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

GROUP	C
EXHIBIT	
4	

Agency / Organization

WMATA

Title

Tunnel Smoke Control Study Phase I August 1985

Docket ID: **DCA 15 FR 004**

WMATA

DeLEUW
CATHER

De Leuw, Cather & Company
General Engineering Consultants • Washington, D.C.

Washington Metropolitan Area Transit Authority

Tunnel Smoke Control Study Phase I

August 1985

DeLEUW
CATHER

De Leuw, Cather & Company
General Engineering Consultants • Washington, D.C.

Washington Metropolitan Area Transit Authority

Tunnel Smoke Control Study Phase I

August 1985

TABLE OF CONTENTS

I. INTRODUCTION

By letter of January 29, 1985, WMATA requested that the GEC survey the operational system relative to providing the tunnel ventilation capability necessary for safe patron evacuation and to identify

- the areas in which the ventilation system would require modification to achieve the suggested air flow,
- the degree of modification required to the ventilation systems in the identified areas,
- the applicability of strategic tunnel blockage to achieve the suggested air flows in concert with or in lieu of ventilation system modifications, and
- the projected costs associated with the ventilation system modification determined as required.

This report represents the first phase of this study of tunnel ventilation system performance in the event of fire on board a disabled train. Sections considered in this phase of the study include 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) as shown on Sketches SCS-E8-1, SCS-F2-1 and 2, and SCS-B9-1 and 2, attached. The portions of the B and F Routes included in this study are longer than originally scheduled. This expansion was necessary to assess the impact of fan systems beyond those closest to the disabled train.

II. SUBWAY ENVIRONMENTAL SIMULATION (SES) COMPUTER PROGRAM

The initial versions of the SES program were designed to provide output consisting of aerodynamic, temperature, humidity and train performance data associated with essentially "normal" (i.e non-fire) operations in any arrangement of stations, tunnels and ventilation shafts. WMATA designs had been based on the available state-of-the-art technology. Version 3 of SES now provides expanded capability through the addition of a fire simulation option. This capability allows the user to simulate both a fire and the response of a ventilation system to that fire. It is, therefore, desirable to reevaluate the ventilation designs to account for possible smoke control in the tunnels.

Various combinations of vehicle fire locations and emergency ventilation system responses were simulated. The actions required to achieve acceptable performance levels are identified in cases where existing or as-designed ventilation systems did not meet the new performance criteria of achieving a 375 feet per minute (FPM) air velocity in the tunnel.

III. BUOYANT EFFECTS

The behavior of tunnel fires and associated air flows differs from most fire situations due to the confined space and buoyant effects. Buoyant effects create a layer of smoke and hot gases flowing away from the fire near the crown of the tunnel, while air supporting combustion moves toward the fire beneath the smoke layer. Ventilation systems may be used to control the flow of smoke. If the ventilation air flow is of sufficient quantity and velocity, all smoke will flow in the same direction as the fan-induced flow. If the direction of the fan-induced flow is towards a lower level in the tunnel and the ventilation air flow is insufficient, the upper layer of smoke may flow towards a higher level, contrary to the direction of the forced ventilation. This phenomenon is called "back-layering." Whether back-layering occurs depends upon fire intensity, tunnel grade and geometry, and the velocity of the ventilating airstream.

In the event of a fire involving a disabled train in a tunnel, a ventilation system is desirable for controlling the direction of smoke movement in order to provide a clear and safe path for evacuating people and to facilitate fire-fighting operations. The capability to prevent back-layering should, therefore, be a major objective in the design of any new tunnel ventilation systems. Since the new SES program is now capable of predicting air flows in the presence of fire, the occurrence of back-layering can be determined by comparing the simulated velocity of the air moving toward the fire with a certain "critical velocity" above which back layering is precluded.

IV. CRITERIA

- <u>Critical Air Velocity</u>

  Computer simulations and limited field testing previously performed by Raymond Kaiser Engineers (RKE) resulted in their recommendation of 75,000 CFM as being the minimum air flow to prevent back-layering in a single-bore, circular tunnel with a four-percent grade. This equates to a velocity of 375 FPM through the clear area of the tunnel. Since air velocity is the critical parameter in a fire situation, a comparison of predicted and required velocities gives a direct indication of the adequacy of a particular system. In addition, due to variations in tunnel areas in relation to tunnel configurations, a constant flow rate gives differing air velocities in accordance with the type of tunnel configuration simulated.

