GROUP	C
EXHIBIT	
5	

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 Emergency Ventilation System Review of Previous Studies August 31, 1987

WMATA

METRORAIL EMERGENCY VENTILATION SYSTEM

Review of Previous Studies

Prepared for:

The Washington Metropolitan Area Transit Authority

By:

Parsons Brinckerhoff Quade & Douglas, Inc.

New York, New York

August 31, 1987
Revised September 16, 1987

TABLE OF CONTENTS

1.0 INTRODUCTION

This report documents the work performed under Task 1, Work Order No. DR-134 of Contract No. 3Z2096. The work was directed toward the review and evaluation of previous studies related to the ability of Washington Metropolitan Area Transit Authority's (WMATA) Ventilation System to control the movement of smoke and heat during a fire emergency. This task is part of an overall program to improve WMATA's ventilation system for smoke control.

Based on the information contained in the seven reports reviewed, three reports have been identified as key studies on WMATA's ventilation system. These reports are:

- Raymond (KE) Inc
  Assessment of Metrorail Ventilation System, Volume 1 and Appendix, May 1983

- Raymond (KE) Inc
  Metrorail Ventilation System Improvements and Vehicle Fire Hardening, December 1983

- DeLeuw, Cather & Company
  Tunnel Smoke Control Study Phase 1, August 1985

The information contained in the remaining four reports (4, 5, 6, 7) were not considered significant in terms of our overall objective of improving the ventilation system effectiveness during a tunnel fire.

The three key reports were reviewed as thoroughly as possible without supporting calculations and computer runs. Although these deficiencies limited the effectiveness of the review, the information in the reports was sufficient to verify or refute the methodologies used and results obtained. Since the organizations that performed these studies are experienced and recognized professionals, we can generally accept their methodologies, measurements and calculations as correct except where our experience leads us to other conclusions. These exceptions are noted herein.

This report is divided into four parts. Following the introduction is a summary and discussion of the salient points of the three key reports reviewed. An aggregate summary of the three reports is then presented. This serves as the basis for our recommendations presented in part four.

2.0 SUMMARY AND DISCUSSION OF KEY REPORTS

The salient points of the methodologies, conclusions and recommendations of the key reports as they relate to the WMATA ventilation system and its improvement are summarized herein. A discussion of each of the reports follows the individual summaries.

2.1 RAYMOND (KE) INC.
Assessment of Metrorail Ventilation System Volume 1 and Appendix, May 1983

2.1.1 Summary

This initial study by RKE was the result of a WMATA directive to assess the performance, capabilities and redundancy of the existing ventilating system relative to emergency objectives. To accomplish these goals, their investigation was grouped within seven tasks described as follows:

TASK 1 **Review of System Documentation**

This task examined the ventilation systems to include redundancy of power feeds, controls, signal and feedback capabilities and to estimate the capability of the system to remove smoke in emergency situations.

TASK 2 **Performance Testing**

RKE performed field measurements of airflow and used them to calibrate the SES computer program for selected underground locations.

TASK 3 **Operational Scenarios**

The SES computer program was used to simulate emergency conditions.

TASK 4 **Information Display**

A rapid method for presenting information for use in an emergency was devised by Radix II Inc as subconsultants to RKE.

TASK 5 **Reliability and Maintainability**

The activities in this section determined the reliability and maintainability of the ventilation equipment and evaluated the adequacy of the operations and maintenance procedures and manuals.

TASK 6 **System Signage**

The adequacy of system signage to direct emergency personnel and evacuating patrons, and to inform maintenance personnel of proper procedures was evaluated by RKE.

TASK 7 **Assessment of the Level of Safety**

This task assessed the contribution of the ventilation system level of safety for evacuating patrons.

With the exception of their ventilation system simulations, the results of their investigations are not summarized here because they are only indirectly related to the performance of the ventilation system which is a primary objective of our investigation. All significant findings from these tasks will be discussed however after the summary of RKE ventilation system simulations.

Operational Scenarios Summary

The evaluation of the Metrorail emergency ventilation capabilities included the development of potential fire scenarios which considered train locations, sizes of train fires, the capability of ventilation systems and system evacuation. The fire scenarios were simulated using SES computer programs which were calibrated using field airflow measurements. The three sites considered were:

- Clarendon Station
- Between the ventilation shaft and fan shaft near Court House Station
- Between the ventilation shaft and fan shaft near Foggy Bottom Station

For the Clarendon Station fire with a heat release rate of 8 million Btu/hr station entrances can be kept free of smoke and hot air by operating the fans in the fan shaft at either end of station. The existing ventilation system is not capable of directing smoke flow from fires with a heat release rate of 20 million Btu/hr or more.

