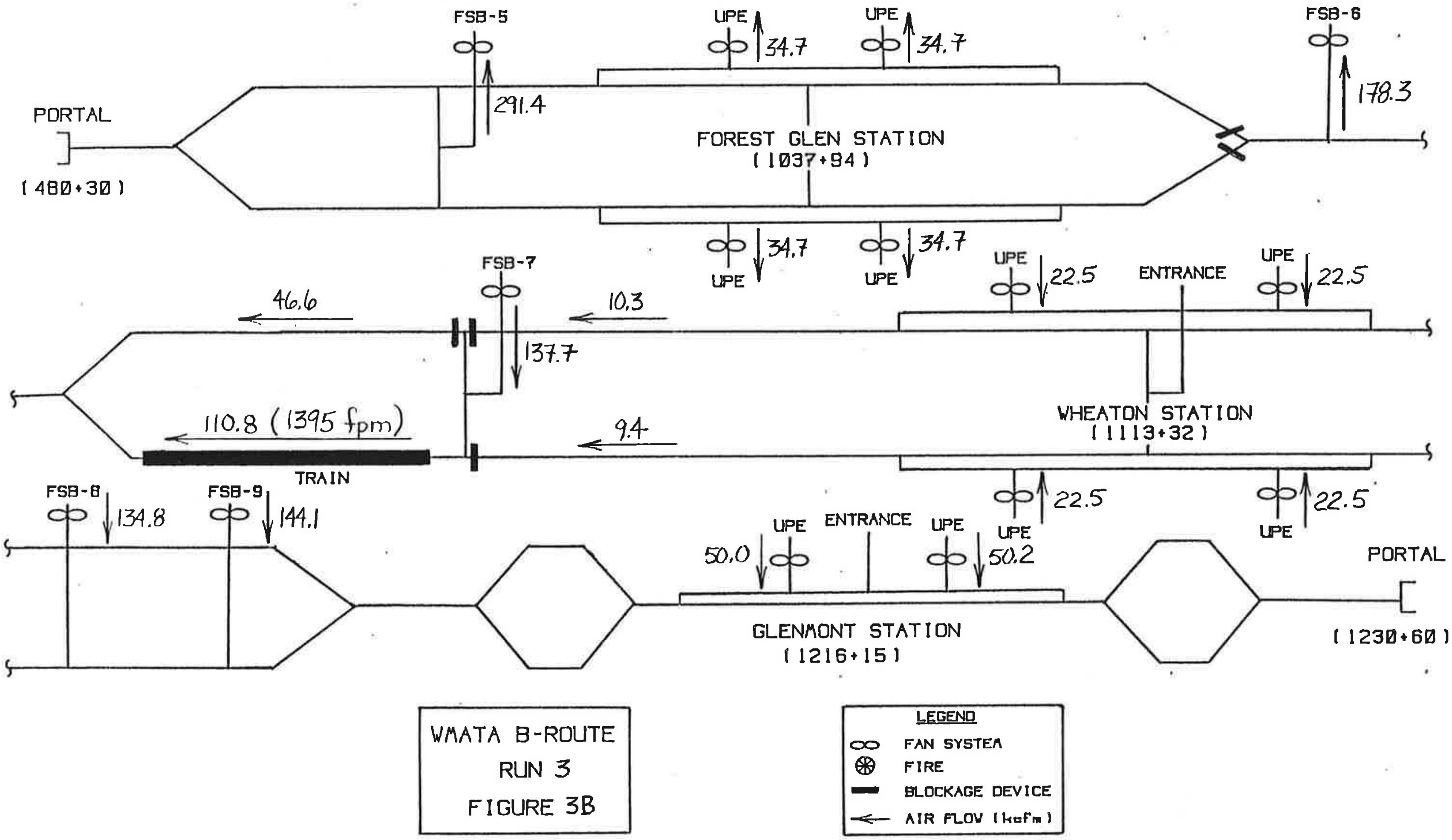
4. The approach of the previous analysis was reasonable and sound. Although changes in the B-Route network were required based on our review of the contract drawings, the changes were insignificant in that the magnitude of the predicted airflow did not significantly change. If the resulting airflows of both studies were compared to the same critical velocity criteria, it is likely that similar recommendations would have resulted.