  The User's Manual of the SES Version 3 program provides a procedure for hand-calculating critical air velocities. For a four-percent grade, the critical air velocity calculates to be 371 FPM. The detailed calculations are shown in Appendix A. As the maximum grade in the WMATA system at this time is four percent, the critical air velocity for the purposes of this study was established as 375 FPM. One section now under design will have an almost five-percent grade and a revised critical velocity will have to be established for this particular case.

- <u>Fire Intensity</u>

  A fire intensity of 20,000,000 BTUH was employed as directed by WMATA's letter of January 29, 1985.

V. STRATEGIES

Strategies to achieve or exceed critical air velocities must account for both buoyant effects and the flow splits resulting from system configuration. Typically, four possible flow paths, formed by the connecting tunnels, exist at the base of a fan shaft. Since the air flow resistance of an unoccupied tunnel is relatively low, a train located in any one tunnel bore will cause a major increase in the resistance of that tunnel bore. This condition will, in turn, reduce air flow past the train and increase the flow in the three clear, tunnel bores as air flows are inversely proportional to resistance.

After consideration of these factors, it was decided that the following actions would be effective:

- o provide blockage in unoccupied bores in order to increase air flow past a burning train,
- o increase total fan capacities to provide larger flow rates in all connecting tunnels,
- o provide limited blockage in station entrances to increase effectiveness of the tunnel ventilation fans, and
- o place all fans on the evacuation side of the train in the supply mode and all fans on the opposite side in the exhaust mode to provide the maximum push-pull effect.

In modifying ventilation systems to meet the critical air velocity criteria, first priority was given to using "blockage" devices as a means of increasing the resistance in the clear tunnels and forcing more air flow past the burning train. Where the projected air flow improvement resulting from use of blockage devices was not sufficient, increases in total fan capacities were considered. Fan capacities were modified by increasing the number of fans, increasing the individual fan capacities or, a combination of both actions. The increase in individual fan capacity was limited to that which could be obtained by increasing the speed and horsepower of the existing or standard fan. These procedures were intended to minimize the impact of required modifications on the ventilation systems planned for the sections studied.

VI. TUNNEL AND STATION BLOCKAGE DEVICES

o Tunnel Devices

Initial consideration was given to a tunnel blocking concept involving the use of parachute type devices constructed of brattice cloth or similar material. However, while a parachute can be automatically deployed, possible problems such as tangled guy lines and the need for on-site adjustments (e.g. pushing the material into voids) would require intervention by WMATA or fire-fighting personnel to insure that the device produces an effective seal. Since a significant time delay prior to parachute deployment could endanger patrons during an emergency, an automatically deployable blocking device which will be effective without intervention is essential.

This requirement led to the conclusion that an inflatable type device that could be locally or remotely activated and be essentially selfsealing was needed. Preliminary discussions with a potential manufacturer, Sheldahl, Inc., Northfield, Minnesota, indicate that such a device is feasible. The preferred tunnel blockage device would consist of a fabric ring or "doughnut" which would be inflated by a compressed gas. The ring would be somewhat larger than the perimeter of the tunnel and would be sufficiently pressurized so as not to be dislodged by the force of fan-induced tunnel air flows. The center of the ring would be filled with fabric and have a resealable opening which would permit passengers and/or rescue personnel to pass through. Since complete blockage of the tunnel is not expected, an 80% effectiveness is being used in this study. The device would normally be folded and stored in a small container attached to the tunnel wall. The inflating gas could be either locally or remotely (OCC) controlled, and the container would be designed to freely release the ring as it inflates. Details of this manufacturer's proposed schemes are included in Appendix B. Design development and prototype testing of the ring will be required, however, prior to its general deployment on the WMATA system.

The inflatable blocking devices would be permanently installed in all four bores at the foot of all fan shafts in order to ensure that any three out of the four bores could be blocked. The bores to be blocked will depend on which track (inbound or outbound) the disabled train is on and which direction the passengers are being evacuated. This arrangement makes the use of dampers to isolate tunnels redundant.