The second scenario represented an incident occurring in a typical single track tunnel between a station (Court House) and midline fan with a 100 ft. stack height. The simulation showed that no combination of existing fans could control the flow of smoke from even an 8 million Btu/hr fire.

The third scenario represented was similar to the second with the exception that the stack height is 50 feet. With the exception of an 8 million Btu/hr fire rate, which the fans were able to only marginally prevent smoke reversal, no combination of existing fans could control the flow of smoke from a fire.

RKE established from this study the following airflows adequacy approaching the incident location for a 40 million Btu/hr fire:

- 75,000 ft^3/min is unacceptable
- 75,000 - 120,000 ft^3/min marginal
- greater than 120,000 ft^3/min adequate

From calculations, RKE established that the airflow rate considered adequate would provide sufficient cooling to limit fire growth and buoyant effects and to dilute products of combustion.

The simulations at the selected tunnel locations showed that the ventilation systems are not capable of reversing even ambient airflows. Therefore from the scenarios examined, RKE determined that the best way to ventilate, that is, the way to move the most air past the fire incident locations, is to operate the fans to augment the airflows in the system. Using this philosophy, RKE was able to suggest operational procedures for all the fans and dampers in the system.

2.1.2 Discussion

RKE conducted the ventilation analysis using the SES Version 2. This version of the program was used primarily for predicting the airflows in tunnel sections which were not affected by fire generated buoyancy forces. Before the availability of Version 3, which was developed to include a fire-model having the ability to account for fire generated buoyancy forces affecting the airflows, Version 2 was often used in a makeshift way to account for these fire generated effects. It has been our experience that the results are sometimes misleading when a modified Version 2 is used as a substitute for Version 3. For this reason, we are not able to verify as correct the results which RKE presents for the SES fire simulations without reviewing their actual SES computer runs or repeating the fire scenarios with SES Version 3 simulations.

The SES model used to evaluate airflows generated by the ventilation system without fires in the tunnel during this phase of their investigation is considered reasonably accurate since the simulation results show substantial concurrence with the on-site airflow measurements.

Fire Size

At the time of this report, RKE believed there was a tendency on the part of many analysts to over emphasize the so-called fuel load which is a compilation by weight and Btu/lb of the combustible materials of a transit vehicle. We also recognize that in the past great importance was placed on fuel load because of absence of the desired heat release rates of materials and the behavior of the interaction of the material burning.

Today, the results of material testing and mathematical modeling are available to some degree, to relate the assumed five heat release rates of a transit vehicle to its fuel load. Although RKE calculated the fuel load of the Rohr transit vehicle with a very comprehensive survey, the justification of their established burning rates of this fuel load are not included in the report. No rationale is presented, either test results or mathematical modeling, to support their selection of the rates used in this report.

System Operation

RKE approached the problem of generating adequate airflow past an incident train by recommending that the ventilation system be operated to effect the greatest airflow past a train, as noted above in Section 2.1.1 on page 5. Given the current capabilities of the ventilation system, this approach is reasonable but may not necessarily be best for aiding passenger evacuation, since the direction of smoke flow induced by the fans may inundate the evacuation path of the majority of the passengers. It is more desirable to have the capability of controlling the movement of smoke in either direction thereby creating a safe evacuation path in relation to where the fire is located on the train. The various options for improving ventilation system performance, which at this point are blockage devices and increasing the number and/or capacity of the existing fans, were not seriously considered in this study.

Existing System Performance

RKE was able to determine the effectiveness of the tunnel ventilation system at a number of locations. The field measurements performed were well executed and are considered a good indication of the system performance. The information obtained from these field surveys will be useful as a benchmark against the effectiveness of any modifications to the tunnel ventilation system.

Maintenance and Reliability

Based on our actual observations and those of Ian J. Cockram of London Transport Inc., the ventilation system now appears to be better maintained and more reliable than RKE observed during the time of their study. Much of the information in this RKE report, however, is either unrelated to the current questions or now dated, and will not be discussed further.

System Signage

The presentation and recommendations by RKE on system signage and information display are generally good. At this date, many of the recommendations may have been adopted by WMATA.

2.2 RAYMOND (KE) INC.

Metrorail Ventilation System Improvements and Vehicle Fire Hardening, December 1983

2.2.1 Summary

As a follow up to their original report "Assessment of Metrorail Ventilation System" RKE investigated alternative methods for improving the effectiveness of the ventilation system in single-track tunnels, and methods for fire-hardening the Rohr vehicle to reduce the fire heat release rate to 20 million Btu/hr or less.