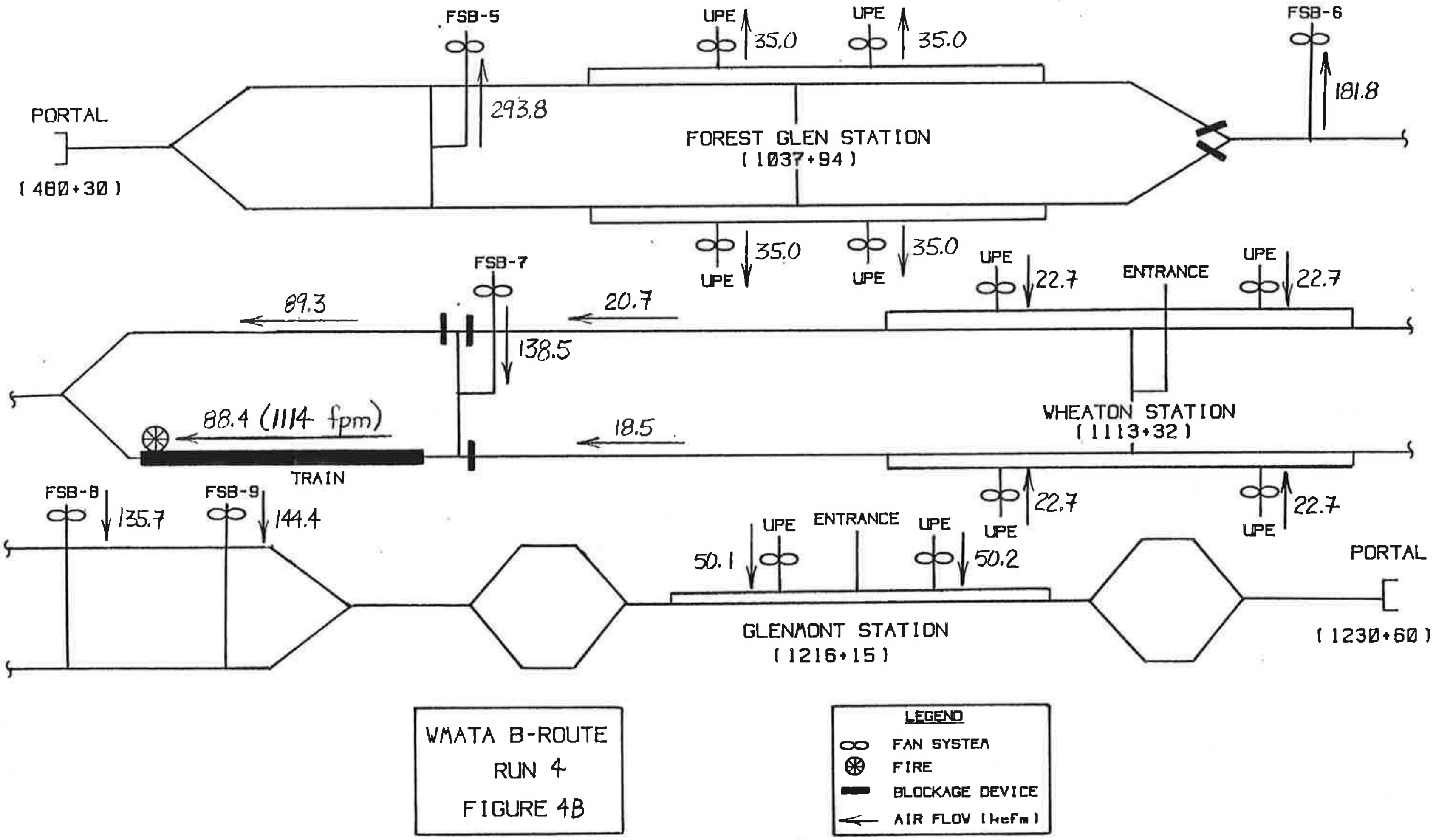
WMATA B-ROUTE
RUN 1
FIGURE 1B



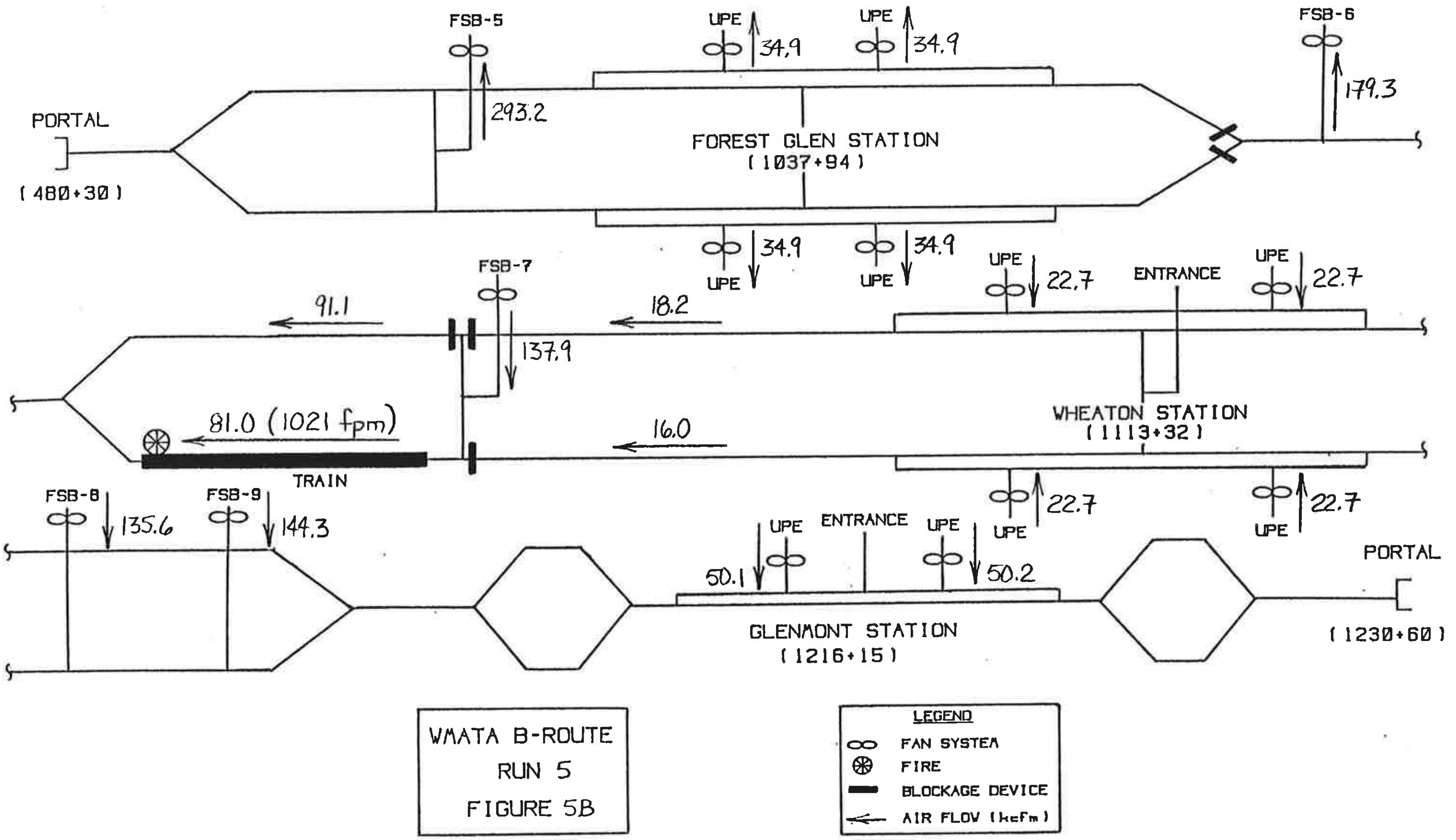
WMATA B-ROUTE
RUN 2
FIGURE 2B



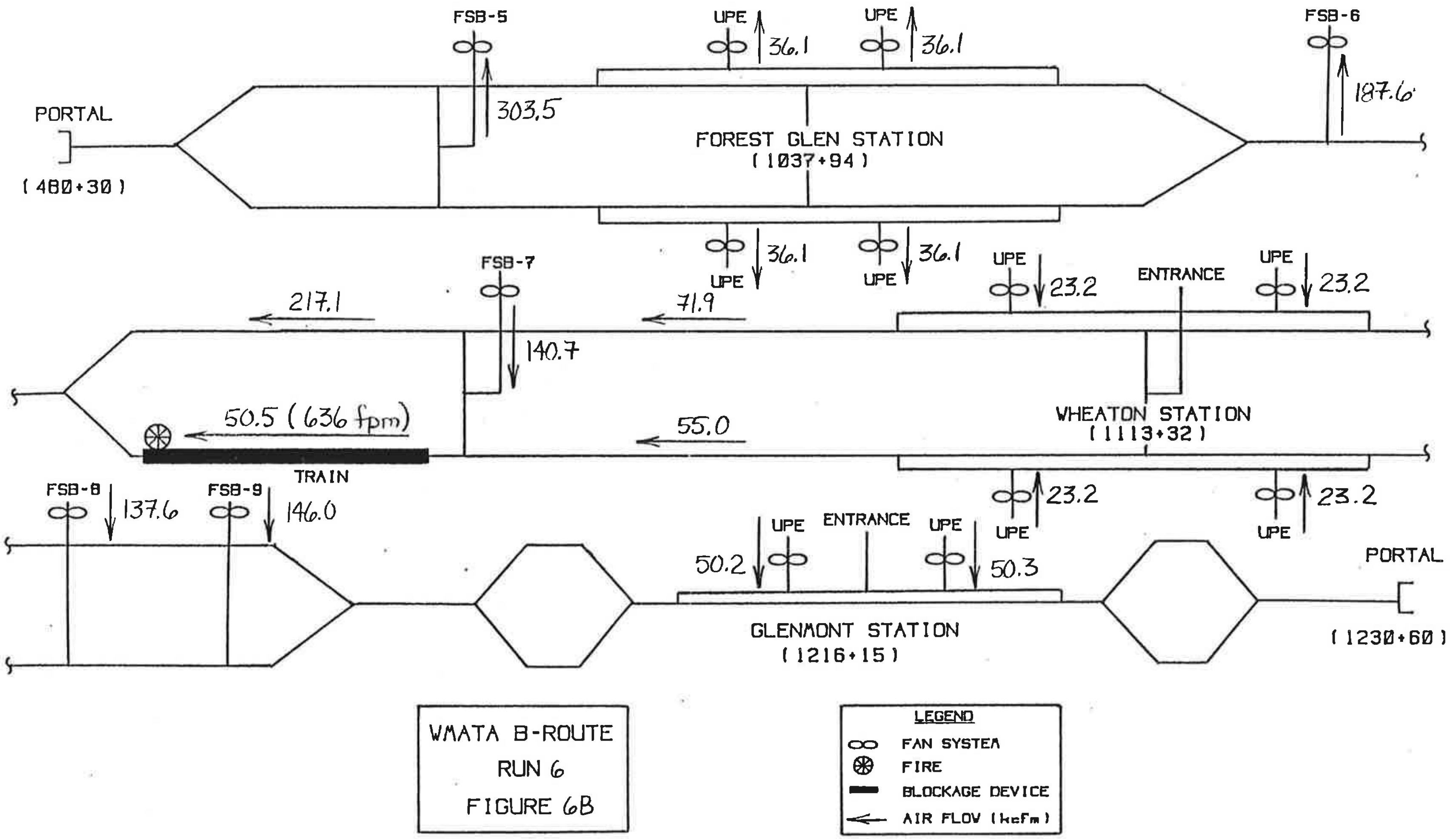
WMATA B-ROUTE
RUN 3
FIGURE 3B



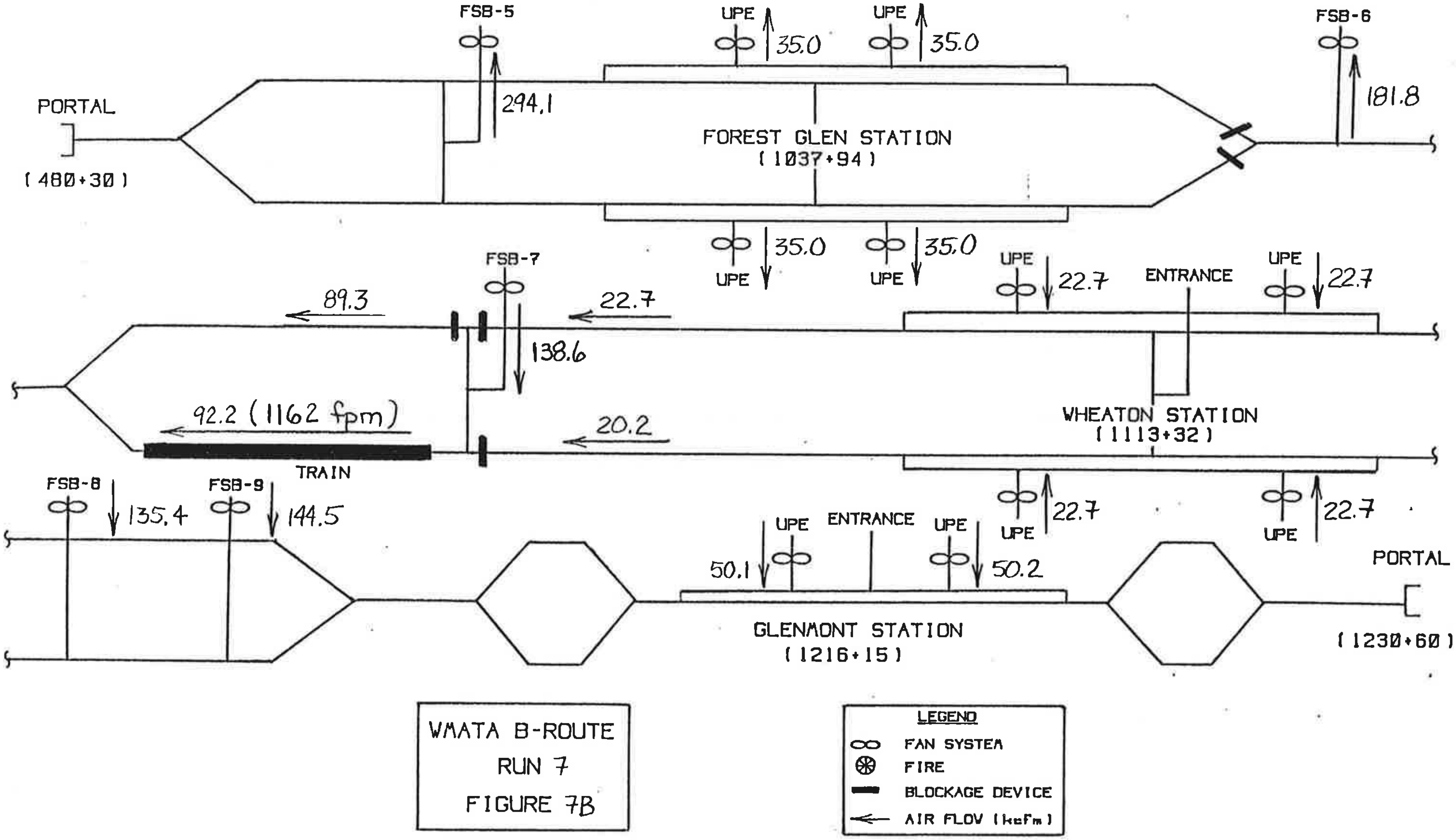
WMATA B-ROUTE
RUN 4
FIGURE 4B



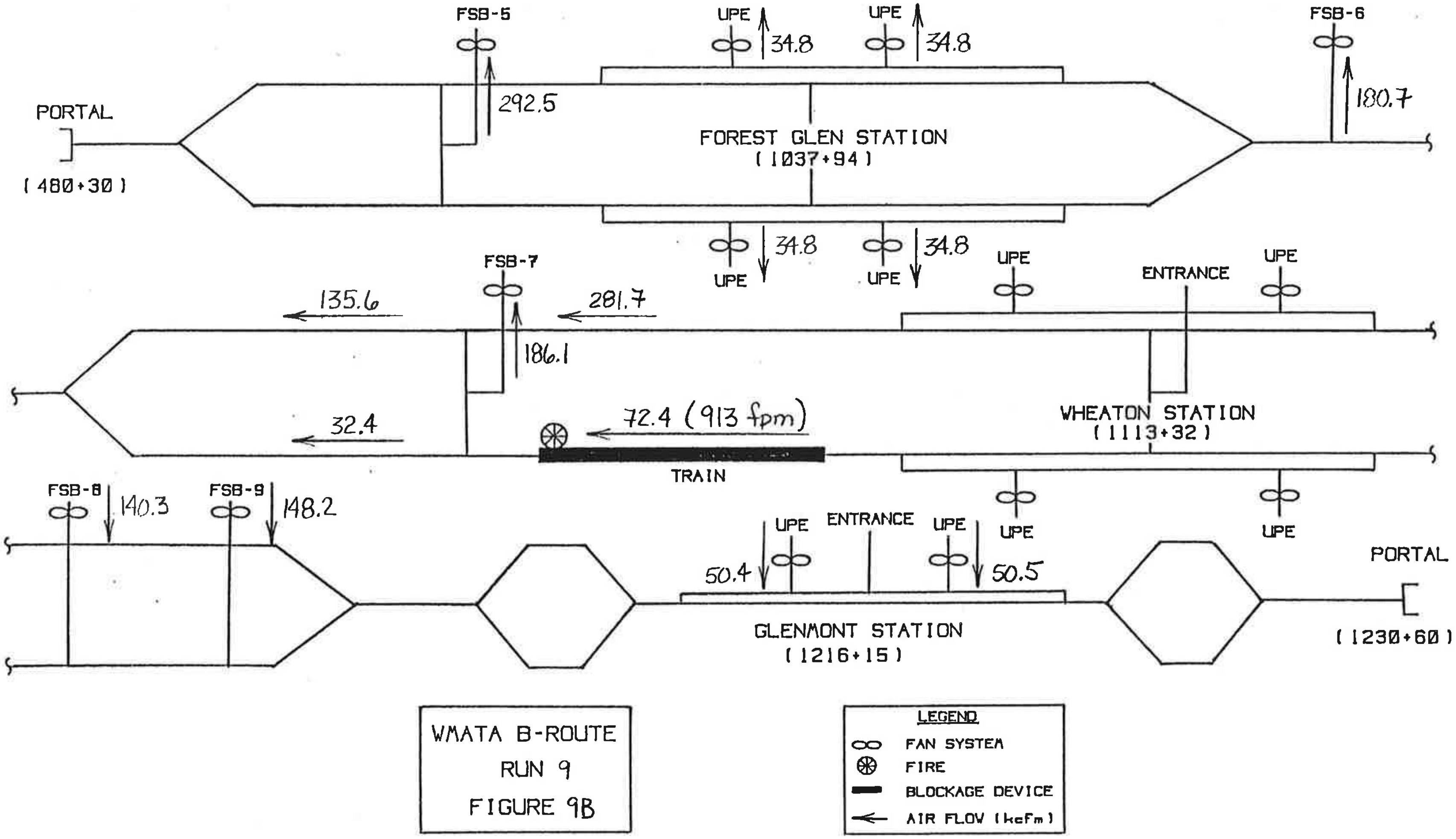
VMATA B-ROUTE
RUN 5
FIGURE 5B



WMATA B-ROUTE
RUN 6
FIGURE 6B



WMATA B-ROUTE
RUN 7
FIGURE 7B



WMATA B-ROUTE
RUN 9
FIGURE 9B

APPENDIX C

DOWNTOWN ROUTE SES SIMULATIONS

This section describes the SES simulations performed. Three train and fire locations, shown in Fig. 4 were selected for examination. In two of the three cases, the ventilation system is operating to move air downgrade in the direction opposing buoyancy. The worst of these two cases is the double track site between Metro Center Station and McPherson Square Station where the grade is 4 percent. The third case, a double track site between McPherson Square Station and Farragut West Station, has buoyancy effects of a 0.35 percent grade aiding the ventilation system. This ventilation strategy was chosen to avoid pulling smoke into the station in the event of a train fire in this particular tunnel location. The mode of operation of the tunnel ventilation fans and station systems and the resulting air velocity in the annulus by the train are presented in Table 4. The resulting airflows in the fan shafts and the tunnel sections in the vicinity of the train are shown schematically in the figures presented in this appendix.

For Runs 1 through 5, the study focused on the A-Route between Farragut North and Metro Center Stations. The front of the train was located at Sta. 27+93 on the outbound track. The dividing wall between trainways is solid over the entire length of the train.

Run 1 (Figure 1C)

The objective of this run was to provide a base case of airflows against which airflows in subsequent runs simulating blockage devices and heat sources are compared.

The tunnel ventilation fans and McPherson Square Station

			TUNNEL VENTILATION FANS									
RUN	FIRE	BLOCK.	FSA-1	FSA-2	FSB-1	FSC-1	FSC-2	FSD-1	STA.SYST. Mc.UPE	VELOCITY BY TRAIN (fpm)	CRITICAL VELOCITY (fpm)	CRITERIA SATISFIED
RUN1	--	NONE	E	S	E	OFF	S	OFF	S	209	---	---
RUN2	--	80%	E	S	E	OFF	S	OFF	S	565	---	---
RUN3	--	90%	E	S	E	OFF	S	OFF	S	813	---	---
RUN4	20M	80%	E	S	E	OFF	S	OFF	S	452	439	YES
RUN5	40M	90%	E	S	E	OFF	S	OFF	S	664	498	YES
RUN6	--	80%	E	E	OFF	S	E	S	S	314	---	---
RUN7	--	80%	OFF	OFF	OFF	S	E	OFF	S	317	---	---
RUN8	--	80%	OFF	OFF	OFF	S	E	OFF	S	997	---	---
RUN9	20M	80%	OFF	OFF	OFF	S	E	OFF	S	758	424	YES
RUN10	40M	80%	OFF	OFF	OFF	S	E	OFF	S	595	471	YES
RUN11	--	80%	OFF	OFF	E	E	S	E	S	584	---	---
RUN12	--	80%	OFF	OFF	E	E	S	E	S	978	---	---
RUN13	--	80%	OFF	OFF	OFF	E	OFF	OFF	S	967	---	---
RUN14	20M	80%	OFF	OFF	E	E	S	E	S	722	481	YES
RUN15	40M	80%	OFF	OFF	E	E	S	E	S	578	540	YES
RUN16	--	JET FANS	OFF	OFF	E	E	S	E	S	978	---	---

BLOCK. – Tunnel Blockage
STA.SYST. – Station Systems
E – EXHAUST
S – SUPPLY

DOWNTOWN ROUTE SES SIMULATIONS
TABLE 4

underplatform exhaust fans, having capacities as shown in Table 3, were operated according to the schedule outlined in Table 4. This "aero" run shows the airflows established by the fans in the absence of both blockage devices and heat sources.

The simulation showed that the airflow by the train was only 18 kcfm. This resulted in an annular air velocity by the train equal to 209 fpm.

Run 2 (Figure 2C).

To increase the airflow by the train, blockage devices were added as shown in Figure 2C. For this simulation, each blockage device was assumed to block 80 percent of the tunnel cross-sectional area in which it was located.

All conditions remained as in Run 1 except for the added blockage devices.

The resulting airflow by the train was 48.6 kcfm, an increase of 170 percent. The airflows in all other tunnel sections near the train were lower.

Run 3 (Figure 3C).

This was a sensitivity run to simulate more "effective" blockage devices. Each of these devices was assumed to block 90 percent of the cross-sectional area in which it was located.

All conditions remained as in Run 2 except for the increase in efficiency of the blockage devices.

The simulation showed that the airflow by the train was to 70.0 kcfm, a 44 percent increase over the flow predicted by the simulation using the less effective blockage devices.

Summary of Runs 1 through 3

By adding blockage devices for airflow control, the available fan capacity can be directed to the location where it is most needed. Strategic placement of blockage devices closing off 80 percent of the cross-sectional area increases the desired airflow by the train by 170 percent. Increasing the "effectiveness" of the blockage devices to 90 percent increases the airflow by another 44 percent. With the more effective blockage device the airflow is approximately four times greater than the base case without blockage devices.

Run 4 (Figure 4C)

This run simulated a 20 million Btuh train fire and its effect in reducing the airflow by the train.

The locations and effectiveness (80 percent) of the blockage devices and mode of fan operation remained as simulated in Run 2. For this simulation the fire was located in the train car closest to fan shaft FSA-1. Passenger evacuation is toward fan shaft FSA-2 opposite to the direction of ventilation.

The simulation showed a 20 percent reduction in air flow by the train, as compared to Run 2 without a fire. The air velocity by the train is 452 fpm. The critical velocity is 439 fpm. Since the critical velocity is exceeded, the airflow by the train is sufficient to prevent back-layering.

Run 5 (Figure 5C)

This run simulated a more severe 40 million Btuh train fire and its effect in reducing airflow by the train. Based on the results of Run 4, more effective (90 percent) blockage devices would be required to meet criteria with this larger fire.

The locations and effectiveness of the blockage devices and mode of fan operation remained as simulated in Run 3. It was anticipated that the "choking" effect of the larger train fire would attenuate the flow by the train to the extent that the critical velocity criteria would not be satisfied using 80 percent efficient blockage devices.

The simulation showed an 18 percent reduction in airflow by the train, as compared to Run 3 without a fire. The air velocity by the train is 664 fpm. The critical velocity is 498 fpm. Since the critical velocity criteria is exceeded, the airflow by the train is sufficient to prevent back-layering.

Summary of Runs 4 and 5

Runs 4 and 5 showed that existing fan capacity operated in accordance with Table 4 is sufficient to control back-layering if blockage devices are used. For train fire heat release rates of 20 and 40 million Btuh, blockage devices having effectiveness of 80 percent and 90 percent, respectively, are required at the locations indicated.

For Runs 6 through 10, the study focused on the C-Route between Farragut West and McPherson Square Stations. The front of the train was located at Sta. 26+50 on the inbound track. The dividing wall between trainways is a line of columns for about half the length of the train and continuous concrete with refuge openings for the remaining half.

Run 6 (Figure 6C)

The objective of this run was to provide a base case of airflows against which airflows in subsequent runs are compared. The tunnel ventilation fans and McPherson Station underplatform exhaust fans were operated according to the schedule outlined in Table 4 to effect a "push-pull" mode of ventilation by the train. From previous simulations using the downtown network it was determined that sufficient airflow by the train was not available without using blockage devices. Therefore, this run included blockage devices (80 percent) at the base of the operating fan shafts as shown in Figure 6C.

To properly simulate the effect of a concrete dividing wall with refuge openings extending over one-half of the train, it was necessary to simulate it as a solid wall. For this base run, blockage devices could not be used to block the airflow path in the trainway adjacent to the tunnel section with the train, since the refuge openings in the dividing wall between the fan shaft and the train would short-circuit the effect of the blockage device.

The simulation showed that the airflow by the train was 19.7 kcfm, corresponding to an annular air velocity of 314 fpm. The airflow in the adjacent trainway was 117.5 kcfm, or approximately six times greater.

Run 7 (Figure 7C)

The effect of operating less tunnel ventilation fans to effect the "push-pull" movement of air by the train was simulated with this aerodynamic run.

The conditions remained as in Run 1 except that the fans in three fan shafts (FSA-1, FSA-2, FSD-1) remote from the train were turned off, as outlined in Table 4. The three blockage devices associated with fan shaft FSA-2 were also removed, as shown in Figure 7C.

The simulation showed that there was no significant change in the airflow by the train. Therefore, to reduce the operational complexity of the ventilation system, these fan shafts and blockage devices were not used in the remaining simulations for this train location.

Run 8 (Figure 8C)

The objective of this run was to increase the airflow by the train by adding a blockage device to the trainway adjacent to the one occupied by the train.

The conditions remained as in Run 7 except that one blockage device (80 percent) was added as shown in Figure 8C. In order for this additional device to be effective, the refuge openings in the concrete dividing walls have to be closed.

The resulting airflow by the train was 62.9 kcfm, corresponding to an annular air velocity of 997 fpm. This value is more than three times the airflow predicted without using the additional blockage device to isolate the adjacent trainway.

Summary of Runs 6 through 8

These aerodynamic simulations showed that it was necessary to both close the refuge openings in the dividing wall and add a blockage device in the adjacent trainway to direct a sufficient airflow by the train. The runs also predicted that there is no significant change in the airflow by the train when certain fan shafts and blockage devices remote from the train location are not used.

Run 9 (Figure 9C)

This run simulated a 20 million Btuh train fire and its effect in reducing the airflow by the train.

The location and effectiveness (80 percent) of the blockage devices and the mode of fan operation remained as simulated in Run 8. For this simulation the fire was located in the train car closest to fan shaft FSC-2. Passenger evacuation was toward McPherson Square Station, opposite to the direction of ventilation.

The simulation predicted a 24 percent reduction in airflow by the train, as compared to Run 8, from 62.9 kcfm to 47.8 kcfm. The corresponding air velocity by the train decreased to 758 fpm. The critical velocity is 424 fpm. Since the critical velocity is exceeded, the airflow by the train is sufficient to prevent back-layering.

Run 10 (Figure 10C)

This run simulated a more severe 40 million Btuh train fire and its effect in reducing the airflow by the train.

The conditions simulated in Run 9 remained the same except for the increase in the fire heat release rate.

The simulation predicted an airflow of 37.5 kcfm by the train. This represents a 22 percent reduction in airflow compared to Run 9, which simulated a smaller 20 million Btuh train fire. The airflow by the train was approximately 40 percent less than the airflow predicted in Run 8 without a fire. The air velocity by the train for the current simulation is 595 fpm, which is greater than the critical velocity of 471 fpm. The existing fan capacities and effectiveness of the blockage devices that were simulated are therefore sufficient to prevent back-layering.