RKE approached the ventilation analysis in this study using the SES Version 2 computer model. Two networks were developed and calibrated using field measurements gathered during their earlier study. For the purpose of this study, an airflow of 75,000 CFM flowing past a train was considered adequate in the presence of a 20 million Btu/hr fire. This airflow was also estimated to be sufficient to limit the temperature of the air to below the fan temperature operational limit of 300°F.

The ventilation analysis was conducted using various strategies to achieve or exceed the 75,000 CFM airflow. The most effective were:

- providing tunnel blockage in the unoccupied tunnel bores
- increasing the capacity of existing fans

The computer simulations were run on the following basis:

- worst-case condition between L'Enfant Plaza Station and the portal on the Pentagon line due to the low resistance of the open portal.

- typical condition between Cleveland Park Station and Woodley Park-Zoo Station (also represents long tunnels on steep grades)

- typical condition downtown between L'Enfant Plaza and Federal Center S.W. Station having a relative short and level tunnel.

From their simulations, RKE determined that to maintain a 75,000 CFM airflow past the train, it would be necessary to increase individual fan capacity in addition to providing blockage devices in the open tunnels.

RKE recommends using separate barriers in each tunnel section as a preferred method of isolating open tunnels for improving ventilation. Various types of barriers were discussed, the most promising being the air block as manufactured by Sheldahl Materials Division and the brattice cloth line curtains as manufactured by Peabody ABC.

The second part of this study focused on fire hardening the Rohr vehicle which was approached by:

- establishing the existing degree of vehicle fire resistance and
- recommending measures to improve vehicle fire hardening which would limit the fire heat release rate to not more than 20 million Btu/hr.

The existing degree of vehicle fire resistance was obtained by refining the fuel load which was investigated in the previous RKE report (1). Various ignition sources and locations for fires were discussed as background for a mathematical model which was used to predict the behavior of the vehicle fire and lead to a fire heat-release rate as a design parameter for the computer simulations.

RKE's interpretation of the mathematical model was that a 20 million Btu/hr fire would serve as a reasonable design criteria to evaluate ventilation system effectiveness provided fire hardening of the vehicle is performed in accordance with their recommendations.

2.2.2 Discussion

As with their previous study, RKE conducted the ventilation analysis using the SES Version 2 program which did not contain the state-of-the-art improvements included in the SES Version 3 program. As discussed before, using

Version 2 to account for fire effects often gives results that may lead to incorrect conclusions. Since this report did not include any information or data on the computer modeling or methodology employed, it is not possible to verify the results which RKE presents for the SES fire simulations.

Nevertheless, the SES results are considered reasonably accurate for evaluating ambient airflows since the simulated networks were calibrated using on-site airflow measurements. (It is not clear however why mass continuity is not satisfied in Figure 4.1-10 of this report.)

Smoke Control

Recognizing the inability of the existing ventilation system to effectively control the movement of smoke, RKE conducted an investigation of potential fire sizes and corresponding heat release rates for the Rohr cars. In the past, conservative estimates of heat release rates were assumed to account for unknown factors involved in a vehicle fire. RKE attempted to refine their estimate by looking at vehicle heat release rates based on component heat release rates combined with mathematical modeling of fire spread. In the past, the common approach to limit the intensity of vehicle fires has been to limit the fuel load. The fuel load is calculated by multiplying the total weight of combustible material by its heat content (Btu/lbm). The fire heat release rate was then based on the fuel load being consumed within a period of about one hour.

To date, NFPA 130 recommends a fuel load limit but does not relate this value to the heat release rates of the fuel load. While useful in the preliminary assessment of the ventilation system, as was performed by RKE in their initial study, RKE approached the problem more definitively in their second study (2) after determining that the existing tunnel ventilation system can not handle a fire heat release rate greater than 20 million Btu/hr. Two key activities undertaken by RKE to substantiate this heat release rate are:

- actual testing of vehicle component material heat release rates
- mathematical modeling to simulate the actual fire performance of the individual materials and the degree of fire propagation.

The actual testing of material provided input data for the mathematical model to predict the rate of heat and smoke release. The mathematical model also predicts the progress of the fire from point of ignition using the rate of fire involvement.

RKE interpreted the results of the mathematical model to mean an in-car fire will not propagate from the seat to the ceiling after fire hardening the vehicle as recommended, and therefore the fire heat release rate would be less than 20 million Btu/hr. There were no details presented in the RKE report as to how this heat release rate was determined, although they state the that mathematical model is capable of estimating the rate.