Summary of Runs 9 and 10

If a train fire is located along the continuous concrete dividing wall with refuge openings between McPherson Square Station and fan shaft FSC-2, it is necessary to close the refuge openings and provide a blockage device in the adjacent trainway. By using this, in combination with strategically placed blockage devices at other locations, sufficient airflow to control even the more severe train fire can be achieved with the existing fan capacities.

If a train fire occurs within the column line portion of tunnel contiguous to McPherson Square Station, the results of previous simulations indicate that back-layering would be controlled for both fire sizes. For this situation, the blockage devices between the fire location and fan shaft FSC-2 should not be used. However, in order to satisfy the critical velocity criteria for all fire locations within this tunnel section, the installation of four blockage devices at the base of fan shaft FSC-2 is required.

For Runs 11 through 16, the study focused on the C-Route between the McPherson Square and Metro Center Stations. The front of the train was located at Sta. 13+75 on the inbound track. The dividing wall between trainways is a line of columns for about 40 percent of the train and continuous concrete with refuge openings for the remaining train length.

Run 11 (Figure 11C)

The objective of this run was to provide a base case of airflows against which airflows in subsequent runs are compared. The tunnel ventilating fans and McPherson Square Station underplatform exhaust fans were operated according to the schedule outlined in Table 4 to effect a "push-pull" mode of ventilation by the train. From previous simulations using the downtown network it was determined that sufficient airflow by the train was not available without using blockage devices. Therefore this run included blockage devices (80 percent) at the base of the operating fan shafts as shown in Figure 11C.

To properly model the effect of a continuous concrete dividing wall with refuge openings it was necessary to simulate it as a solid wall. For this base run, blockage devices could not be used to block the airflow path in the trainway adjacent to the tunnel section with the train, since the openings in the dividing wall between the fan shaft and the train would short-circuit the effect of the blockage device.

The simulation showed that the airflow by the train was 36.8 kcfm, corresponding to an annular air velocity of 584 fpm. The airflow in the adjacent trainway was 132.1 kcfm, or approximately three times greater.

Run 12 (Figure 12C)

The objective of this run was to increase the airflow by the train by adding a blockage device to isolate the single track tunnel adjacent to the train.

The conditions remained as in Run 11 except that one blockage device (80 percent) was added as shown in Figure 12C.

For this additional blockage device to be effective, the refuge openings in the continuous concrete dividing walls would have to be closed. The resulting airflow by the train was 61.7 kcfm, with a corresponding annular air velocity of 978 fpm. This is almost 1.7 times greater than the airflow predicted without using the additional blockage device to isolate the adjacent trainway.

Run 13 (Figure 13C)

The effect of operating less tunnel ventilation fans to effect the "push-pull" movement of air by the train was simulated with this aerodynamic run.

The conditions remained as in Run 12 except the fans in fan shafts FSB-1, FSC-2 and FSD-1 were turned off, as outlined in Table 4. The blockage devices at FSC-2 and at the connection track were also removed as shown in Figure 13C.

The simulation showed that there was no significant change in the airflow by the train. To reduce the operation complexity of the ventilation system, these fan shafts and blockage devices need not be used for this train location.

Summary of Runs 11 through 13

These aerodynamic simulations showed that it was necessary to close the refuge openings in the continuous concrete dividing wall and add a blockage device in the adjacent trainway to direct a reasonable airflow by the train. The runs also predicted that the effect of using certain fan shafts and blockage devices remote from the train location is not of significant benefit.

Run 14 (Figure 14C)

This run simulated a 20 million Btuh train fire and its effect in reducing the airflow by the train.

The location and effectiveness (80 percent) of the blockage devices and mode of fan operation remained as simulated in Run 12. For this simulation, the fire was located in the train car closest to fan shaft FSC-1 as shown in Figure 14C. Passenger evacuation is toward McPherson Square Station, opposite to the direction of ventilation.

The simulation predicted a 25 percent reduction in airflow by the train, as compared to Run 12 without a fire. The air velocity by the train decreased to 722 fpm. The critical velocity is 481 fpm. Since the critical velocity is exceeded, the airflow by the train is sufficient to prevent back-layering.

Run 15 (Figure 15C)

A more severe 40 million Btuh train fire was simulated to show its effect in reducing airflow by the train.

The conditions simulated in Run 14 remained the same except the fire heat release rate was increased to 40 million Btuh.

The simulation results, presented in Figure 15C, show a reduction in airflow by the train of about 20 percent as compared to Run 14. The airflow by the train was approximately 40 percent less than the airflow predicted without a fire (Run 12). The air velocity by the train for the current simulation is 578 fpm, which is greater than the critical velocity of 540 fpm. The existing fan capacities and the blockage devices simulated are therefore sufficient to prevent back-layering.

Summary of Runs 14 and 15

If a train fire is located along the continuous concrete dividing wall with refuge openings between Metro Center Station and McPherson Square Station, it is necessary to close the refuge openings and provide a blockage device in the adjacent trainway. By using this, in combination with strategically placed blockage devices at other locations, sufficient airflow to control even the more severe train fire can be achieved with the existing fan capacities.

If a train fire occurs within the column line portion of the tunnel contiguous to McPherson Square Station, the results of previous simulations indicate that back-layering would be controlled for both fire sizes. For this situation, the blockage devices between the fire location and fan shaft FSC-1 should not be used. However, in order to satisfy all fire locations within this tunnel section, the installation of four blockage devices at the base of FSC-1 is required.

Although more fans and blockage devices were used in Runs 14 and 15, it was shown, by comparison of results for Runs 12 and 13, that they had an insignificant effect on the airflow by the train. Consequently, it follows that the results of Runs 14 and 15 would be valid if fan operation and location of blockage devices was as shown for Run 13 in Table 4.

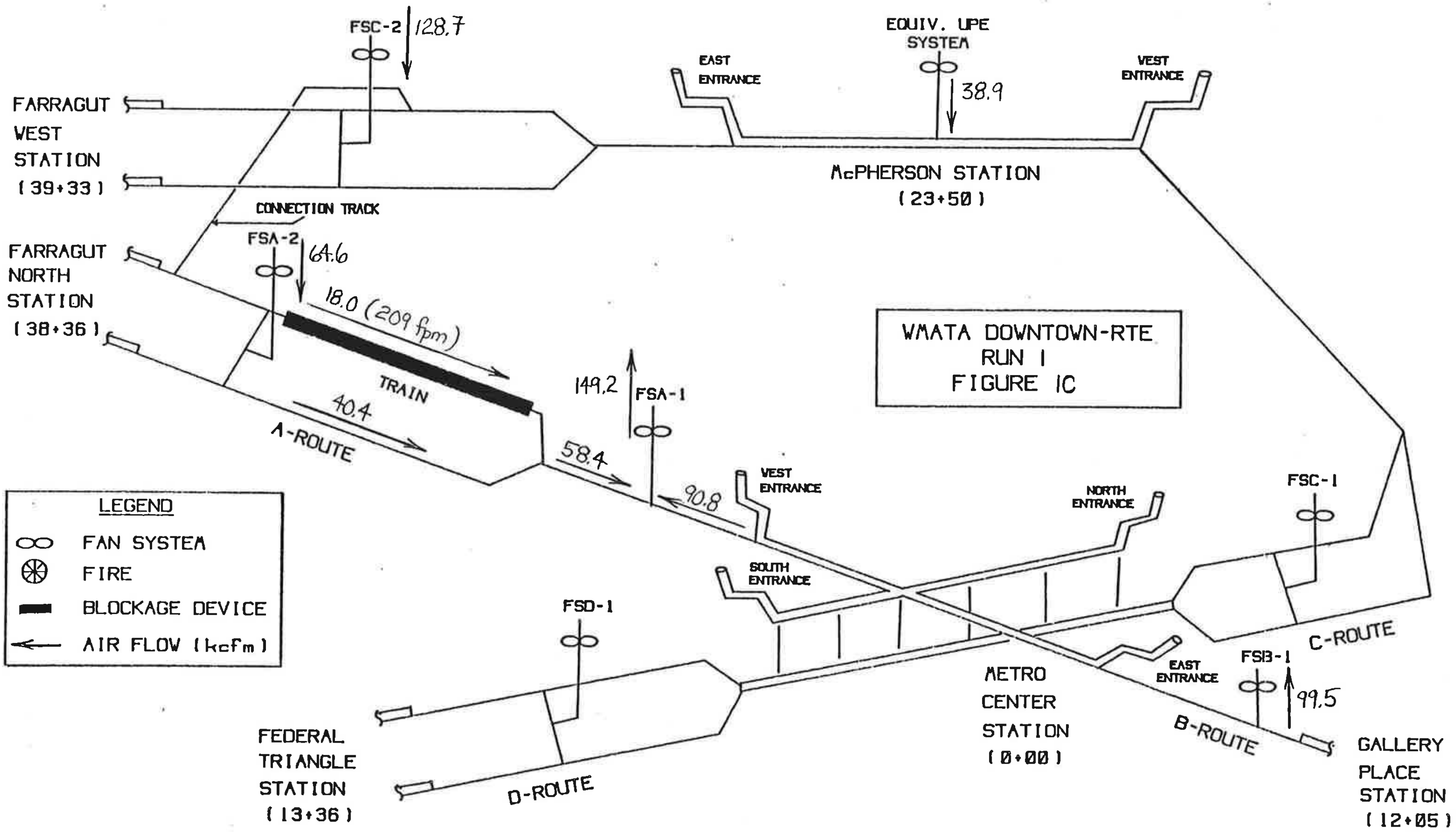
Run 16 (Figure 16C)

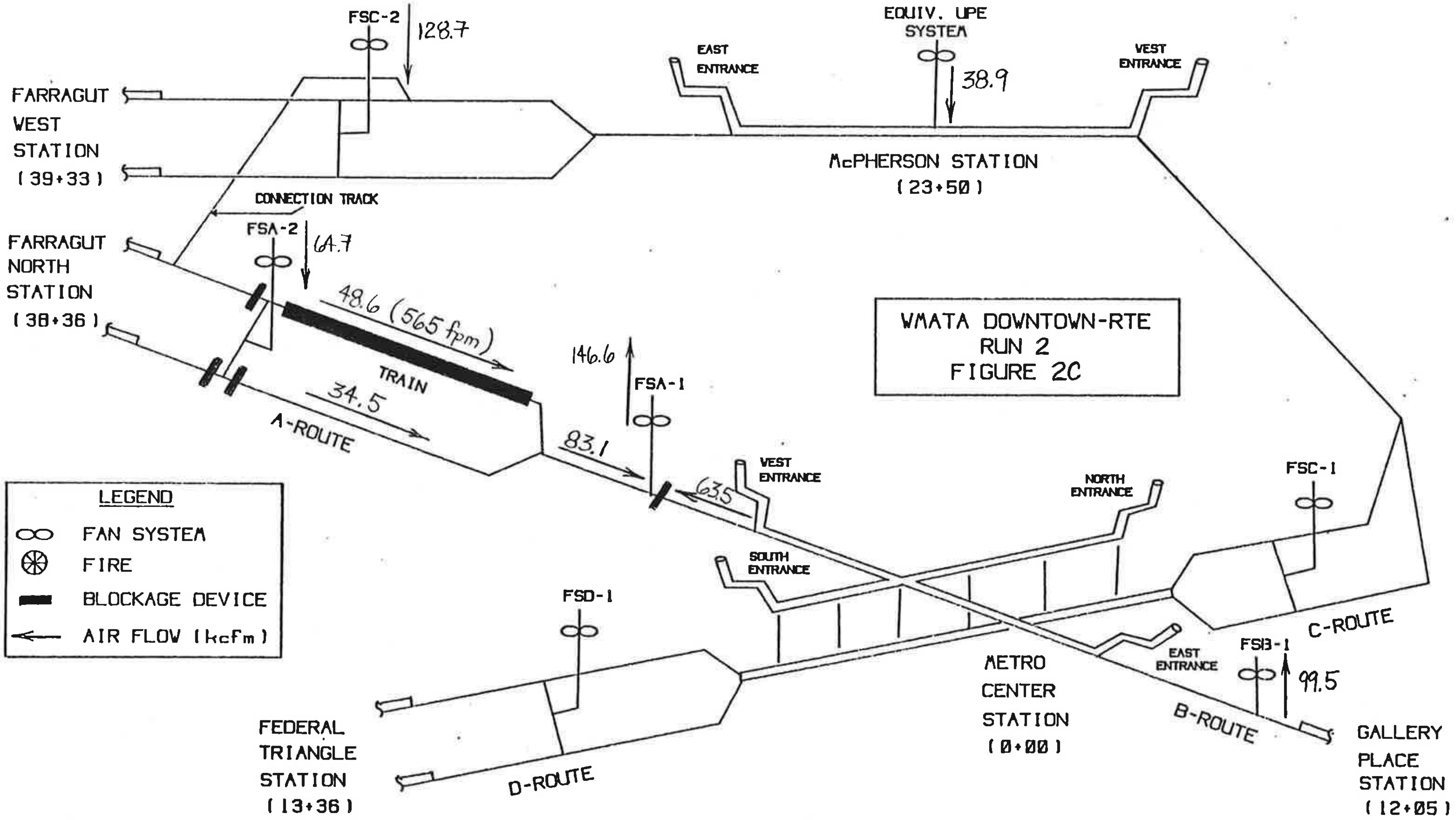
This run investigated the use of jet fans as analternative to blockage devices for increasing ventilation by the train.

The conditions for this aerodynamic simulation remained as in Run 12 except that where blockage devices had been used, the effect of operating jet fans in the tunnel sections was simulated. The jet fan capacity was selected such that the pressure differentials created by operating the jet fans would duplicate those of the blockage devices. This required that the jet fans deliver approximately 300 pounds of thrust in each of the three tunnel sections.

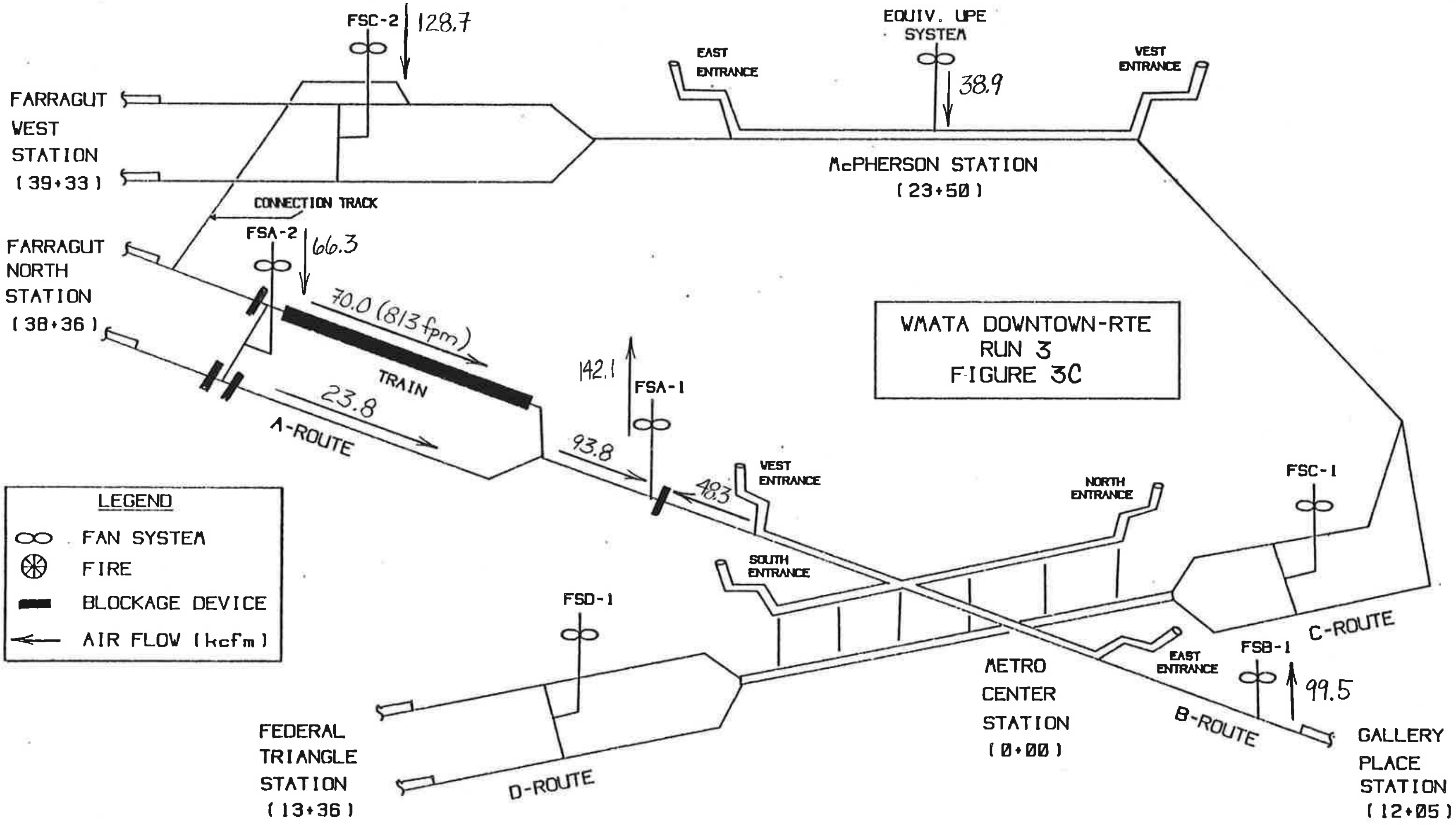
The results of the simulation, when compared to Run

12, show that the effect of blockage devices can be closely duplicated by using jet fans. A fire simulation confirmed the potential effectiveness of using jet fans, in lieu of blockage devices, to prevent back-layering.

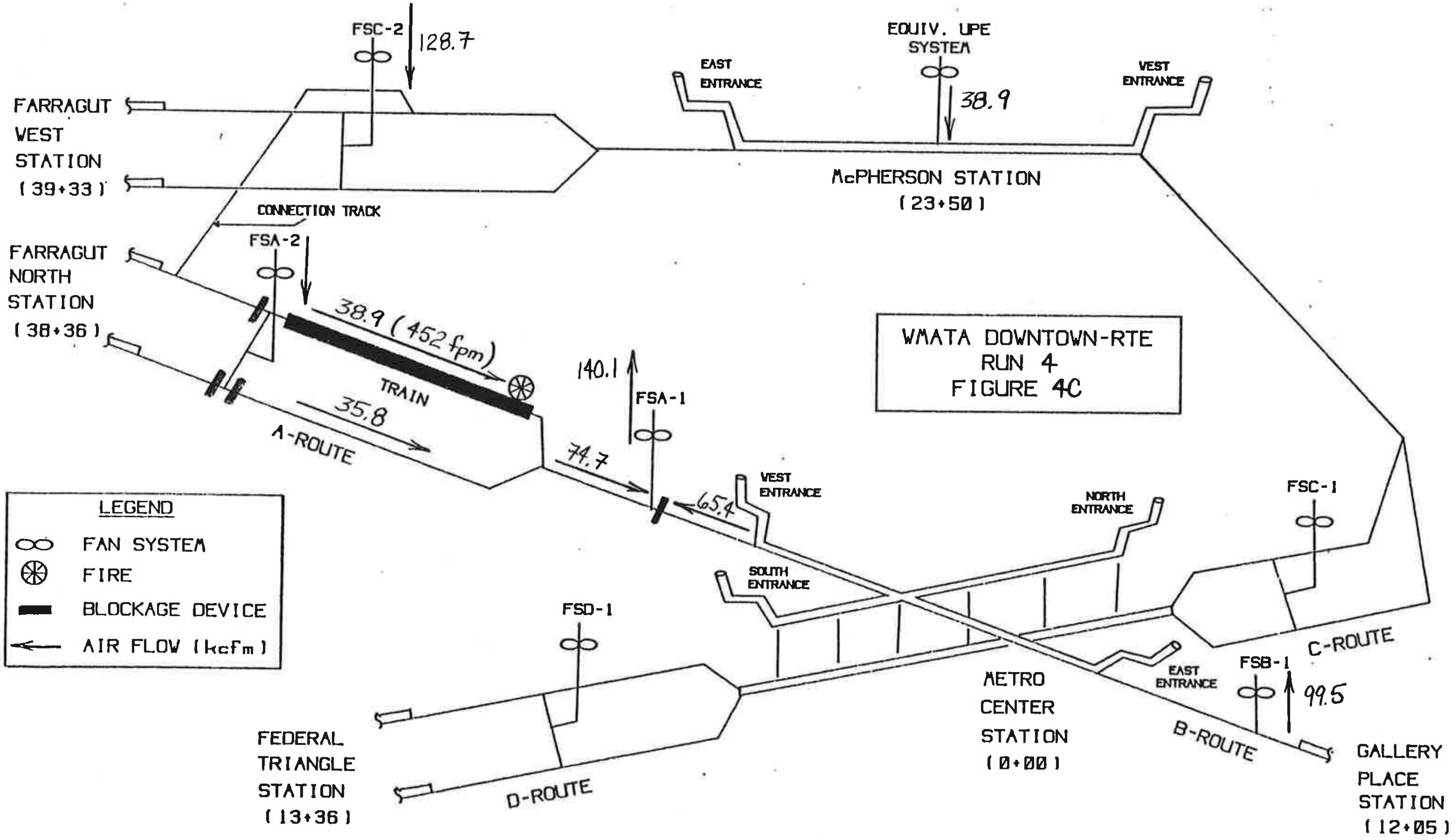

FSC-2
128.7
EQUIV. UPE SYSTEM
38.9
EAST ENTRANCE
WEST ENTRANCE
FARRAGUT WEST STATION (39+33)
McPHERSON STATION (23+50)
CONNECTION TRACK
FSA-2
64.6
FARRAGUT NORTH STATION (38+36)
18.0 (209 fpm)
TRAIN
40.4
A-ROUTE
149.2
FSA-1
58.4
90.8
WVMATA DOWNTOWN-RTE
RUN 1
FIGURE 1C
WEST ENTRANCE
NORTH ENTRANCE
SOUTH ENTRANCE
FSC-1
C-ROUTE
LEGEND
FAN SYSTEM
FIRE
BLOCKAGE DEVICE
AIR FLOW (kcfm)
FSD-1
FEDERAL TRIANGLE STATION (13+36)
D-ROUTE
METRO CENTER STATION (0+00)
EAST ENTRANCE
FSB-1
99.5
B-ROUTE
GALLERY PLACE STATION (12+05)