In general, the approach used by RKE to determine the fuel load and heat release rate was reasonable and sound. The RKE conclusion regarding a heat release rate of 20 million Btu/hr should be further reviewed, however, since the data presented from the mathematical modeling is not complete enough to support this value. It is apparent, however, that if the in-car fire hardening recommendations were not followed the fire would propogate from the seat to the ceiling and the car would soon be totally involved. Undoubtedly this would result in a heat release rate much greater than 20 million Btu/hr.

2.3 DeLeuw, Cather & Company
Tunnel Smoke Control Study, Phase 1, August, 1985

2.3.1 Summary

As general engineering consultant (GEC) to WMATA, DeLeuw Cather surveyed the operational system relative to providing sufficient tunnel ventilation capability for safe patron evacuation during a train fire. To achieve this capability the following were identified:

- areas and degree of ventilation modification required.

- applicability of tunnel blockage to achieve the required tunnel airflow.

- projected costs associated with ventilation system modification

Sections considered in this study were portions of the B Route (Sta. 480 + 30 to 1230 + 60), E Route (Sta. 509 + 15 to 576 + 00) and F Route (Sta. 52 + 66 to 204 + 18).

The SES Version 3 program was used to predict the airflow velocity at the incident locations. This velocity was compared to critical velocities of 370 to 375 ft/min which were calculated in accordance with the method outlined in the Subway Environmental Design Handbook Volume II(10) (except incident area was not used). The critical air velocity is defined as that velocity at a fire incident location sufficient to prevent smoke backlayering. The fire heat release rate used in the calculation of critical velocity and in the simulations was 20 million Btu/hr, as previously established by RKE and as directed by WMATA.

Various ventilation strategies were considered to achieve or exceed the critical air velocities, the most effective being:

- provide tunnel blockage in the unoccupied tunnel bores

- increase total fan capacities.

- provide blockage at station entranceways.

- create a push-pull ventilation effect around the fire by operating fans on the evacuation side of a fire in supply and those on the opposite side in exhaust.

In terms of modifying the ventilation system, the first choice was to use "blockage" devices. This was followed by increasing existing fan capacities, and then followed by increasing the number of fans.

The computer simulations were run on the following basis:

- Apparent worst-case situations were created by positioning the train in steep tunnel sections. This maximizes the retarding effect of buoyancy on airflow when ventilating downgrade.

- Fire location was considered at either end of the train. The ventilation system was operated to prevent smoke from moving across the train thus providing fresh air in the faces of passengers evacuating in the opposite direction.

- Simulations of different ventilation strategies were performed until the critical air velocity required to control the direction of smoke movement was satisfied. The train and fire were repositioned and additional simulations performed until the critical velocities at all locations were met or exceeded.

- Any increase in fan capacity deemed necessary was considered as a minimum capacity for later simulations.

The simulations indicated that it is necessary to increase individual fan capacities and/or provide additional fans in addition to providing "blockage" at station entrances and tunnels in order to insure the critical air velocity being met.

In addition to the ventilation system modifications for these three routes, DeLeuw Cather recommended field tests to verify SES computer run results in cases where program results only minimally exceed criteria. DeLeuw Cather also recommended establishing a standard operating procedure for WMATA personnel that would specify fan and blockage device activation strategies for a given tunnel fire location.

2.3.2 Discussion

The basis of the DeLeuw Cather fire model was a fire rate of 20 million Btu/hr. This rate was previously used by Raymond (KE) Inc. (1) and was given to DeLeuw Cather by WMATA as the starting point for their analysis. In addition, RKE identified an airflow of 75,000 ft^3/min in the incident bore as the required airflow. This airflow was the criteria for the DeLeuw Cather study.

Using the fire rate and airflow as given criteria, Deleuw Cather incrementally modified existing ventilation systems until adequate ventilation rates were achieved. Tunnel blockage devices with an assumed 80% blockage area, fans with higher speed and horsepower motors and more fans were the modifications considered for the existing ventilation systems.

As per the RKE recommendation cited above, the DeLeuw Cather study applied the SES Version 3 program to determine the extent of ventilation system modifications required to meet the established ventilation rate criterion.

Based upon our preliminary analysis, it appears that for the given fire rate of 20 million Btu/hr the required airflow could be significantly less than the RKE recommended value of 75,000 ft^3/min. This assertion is based on our evaluation of the expression for the critical air velocity required to control smoke backlayering which is included as an integral part of the fire model in SES Version 3. The critical velocity is the average tunnel air velocity across the fire incident area; i. e., the annular space between the train and the tunnel surfaces. The result of this evaluation indicates the proposed airflow quantities could be reduced by approximately 40% to meet the critical velocity criterion.