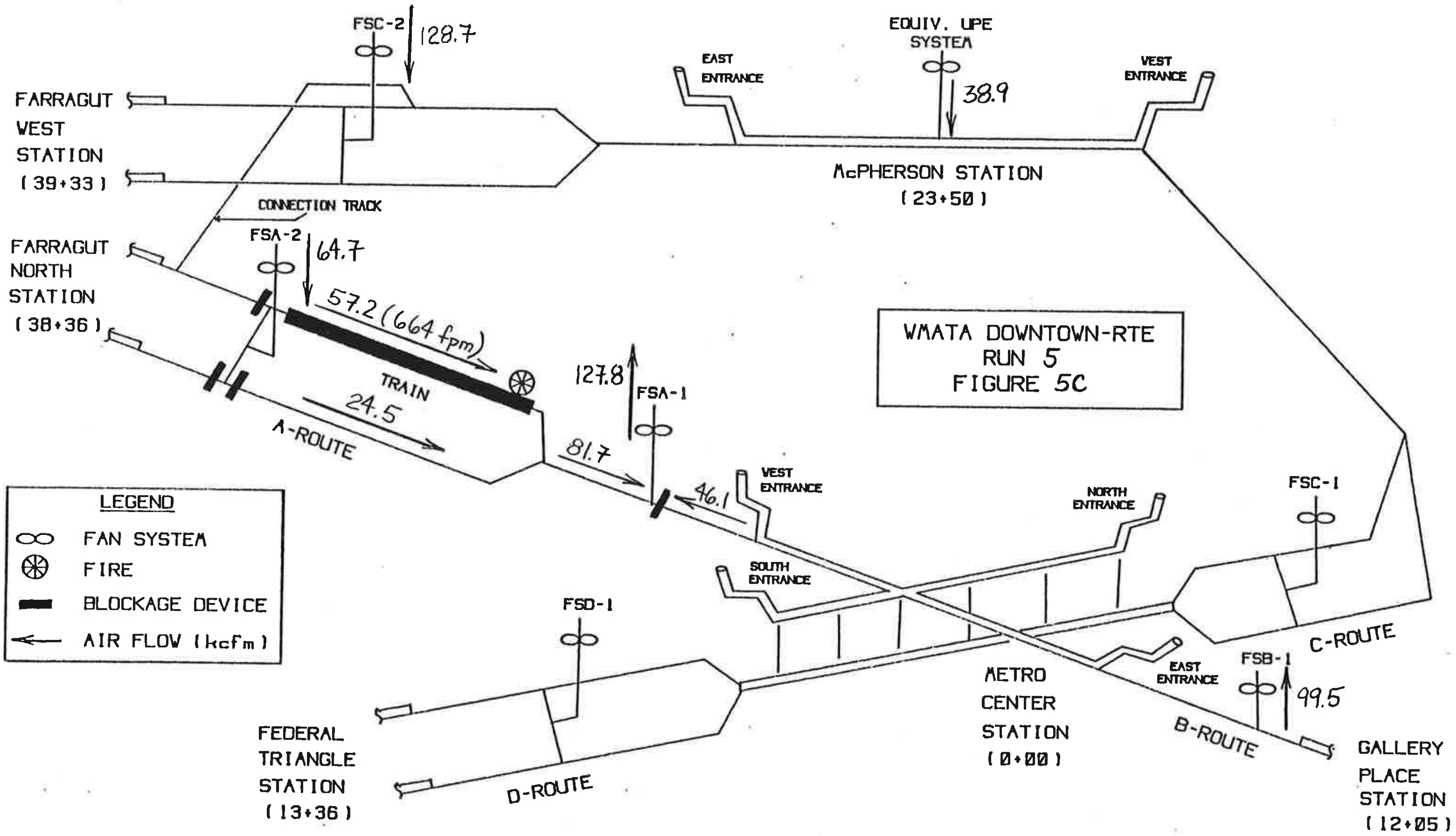


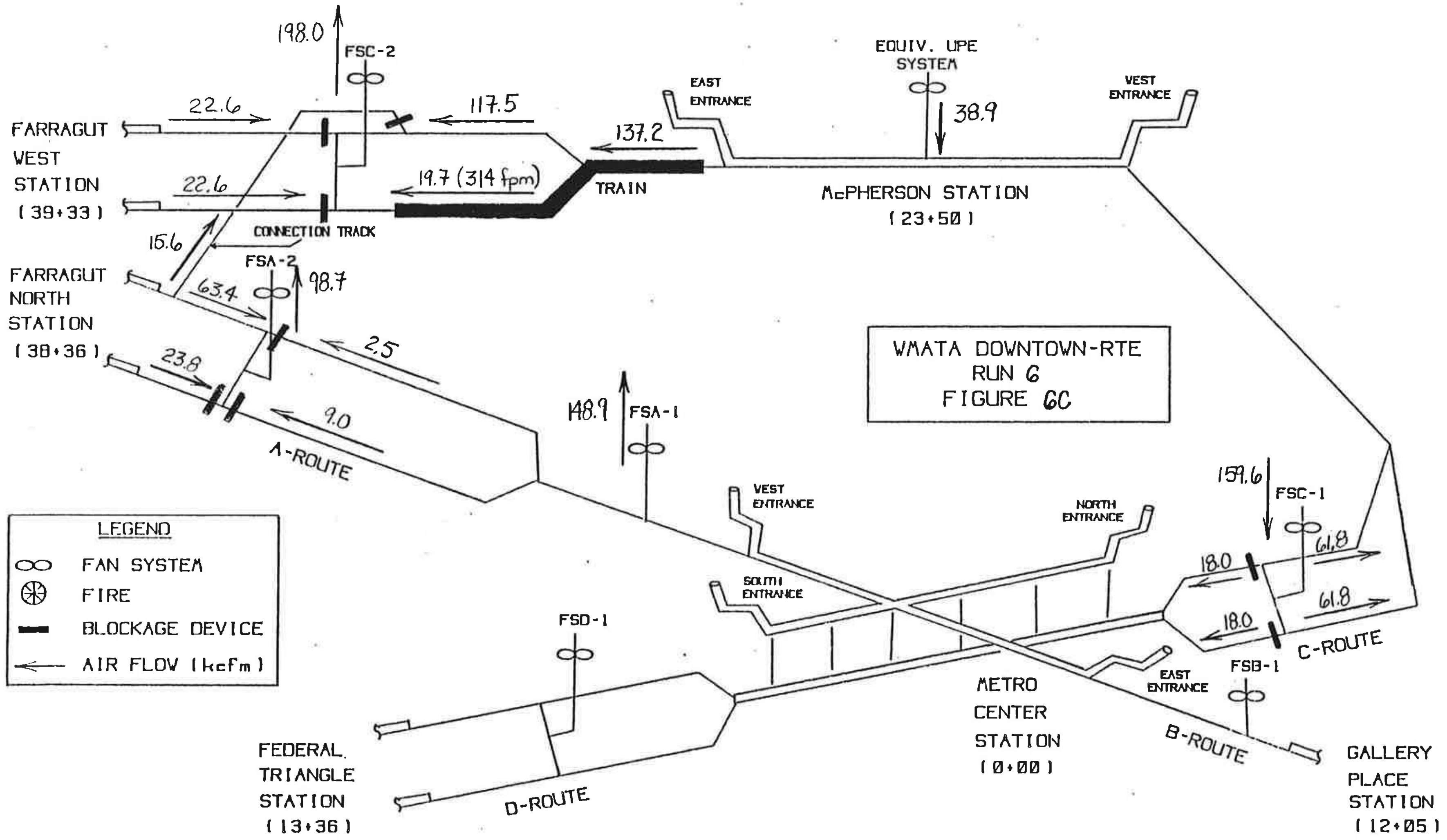
WMATA DOWNTOWN-RTE
RUN 2
FIGURE 2C

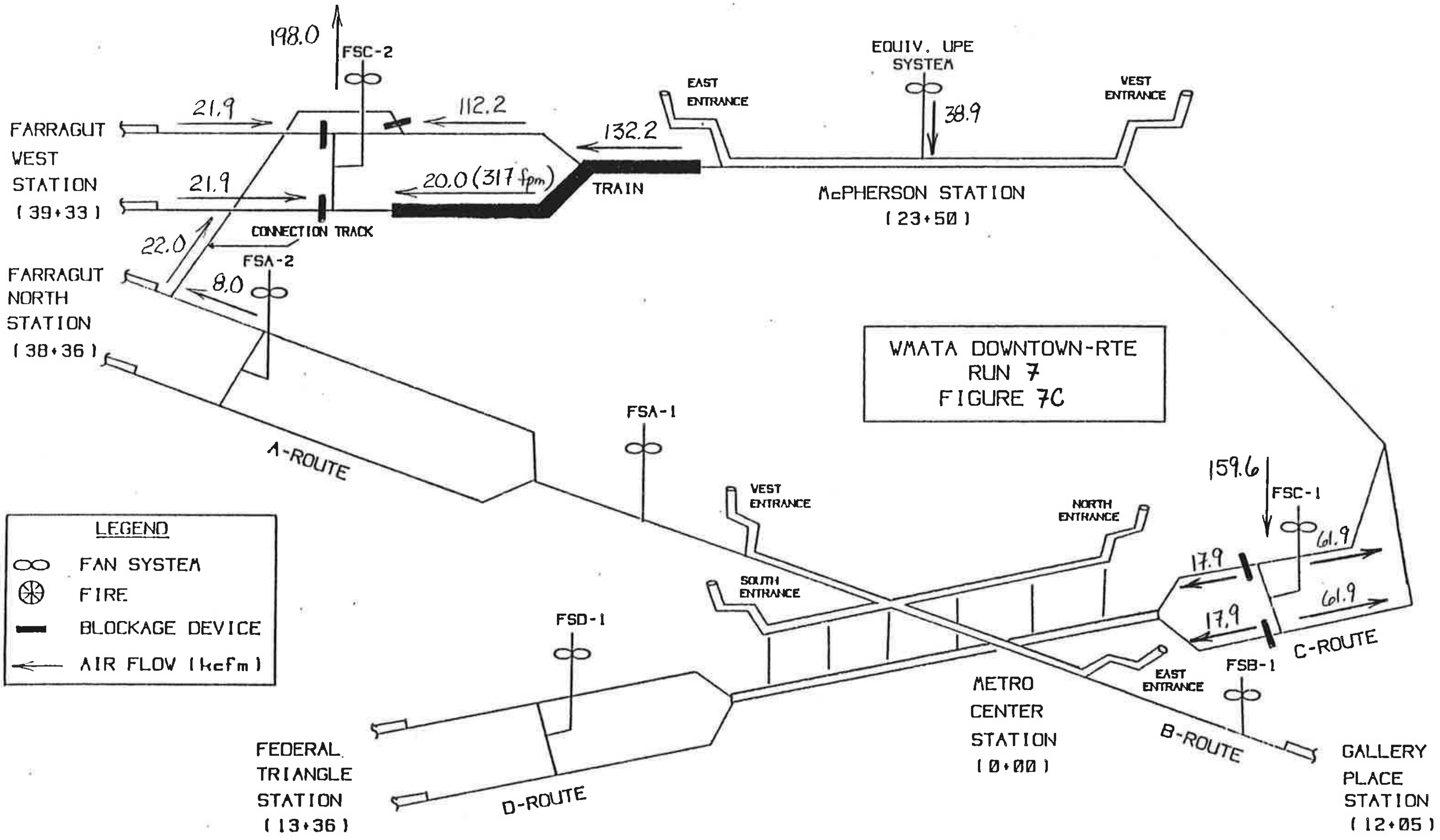


WMATA DOWNTOWN-RTE
RUN 3
FIGURE 3C

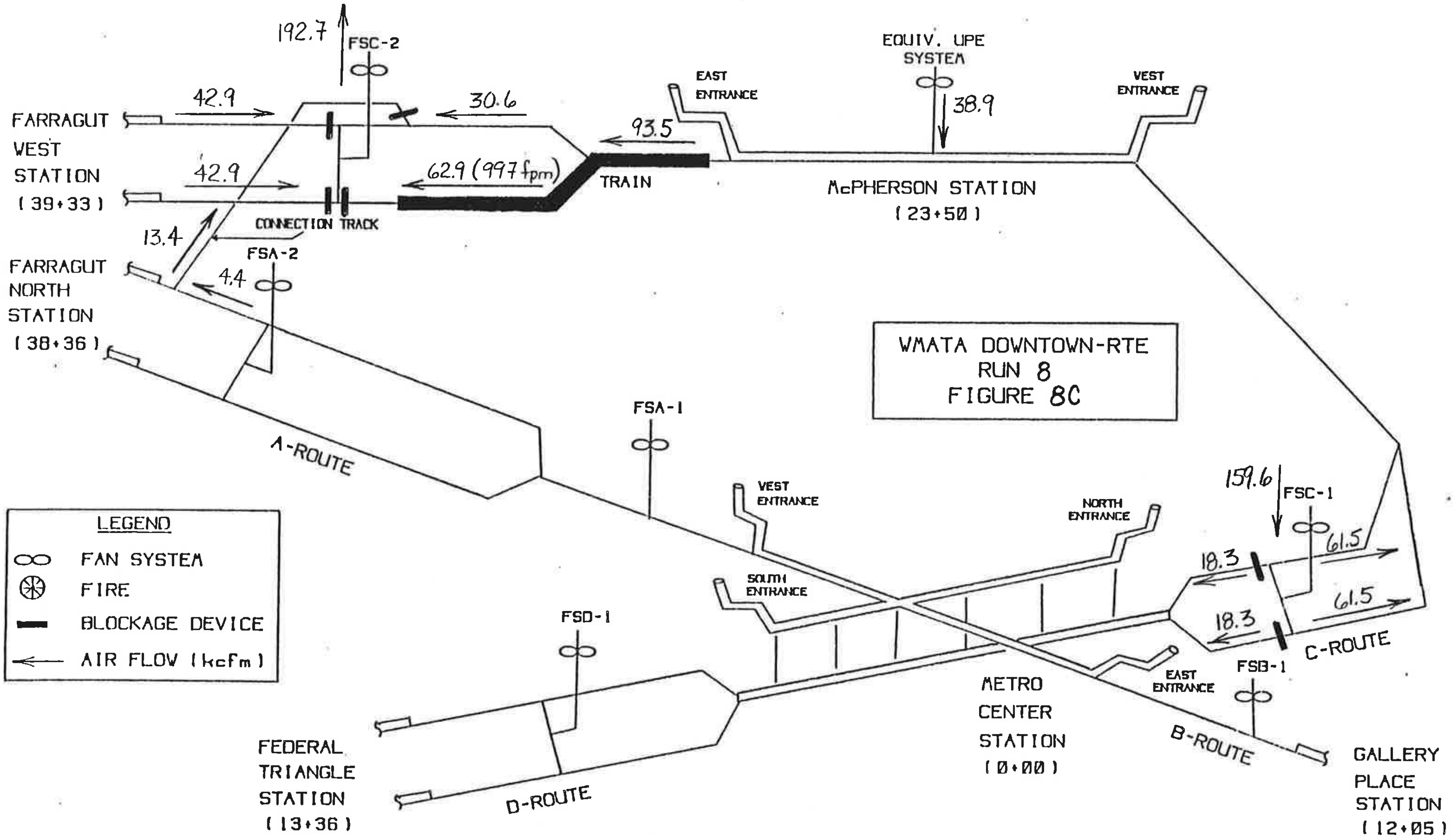

VMATA DOWNTOWN-RTE
RUN 4
FIGURE 4C
FARRAGUT WEST STATION (39+33)
FSC-2
128.7
EAST ENTRANCE
EQUIV. UPE SYSTEM
38.9
VEST ENTRANCE
McPHERSON STATION (23+50)
CONNECTION TRACK
FARRAGUT NORTH STATION (38+36)
FSA-2
38.9 (452 fpm)
TRAIN
35.8
A-ROUTE
140.1
FSA-1
74.7
65.4
VEST ENTRANCE
SOUTH ENTRANCE
NORTH ENTRANCE
FSC-1
C-ROUTE
EAST ENTRANCE
FSB-1
99.5
B-ROUTE
METRO CENTER STATION (0+00)
GALLERY PLACE STATION (12+05)
FSD-1
D-ROUTE
FEDERAL TRIANGLE STATION (13+36)
LEGEND
FAN SYSTEM
FIRE
BLOCKAGE DEVICE
AIR FLOW (kcfm)


FSC-2
128.7
EQUIV. UPE SYSTEM
38.9
EAST ENTRANCE
VEST ENTRANCE
FARRAGUT VEST STATION (39+33)
McPHERSON STATION (23+50)
CONNECTION TRACK
FSA-2
64.7
FARRAGUT NORTH STATION (38+36)
57.2 (664 fpm)
TRAIN
24.5
A-ROUTE
127.8
FSA-1
81.7
46.1
VEST ENTRANCE
WMATA DOWNTOWN-RTE
RUN 5
FIGURE 5C
LEGEND
FAN SYSTEM
FIRE
BLOCKAGE DEVICE
AIR FLOW (kcfm)
NORTH ENTRANCE
FSC-1
SOUTH ENTRANCE
FSD-1
C-ROUTE
EAST ENTRANCE
FSB-1
99.5
METRO CENTER STATION (0+00)
B-ROUTE
GALLERY PLACE STATION (12+05)
FEDERAL TRIANGLE STATION (13+36)
D-ROUTE

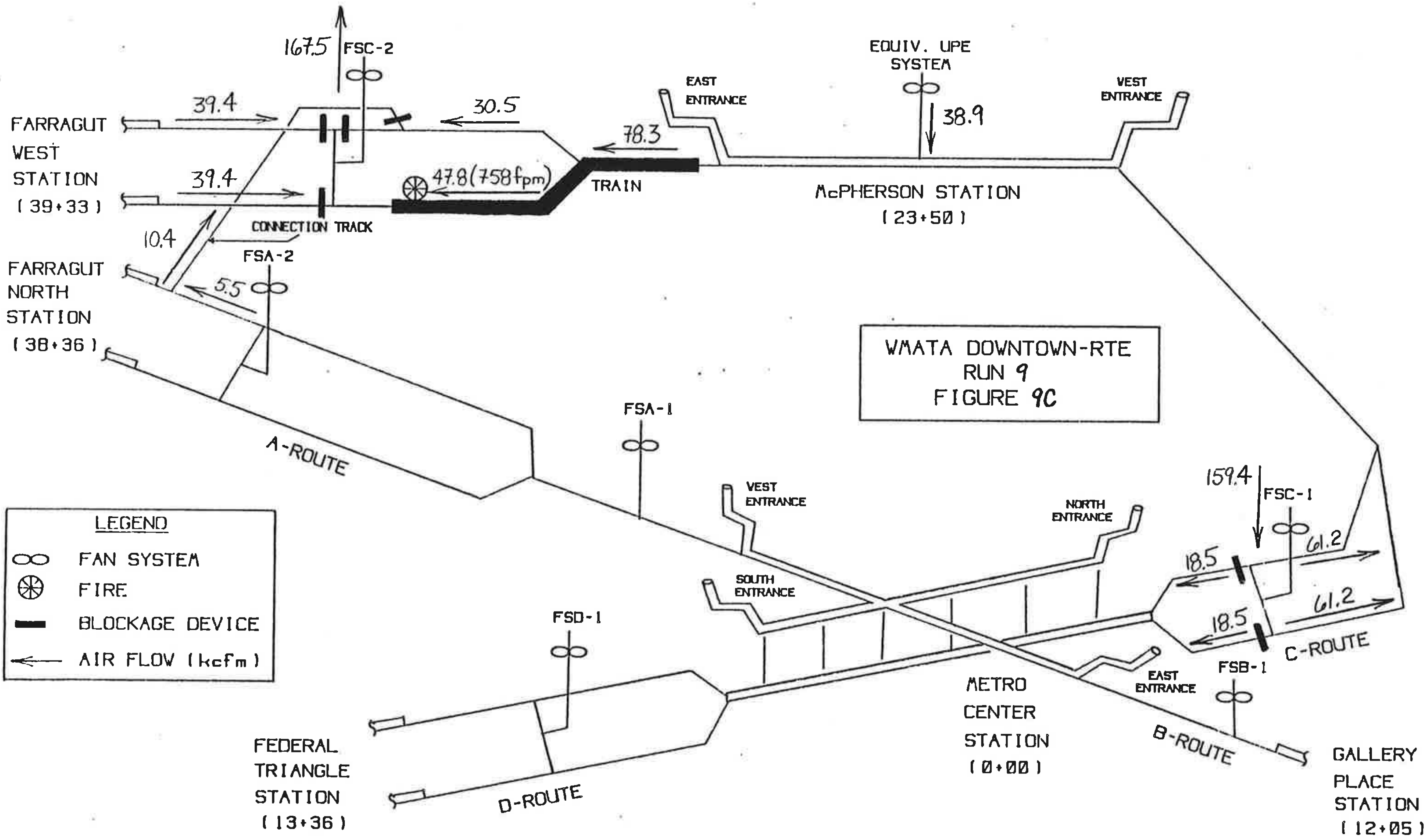

198.0
FSC-2
22.6
117.5
137.2
EAST ENTRANCE
EQUIV. UPE SYSTEM
38.9
WEST ENTRANCE
FARRAGUT WEST STATION (39+33)
22.6
19.7 (314 fpm)
TRAIN
McPHERSON STATION (23+50)
CONNECTION TRACK
15.6
FSA-2
98.7
FARRAGUT NORTH STATION (38+36)
63.4
2.5
23.8
9.0
A-ROUTE
VMATA DOWNTOWN-RTE
RUN 6
FIGURE 6C
148.9
FSA-1
159.6
FSC-1
WEST ENTRANCE
NORTH ENTRANCE
61.8
18.0
SOUTH ENTRANCE
18.0
61.8
C-ROUTE
LEGEND
FAN SYSTEM
FIRE
BLOCKAGE DEVICE
AIR FLOW (kcfm)
FSD-1
EAST ENTRANCE
FSB-1
METRO CENTER STATION (0+00)
B-ROUTE
GALLERY PLACE STATION (12+05)
FEDERAL TRIANGLE STATION (13+36)
D-ROUTE

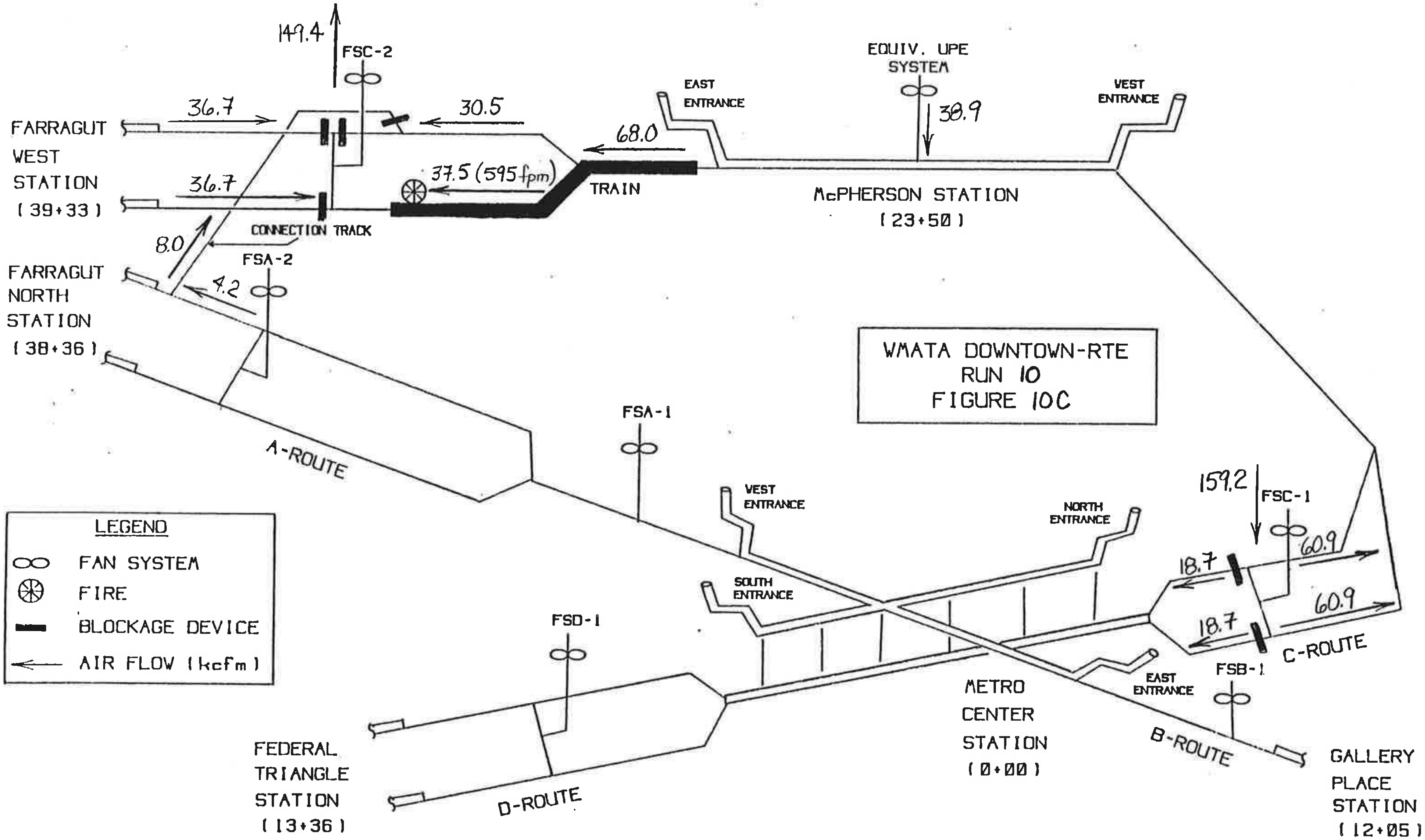


WMATA DOWNTOWN-RTE
RUN 7
FIGURE 7C

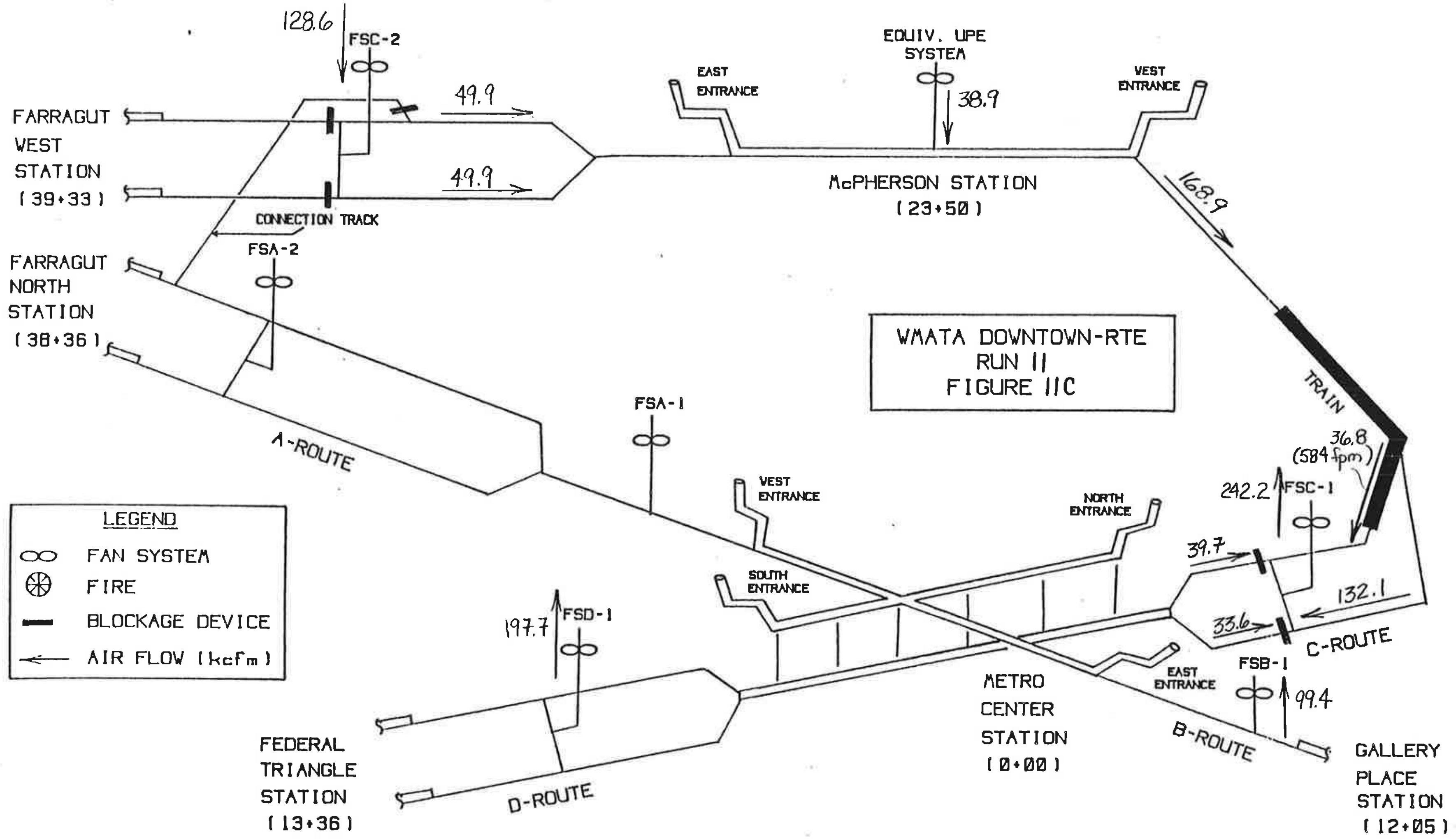


VMATA DOWNTOWN-RTE
RUN 8
FIGURE 8C

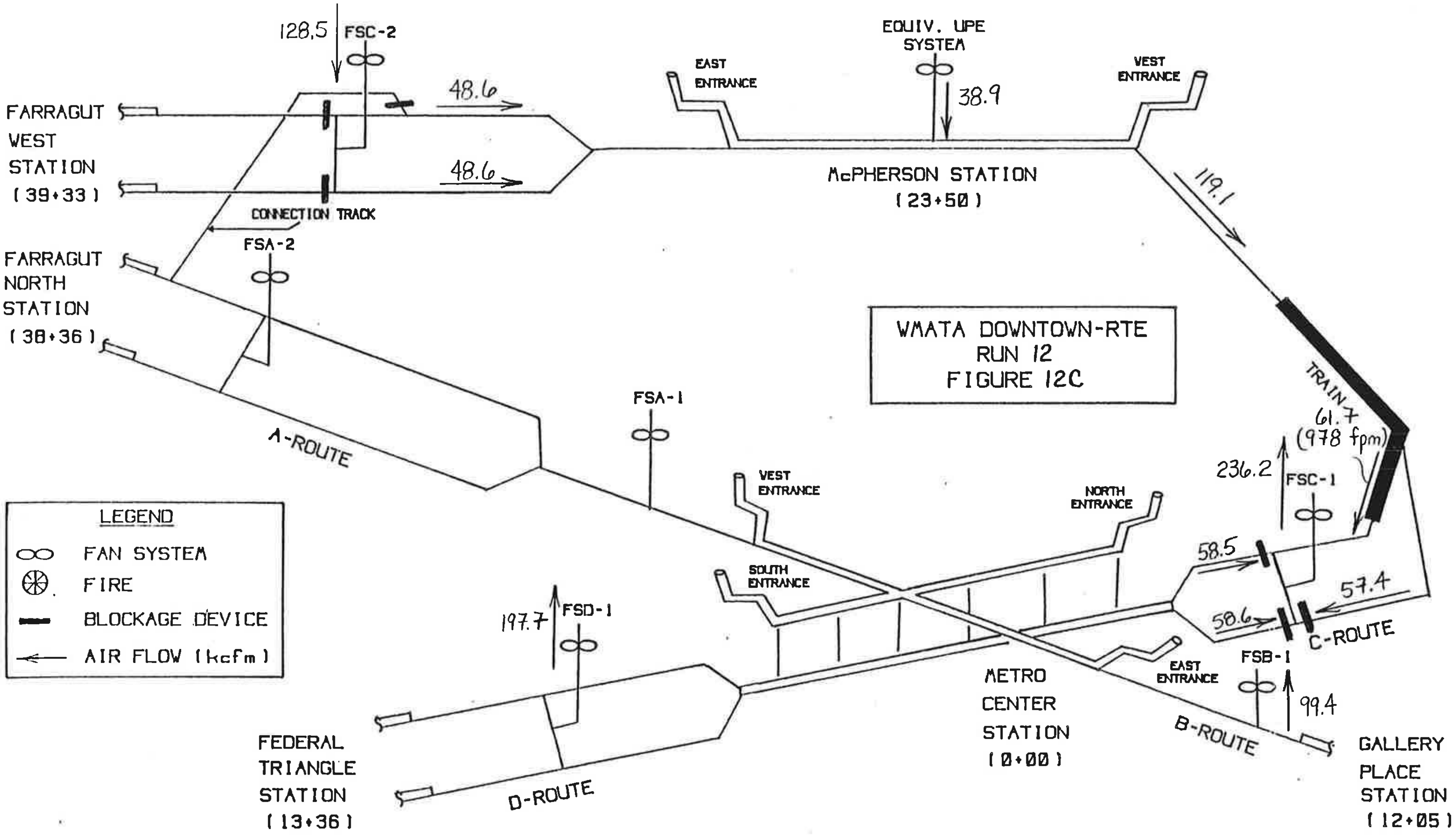

VMATA DOWNTOWN-RTE
RUN 9
FIGURE 9C
LEGEND
FAN SYSTEM
FIRE
BLOCKAGE DEVICE
AIR FLOW (kcfm)
167.5
FSC-2
39.4
30.5
78.3
FARRAGUT
WEST
STATION
(39+33)
39.4
47.8(758fpm)
TRAIN
CONNECTION TRACK
10.4
FSA-2
5.5
FARRAGUT
NORTH
STATION
(38+36)
EAST
ENTRANCE
EQUIV. UPE
SYSTEM
38.9
WEST
ENTRANCE
McPHERSON STATION
(23+50)
A-ROUTE
FSA-1
WEST
ENTRANCE
NORTH
ENTRANCE
159.4
FSC-1
61.2
18.5
18.5
61.2
SOUTH
ENTRANCE
FSD-1
EAST
ENTRANCE
FSB-1
C-ROUTE
METRO
CENTER
STATION
(0+00)
B-ROUTE
GALLERY
PLACE
STATION
(12+05)
FEDERAL
TRIANGLE
STATION
(13+36)
D-ROUTE