The corrective actions presented by DeLeuw Cather reflect the completeness with which the analysis was executed. Depending upon the current state of the fire hardening characteristics of the Rohr and Breda vehicles and in consideration of our preliminary findings relative to the required airflow rates, it would appear that a revised analysis utilizing SES Version 3 would be appropriate at this time.

The keys to the analysis and modification of WMATA ventilation systems to effect smoke control during a tunnel fire are the tunnel and station blockage devices. Because of the unknowns associated with these devices, more conventional technology such as using impulse fans (where feasible to install in the existing tunnels) to increase tunnel airflow should be thoroughly investigated before development of blockage devices.

Among the recommendations which DeLeuw Cather presents are ventilation systems modifications. These modifications may no longer be appropriate based on a revised fire heat release rate and analysis as suggested above. Recommendations such as hot smoke tests, to verify the effectiveness of the modifications, and the establishment of ventilation equipment and blockage device operating procedures during a fire emergency are practical recommendations which should be adopted when the ventilation scheme is finalized.

3.0 CONCLUSIONS

1. The fuel load inventory performed by RKE for the Rohr vehicles appears to be accurate but should be verified with the current composition of the vehicles.

2. We generally agree that the existing ventilation system is unable to control smoke without modification. The extent of the modifications proposed in the reports we reviewed should be reexamined in consideration of the manner in which the critical air velocity was evaluated.

3. Critical air velocity calculations should be based on the train-tunnel annular area. It appears that the DeLeuw Cather calculations used the open tunnel area which yields airflow quantities approximately 67% higher than required for smoke control with a 20 million Btu/hr fire.

4. The heat release rate of 20 million Btu/hr should be reviewed. Results of the mathematical model not included in the RKE reports need to be reviewed before we can concur with this key value.

$$v = \left(\frac{Q}{A}\right)^{1/3}$$

5. To maximize the effectiveness of the existing ventilation system, it can be operated to augment the existing ambient airflows. However, this operating procedure must be confirmed as appropriate in a specific fire situation since this direction of airflow may be perilous for the majority of the evacuating passengers.

6. We agree that cost wise it appears that a universal type tunnel blockage device is more practical and economical than individual damper and wall designs since WMATA's tunnel ventilation facilities are not uniform. Further study and research testing of such devices are mandatory, however, before commitments to their use can be endorsed.

7. The WMATA ventilation system lacks the capability to control smoke from even a moderate fire (20 million Btu/hr) without equipment modifications and/or additions.

4.0 RECOMMENDATIONS

The following recommendations relate to the remainder of the work to be performed under the current work order:

1. Update the fuel load survey for the Rohr vehicles based on fire hardening improvements performed on the vehicles as a result of the RKE December 1983 report (3).

2. Perform a fuel load survey for the Breda vehicles as was performed by RKE for the Rohr vehicles.

3. Develop a heat release rate for the modified Rohr or Breda vehicle by the following:

    - review mathematical modeling approach used by RKE and their consultants to determine fire heat release rates

- if approach found to be acceptable, extrapolate test results to materials in current use

4. Calculate critical air velocity criteria using tunnel-train annular area for use with SES Version 3 simulations identified in Item 5 below.

5. Repeat selective SES fire simulations performed by RKE and/or DeLeuw Cather for single track tunnels. One of the computer runs will simulate a downtown site which will serve as the prototype site.

6. Investigate the potential use of tunnel impulse fans as an alternative to tunnel blockage devices. AO-6

7. Begin investigation into tunnel blockage devices. or alternatives means

8. Investigate the ventilation requirements for a tunnel fire in a typical double track tunnel.

9. Perform Tasks 4 through 7 of the referenced work order as identified therein.

REFERENCES

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

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

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

4. Washington Metropolitan Area Transit Authority, "Report on Ventilation, Fire Protection, and Emergency Egress System on the Metrorail System", No date.

5. DeLeuw, Cather and Company, "Subway Environmental Simulation Program and Subway Environmental Design Handbook Validation through Field Testing", UMPTA-DC-06-0267-86-1 thru 4, February, 1983.

6. DeLeuw, Cather and Company, "Air Conditioning for Passenger Stations", June, 1968.

7. Boeing Aerospace Company, Engineering Technology, "WMATA Metrorail System Analysis, Volume 1", March, 1983.

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

9. NFPA 130, "Standard for Fixed Guideway Transit Systems."

10. Associated Engineers, Subway Environmental Design Handbook, Volume 1 Principles and Applications, U. S. Department of Transportation, Washington, DC, 1975.