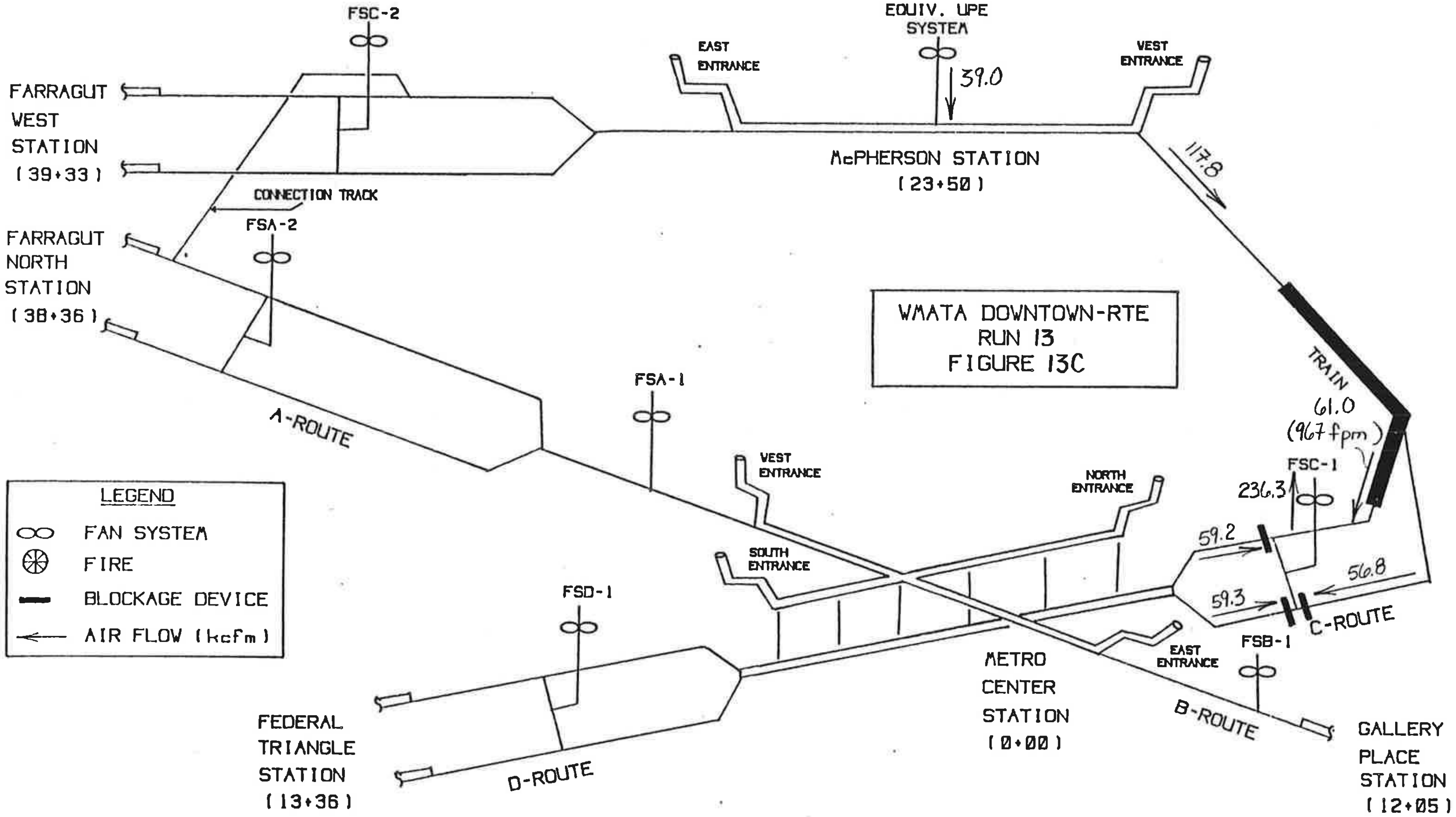
WMATA DOWNTOWN-RTE
RUN 10
FIGURE 10C

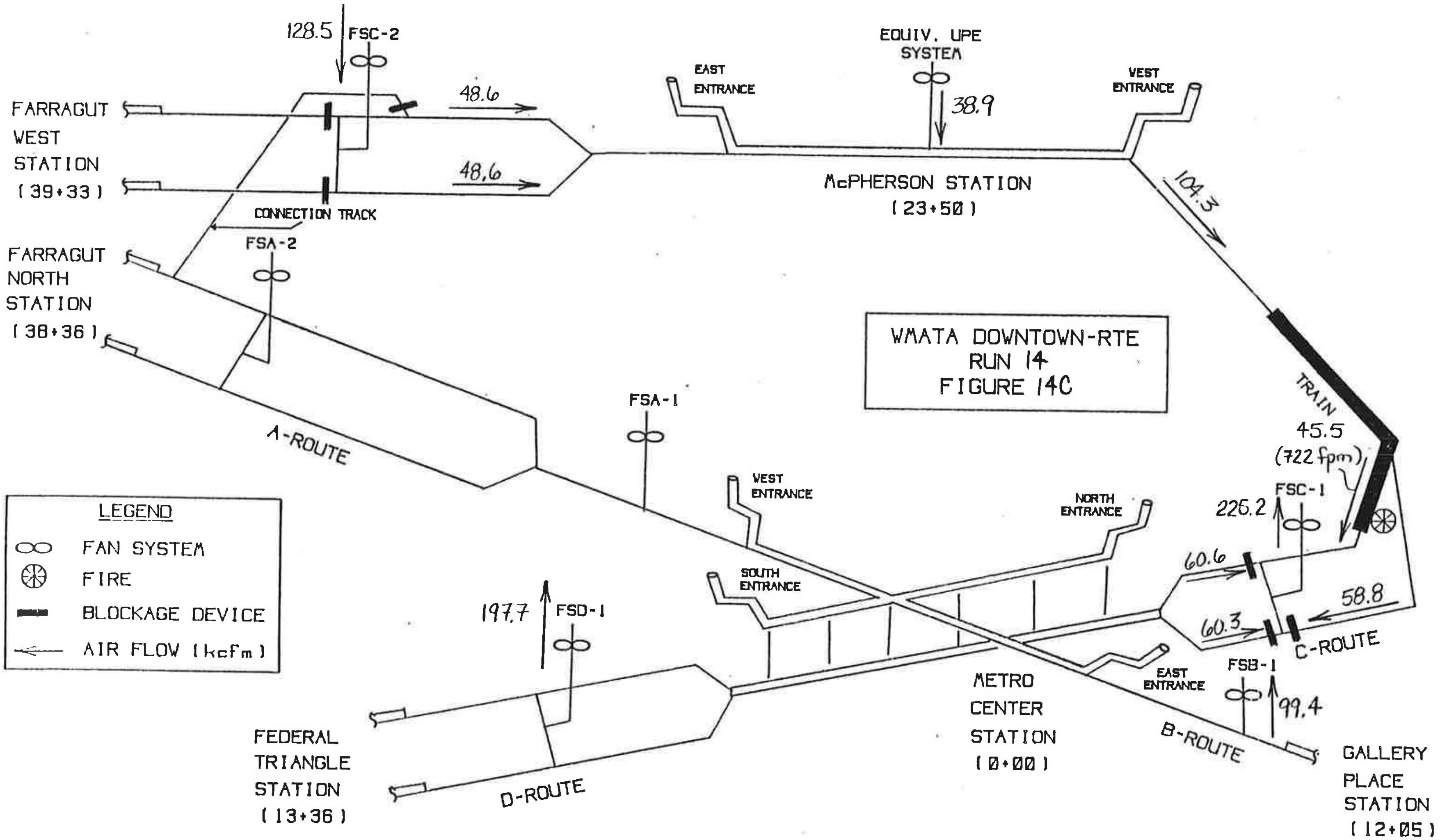


WMATA DOWNTOWN-RTE
RUN 11
FIGURE 11C

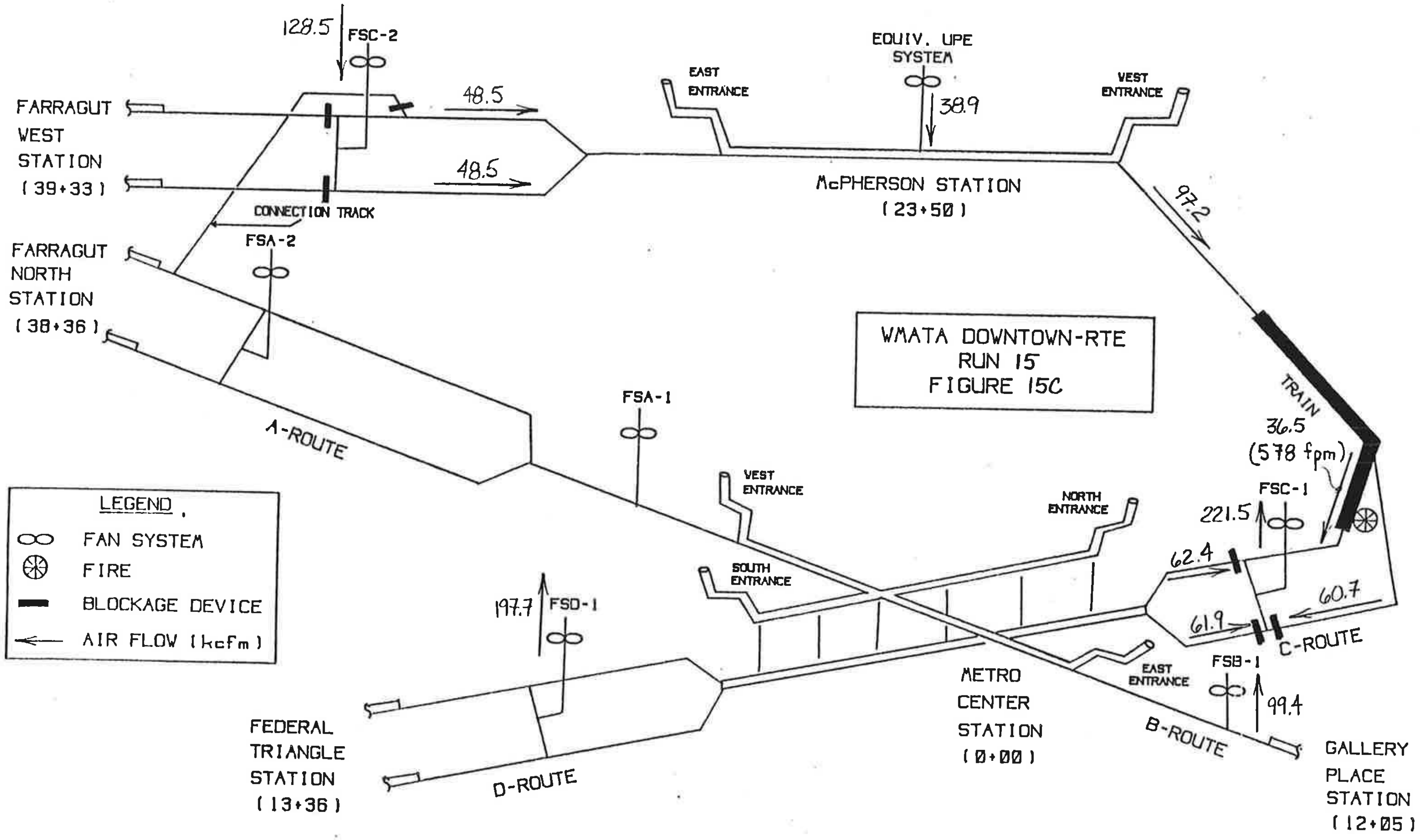


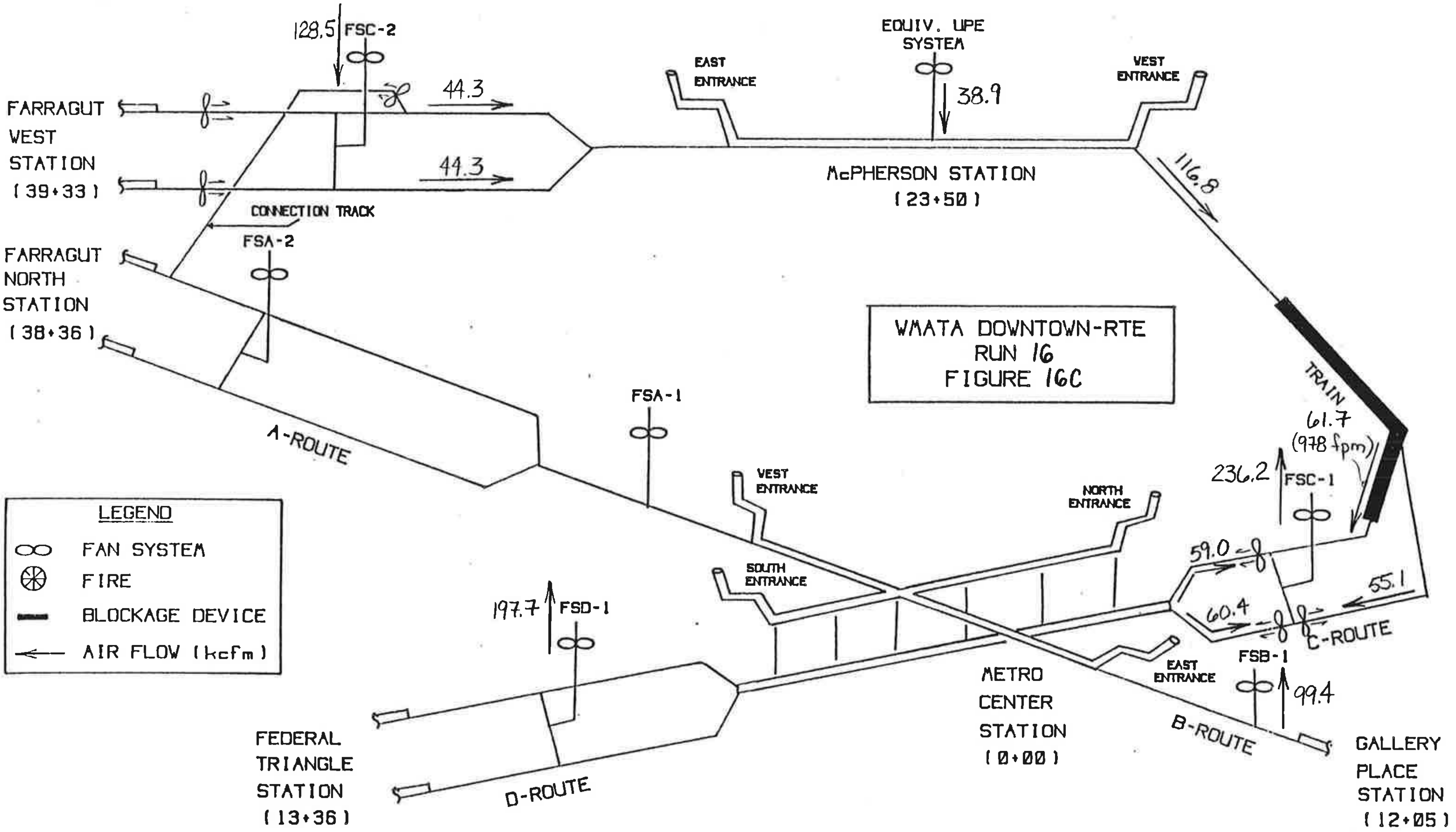
WMATA DOWNTOWN-RTE
RUN 12
FIGURE 12C


VMATA DOWNTOWN-RTE
RUN 13
FIGURE 13C
FSC-2
EQUIV. UPE SYSTEM
39.0
EAST ENTRANCE
VEST ENTRANCE
FARRAGUT WEST STATION (39+33)
McPHERSON STATION (23+50)
117.8
CONNECTION TRACK
FSA-2
FARRAGUT NORTH STATION (38+36)
TRAIN
61.0
(967 fpm)
A-ROUTE
FSA-1
FSC-1
236.3
VEST ENTRANCE
NORTH ENTRANCE
59.2
56.8
SOUTH ENTRANCE
59.3
C-ROUTE
FSD-1
EAST ENTRANCE
FSB-1
METRO CENTER STATION (0+00)
B-ROUTE
GALLERY PLACE STATION (12+05)
FEDERAL TRIANGLE STATION (13+36)
D-ROUTE
LEGEND
FAN SYSTEM
FIRE
BLOCKAGE DEVICE
AIR FLOW (kcfm)



WMATA DOWNTOWN-RTE
RUN 14
FIGURE 14C


WMATA DOWNTOWN-RTE
RUN 15
FIGURE 15C
LEGEND
FAN SYSTEM
FIRE
BLOCKAGE DEVICE
AIR FLOW (kcfm)
FARRAGUT WEST STATION (39+33)
FARRAGUT NORTH STATION (38+36)
CONNECTION TRACK
FSC-2
128.5
48.5
48.5
FSA-2
A-ROUTE
FSA-1
EAST ENTRANCE
EQUIV. UPE SYSTEM
38.9
WEST ENTRANCE
McPHERSON STATION (23+50)
97.2
TRAIN
36.5
(578 fpm)
FSC-1
221.5
62.4
60.7
61.9
C-ROUTE
WEST ENTRANCE
NORTH ENTRANCE
SOUTH ENTRANCE
EAST ENTRANCE
FSB-1
99.4
B-ROUTE
GALLERY PLACE STATION (12+05)
METRO CENTER STATION (0+00)
FSD-1
197.7
D-ROUTE
FEDERAL TRIANGLE STATION (13+36)


128.5
FSC-2
44.3
44.3
FARRAGUT
WEST
STATION
(39+33)
CONNECTION TRACK
FSA-2
FARRAGUT
NORTH
STATION
(38+36)
A-ROUTE
EAST
ENTRANCE
EQUIV. UPE
SYSTEM
38.9
WEST
ENTRANCE
McPHERSON STATION
(23+50)
116.8
WMATA DOWNTOWN-RTE
RUN 16
FIGURE 16C
TRAIN
61.7
(978 fpm)
236.2
FSC-1
FSA-1
WEST
ENTRANCE
NORTH
ENTRANCE
SOUTH
ENTRANCE
59.0
60.4
55.1
C-ROUTE
LEGEND
FAN SYSTEM
FIRE
BLOCKAGE DEVICE
AIR FLOW (kcfm)
197.7
FSD-1
EAST
ENTRANCE
FSB-1
99.4
METRO
CENTER
STATION
(0+00)
B-ROUTE
GALLERY
PLACE
STATION
(12+05)
FEDERAL
TRIANGLE
STATION
(13+36)
D-ROUTE

APPENDIX D

FIRE MODEL

The SES Fire Model is a quasi-steady state, one-dimensional model capable of simulating the overall effects of a tunnel fire on the airflow induced by the ventilation system. It can indicate whether or not the ventilating airflows are sufficient to prevent back-layering when compared with the critical velocity. If the ventilating air moving toward the fire is equal to or exceeds the critical velocity, then back-layering is precluded.

The critical velocity is determined from the following coupled equations:

$$Vc = Kg \cdot K \cdot \left(\frac{g \cdot H \cdot Q}{Cp \cdot \rho_\infty \cdot A \cdot T_f} \right)^{1/3} \qquad \text{Equation 1}$$

$$Tf = \frac{Q}{Cp \cdot \rho_\infty \cdot A \cdot Vc} + T_\infty \qquad \text{Equation 2}$$

Where:

Vc = critical velocity, ft/sec
g = acceleration due to gravity, ft/sec^2
H = tunnel height, ft
Q = fire heat release rate, Btu/sec
ρ_∞ = ambient air density, lbm/ft^3
Cp = specific heat of air at constant pressure,
Btu lbm-deg R
A = net cross-sectional area of tunnel, ft^2
Tf = hot gas temperature, deg R
K = 0.61 (dimensionless)
Kg = grade correction factor (dimensionless)
T_∞ = ambient temperature, deg R

The simultaneous solution of these two equations determines the critical velocity. The velocity of the ventilating air moving toward the fire, to which this criterion must be applied, is provided by the SES fire model.

The SES program has the ability to model the effects of a subway fire by considering various aerodynamic and thermodynamic factors. The first of these is the throttling effect that a tunnel fire has on the ventilating airflow. This is caused by the rapid expansion of the hot air around the fire site, and the consequent impingement on the airflow past the fire site. Also, as a consequence of the law of conservation of mass, the velocity of the hot gases downstream of the fire increases inversely proportional to the density (or equivalently, directly proportional to the absolute temperature of the gases), hence increasing the viscous pressure losses in this section of the tunnel. These pressure changes will reduce the tunnel airflow. The density differences between the hot gases and the ambient air give rise to pressure differentials which can either augment or retard the tunnel airflows, depending on the direction of ventilation (uphill or downhill). The elevated air temperatures produced by a fire cause the tunnel walls to heat up. This transient heating of the wall surface is an important factor in determining the conditions downwind of the fire. Allowing the wall surface temperature to respond properly improves the accuracy of the predicted air temperatures which are subsequently used to calculate the buoyant pressure differential.

The model treats the wall as a one-dimensional slab of infinite thickness with uniform thermal properties and an arbitrary time-dependent heat flux at the wall surface. This approach is appropriate because firstly, temperature changes resulting from heating at the wall surface will be confined to within a short distance of the wall surface, and secondly the wall surface temperature is of interest rather than the temperature at some depth below the surface.

The heat conduction equation is solved by using an approximate integral method. This method was chosen because it requires relatively little computation time, and provides good accuracy (results range from 3 percent to 9 percent of the theoretical value).

Heat is transferred to the wall by convection and radiation. Radiation will be the dominant mode of heat transfer at the fire site, while downwind of the fire, both modes will be nearly the same order of magnitude.

At the site of the fire, heat is radiated from the flame directly to the tunnel wall at an "effective fire temperature". The effective fire temperature and a parameter called the equivalent fire area are input items. Downwind of the fire site, the hot smoke is assumed to be radiating to the tunnel wall at a temperature equivalent to the "bulk" air temperature at a given location. Only radiation effects in the transverse direction from smoke to tunnel wall are considered.

The changes in air density associated with elevated temperatures affect the performance characteristics (pressure vs. volume flow curve) of the exhaust fans. These effects have been accounted for in the model.

A typical application of the fire model consists of the following steps:

- Perform an SES simulation to determine the tunnel air velocity and the hot air temperature.
- Determine the required air velocity from the simultaneous solution of the two equations given previously.
- If the predicted air velocity exceeds the required air velocity, the ventilation system is considered adequate.

- If the predicted air velocity is less than the criterion, change the system and repeat the process.

Note that the SES is essentially a one-dimensional, incompressible, turbulent, slug-flow model. The throttling and buoyancy effects which are primarily caused by changes in density are conveniently accounted for by noting that changes in density are inversely proportional to changes in the absolute temperature of the gas (air), a quantity which is computed by the program.

The SES Fire Model has been designed with the ability to simulate the "overall" effects of a tunnel fire on the ventilation system. This level of detail is considered sufficient for evaluating the adequacy of an emergency ventilation system.

APPENDIX E

DESCRIPTION OF B-ROUTE NETWORK

General Route: The B-Route network simulated, shown in Figure 1, runs from the portal outbound of Silver Spring Station at Sta. 480+30 to the portal outbound of Glenmont Station Sta. 1230+60. There are three stations on the route: Forest Glen Station, Wheaton Station and Glenmont Station. Forest Glen Station is located at Sta. 1036+94 to 1038+94. Wheaton Station is located at Sta. 1112+32 to Sta. 1114+32, and Glenmont Station is at Sta. 1214+65 to 1217+65. The route is scheduled for revenue service during the next decade.

Fan Shafts and Evacuation Routes: There are five fan shafts and one dedicated evacuation shaft. Fan shaft 5 (FSB-5) is located at Sta. 1017+19, (between the portal and Forest Glen Station). Fan shaft 6 (FSB-6) is at Sta. 1057+48 and Fan shaft 7 (FSB-7) is at Sta. 1101+39, both of which are between Forest Glen Station and Wheaton Station. Fan shaft 8 (FSB-8) and fan shaft 9 (FSB-9) are located at Sta. 1147+97 and Sta. 1191+67, respectively, between Wheaton Station and Glenmont Station. The dedicated evacuation shaft (EB-1) is located at Sta. 982+43. During an emergency, fan shafts and stations can also be evacuation routes and exits.

Tunnel Structures: From the portal to Sta. 964+80 the tunnel is a double box section. Single track rock tunnels run from Sta. 964+80 to Sta. 1203+68. A cut-and-cover tunnel section runs from Sta. 1203+68 to 1224+88. Another double box section runs from Sta. 1224+88 to the portal at Sta. 1230+60.

Route Grades: The grades along the route are between -3.3% and +4.0%. The tunnel section from the portal to Sta.

1014+43 has a grade of -3.3%. The tunnel section from Sta. 1014+43 to Sta. 1092+57 has a +0.35% grade. From Sta. 1092+57 to Sta. 1117+50, the grade is +4.0%. From Sta. 1117+50 to 1128+69, the grade is +0.35%. The section from Sta. 1128+69 to 1142+60 has a -2.8% grade. From Sta. 1142+60 to 1174+50, the grade is +0.35%. The section between Sta. 1174+50 and 1206+60 has +3.95% grade. From Sta. 1206+60 to 1225+13 the grade is -0.35%. From Sta. 1225+13 to 1229+13 and from Sta. 1229+13 to 1230+60, the grades are +0.49% and +0.35%, respectively.

DESCRIPTION OF DOWNTOWN ROUTE

General Route: The Downtown network used in this analysis consists of four lines: (A-Route, B-Route, C-Route and D-Route), intersecting at a transfer station (Metro Center Station). A connection service track joins C-Route with A-Route. The C-Route runs from Farragut West Station at Sta. 39+33 to Metro Center Station at Sta. 0+00, going through McPherson Square Station at Sta. 23+50. The D-Route begins at Metro Center Station and runs to Federal Triangle Station at Sta. 13+36. The A-Route extends from Farragut North Station Sta. 38+36 to Metro Center Station. The B-Route begins at Metro Center Station and ends at Sta. 12+05. The ends of the network are modeled by the equivalent aerodynamic effects of the four surrounding stations mentioned.

Fan Shafts: The network includes six fan shafts. On the C-Route, fan shaft FSC-2 is located at Sta. 33+00, between Farragut West Station and McPherson Square Station; fan shaft FSC-1 is located at Sta. 8+50 between McPherson Square Station and Metro Center Station. Fan shaft FSD-1 is located on the D-Route at Sta. 7+30 between Metro Center Station and Federal Triangle Station. The A-Route and B-Route include fan shafts

FSA-1, FSA-2 and FSB-1. Fan shafts FSA-1 and FSA-2 are located between Farragut North Station and Metro Center Station, at Sta. 12+02 and Sta. 28+75, respectively. FSB-1 is between Metro Center Station and Gallery Place Station, at Sta. 7+80.

Tunnel Structures: The A-Route is comprised of single track, horseshoe-shaped tunnels from Sta. 38+36 to Sta. 15+10. Double track, cut-and-cover sections run from Sta. 15+10 to Sta. 3+00 on A-Route and from Sta. 3+00 to Sta. 12+05 on the B-Route. These sections have a continuous concrete dividing wall with refuge openings.

The C-Route has a double track cut-and-cover section from Sta. 39+33 to Sta. 26+50, with the continuous concrete dividing wall ending at Sta. 29+82. Columns divide the tracks in the section from Sta. 29+82 to Sta. 26+50. Similarly, on the other side of McPherson Square Station, columns run from Sta. 20+50 to Sta. 17+41, where the continuous concrete dividing wall with refuge openings begins. This section runs from Sta. 17+41 to Sta. 13+75. At Sta. 13+75, the cross section changes to single track circular tunnels, which extend to Metro Center Station. Similar circular tunnels on the D-Route extend from Metro Center Station to Sta. 13+36. The connection track, running from the outbound track of C-Route to the outbound track of A-Route, is a single track horseshoe-shaped tunnel.

Route Grades: The C-Route, from Farragut West Station to Metro Center Station, has the following grades: -0.35% from Sta. 39+33 to Sta. 37+00, -2.0% from Sta. 37+00 to Sta. 32+50, -0.35% from Sta. 32+50 to Sta. 18+50, -4.0% from Sta. 18.50 to Sta. 8+50, and -0.35% from Sta. 8+50 to Sta. 0+00. On the D-Route the grades are: +0.35% from Sta. 0+00 to Sta. 7+30, and +0.48% from Sta. 7+30 to Sta. 13+36 at Federal Triangle Station. The A-Route, from Farragut North Station to Metro Center Station has the following grades: +0.35% from Sta.

38+36 to Sta. 35+50, -0.929% from Sta. 35+50 to Sta. 8+50, and +0.35% from Sta. 8+50 to Sta. 0+00. On the B-Route the grades are: -0.35% from Sta. 0+00 to Sta. 7+30, +0.35% from Sta. 7+30 to Sta. 12+05. The connection track, from C-Route to A-Route has a length of 658 feet and a grade of -0.757%.

Sheldahl

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Northfield, MN 55057-0170
507/663-8000 • TWX: 910-565-2180

5 May 1989

Mr. Ferdinand Sasse
Sr. Industrial Engineer
Parsons Brinckerhoff
Spring Park Technology Center
460 Spring Park Place
Herndon, VA, 22070

Ferd:

As discussed earlier this week, I have enclosed preliminary sketches of deployable air blocks that are mechanical in nature as opposed to the inflatable concepts previously proposed.

At this point, I have not altered the inflatable concepts described in my 1985 proposal although I now believe there are a few changes that should be made in the configurations - that can come later.

The enclosed sketches cover 2 approaches that are passive in the sense that deployment of the air blocks would be obtained with the aid of gravity and the tunnel air flow. The third approach would require small gear motors for operation.

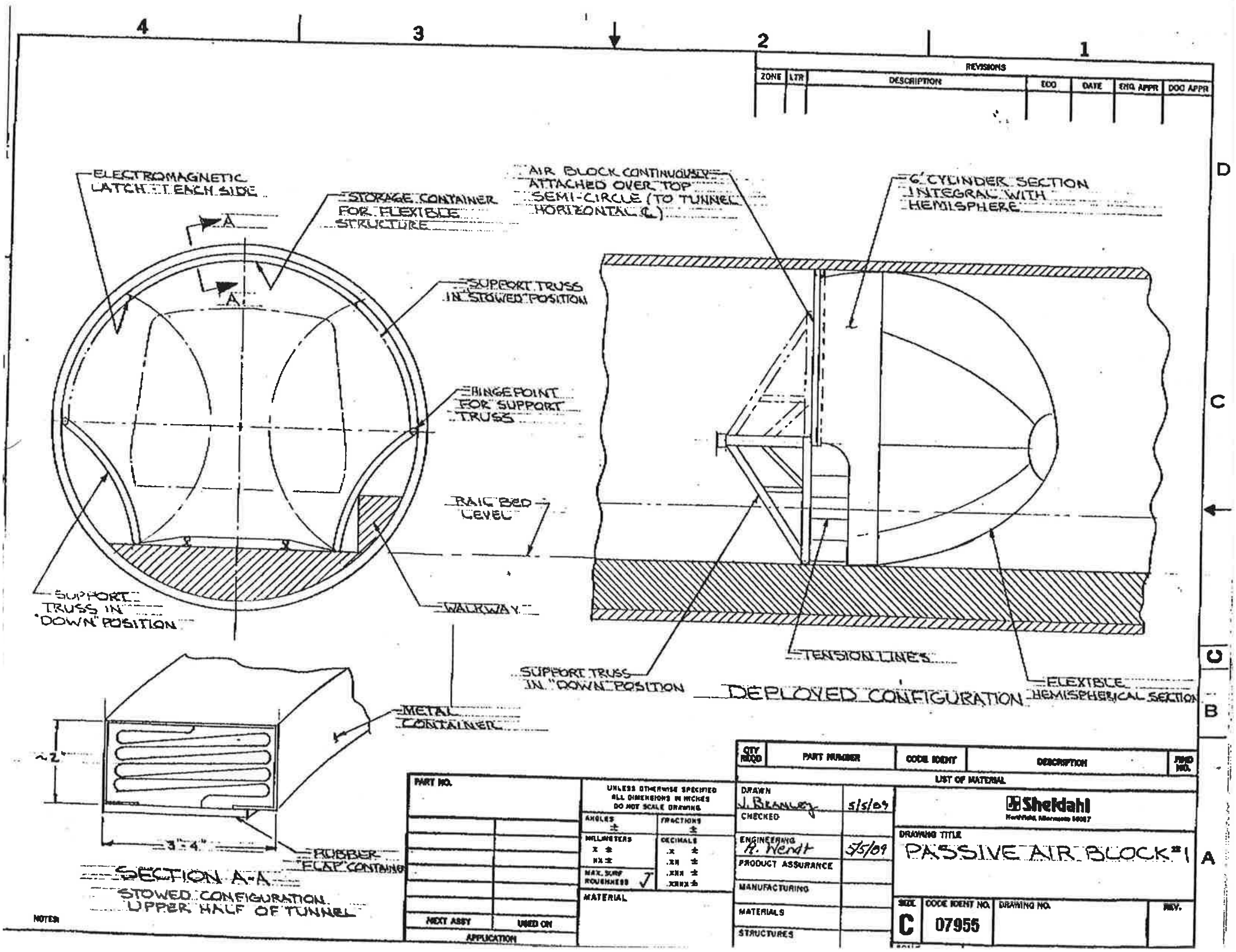
The tunnel configuration (in particular the walkway) has made the mechanical devices a little difficult to visualize and implement: however, I think we have some viable concepts. In any case, I feel refinement of the concepts, and perhaps generation of new concepts, is the first task of our work once we get started.

I will be following up this letter with a more comprehensive proposal early next week. In the meantime, don't hesitate to call if the enclosed sketches are not clear.

Sincerely,

[redacted]

Alfred J. Wendt
Sr. Engineer
Technical Sales



DEPLOYED CONFIGURATION

SECTION A-A
STOWED CONFIGURATION
UPPER HALF OF TUNNEL

PART NO.	
NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED
ALL DIMENSIONS IN INCHES
DO NOT SCALE DRAWING

ANGLES ±	FRACTIONS ±
MILLIMETERS X ± XX ±	DECIMALS .X ± .XX ± .XXX ± .XXXX ±
MAX. SURF ROUGHNESS √	
MATERIAL	

QTY REQD	PART NUMBER	CODE IDENT	DESCRIPTION	FIND NO.
LIST OF MATERIAL				

DRAWN J. Branley	5/5/09
CHECKED	
ENGINEERING R. Wendt	5/5/09
PRODUCT ASSURANCE	
MANUFACTURING	
MATERIALS	
STRUCTURES	

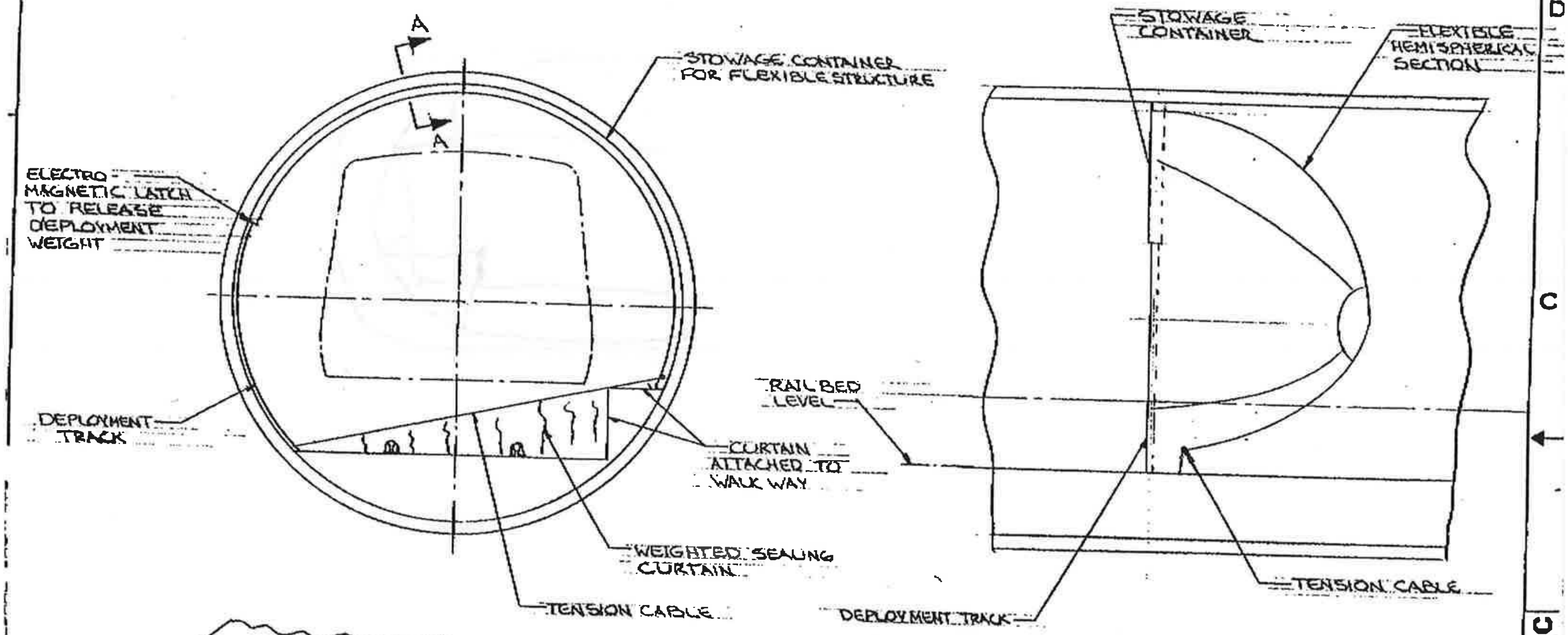
Sheldahl
Northfield, Minnesota 55057

DRAWING TITLE
PASSIVE AIR BLOCK #1

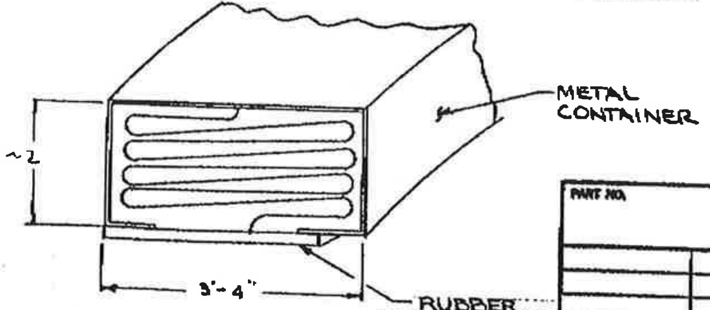
SIZE	CODE IDENT NO.	DRAWING NO.	REV.
C	07955		

ZONE	LTR	DESCRIPTION	ECO	DATE	ENG APPR	DOC APPR

REVISIONS



DEPLOYED CONFIGURATION



SECTION A-A
STOWED CONFIGURATION

NOTES:

QTY REQD	PART NUMBER	CODE IDENT	DESCRIPTION	FIND NO.

LIST OF MATERIAL

PART NO.

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS IN INCHES DO NOT SCALE DRAWING
ANGLES ±
FRACTIONS ±
MILLIMETERS X ± XX ±
DECIMALS .X ± .XX ± .XXX ± .XXXX ±
MAX. SURF ROUGHNESS √
MATERIAL

DRAWN	J BRANLEY	5/5/89
CHECKED		
ENGINEERING	R. Wendt	5/5/89
PRODUCT ASSURANCE		
MANUFACTURING		
MATERIALS		
STRUCTURES		

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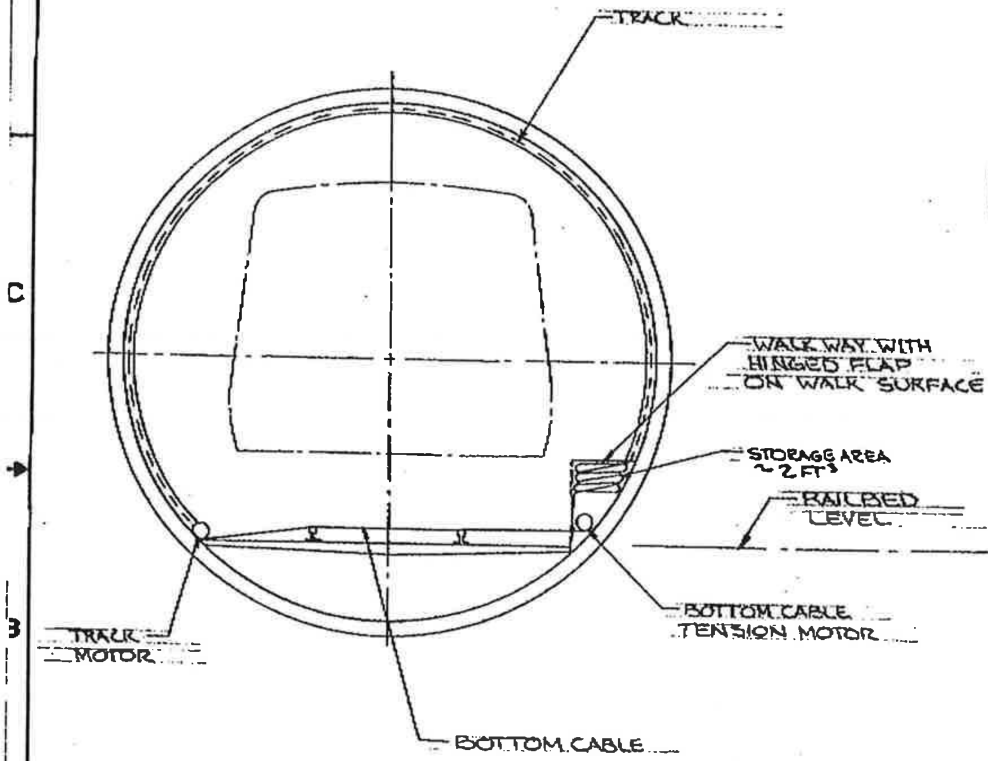
Northfield, Minnesota 55057

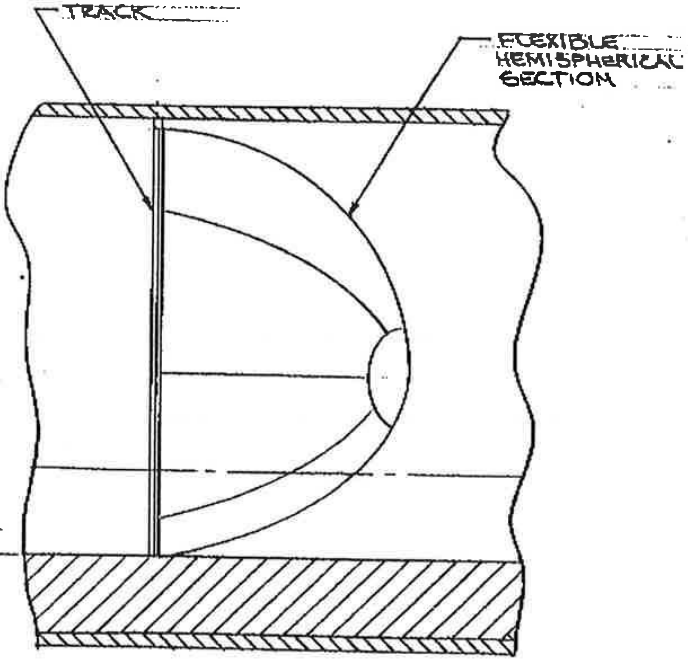
DRAWING TITLE
PASSIVE AIR BLOCK #2

SIZE	CODE IDENT NO.	DRAWING NO.	REV.
C	07955		

SCALE

REVISIONS						
ZONE	LTR	DESCRIPTION	ECO	DATE	ENG APPR	DOC APPR





DEPLOYED CONFIGURATION

Note: SEQUENCE OF OPERATION - (1) DEPLOY AIR BLOCK WITH TRACK MOTOR, (2) TENSION LOWER PORTION WITH "BOTTOM CABLE TENSION MOTOR"

NOTES

QTY REQD	PART NUMBER	CODE IDENT	DESCRIPTION	FIND NO.
LIST OF MATERIAL				

PART NO.	
NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED
ALL DIMENSIONS IN INCHES
DO NOT SCALE DRAWING

ANGLES ±	FRACTIONS ±
MILLIMETERS .X ± .XX ±	DECIMALS .X ± .XX ± .XXX ± .XXXX ±
MAX. SURF ROUGHNESS √	
MATERIAL	

DRAWN J. BRANLEY	5/5/89
CHECKED	
ENGINEERING R. Wendt	5/5/89
PRODUCT ASSURANCE	
MANUFACTURING	
MATERIALS	
STRUCTURES	

Sheldahl
Northfield, Minnesota 55057

DRAWING TITLE
IRIS AIR BLOCK

SIZE	CODE IDENT NO.	DRAWING NO.	REV.
C	07955		

SCALE | WT. | SHEET | OF