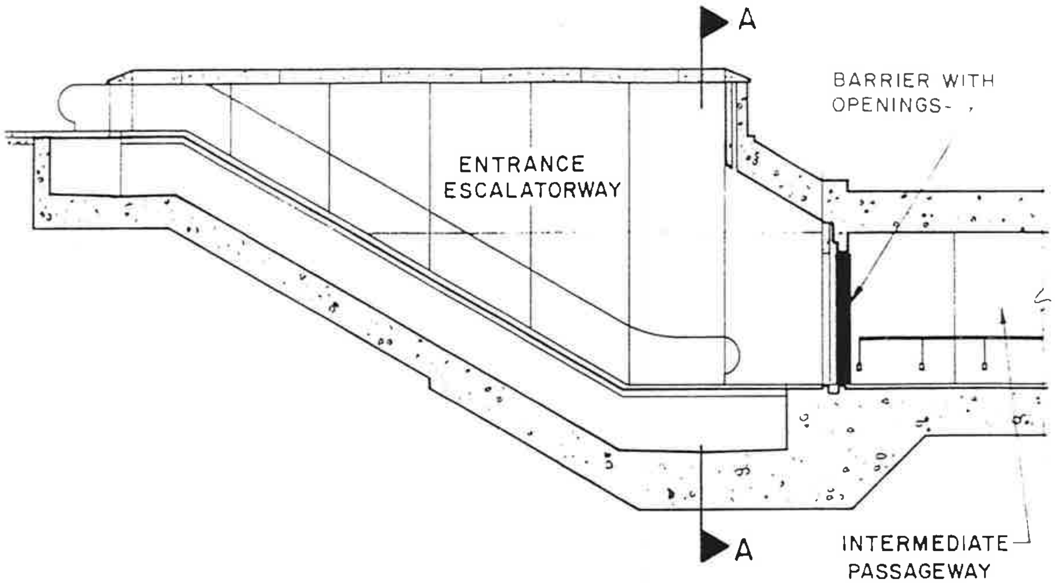
o Station Devices

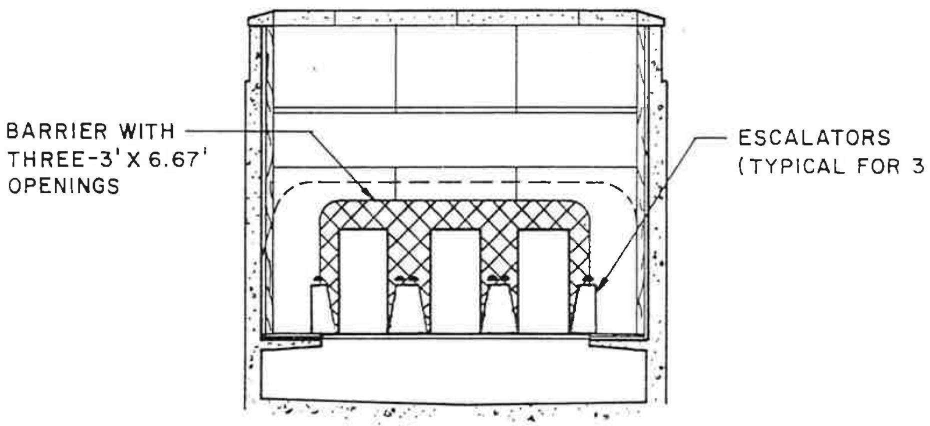
To further increase the effectiveness of the tunnel ventilation systems, station entrances were simulated as partially sealed under certain conditions. As envisioned, entrance blockage devices would leave openings for patron evacuation in quantities and widths consistent with existing entrance escalator exit capacities as determined by NFPA 130. The remaining, unused area would be sealed off by a roll-down gate or similar device. These devices would be positioned in close proximity to the entrance escalators in order to prevent the introduction of an additional barrier to patron flow. Since the use of escalators tends to regiment patron flows, additional queues will not be caused as a result of blockage devices positioned in this manner. A conceptual illustration of the configuration and location of such a device is shown in Figure 1.

VII. COMPUTER INPUT DATA

Program input such as geometric, tunnel, weather, ventilation shaft, and other physical data remained fixed for all runs along a specific route. The fire intensity was established by WMATA and therefore remained unchanged during all runs conducted during this study. However, other data was changed as the situation was changed. Examples of variable data are as follows:

- train Location,
- fire Location,
- fan Type,





SECTION A-A

FIGURE 1

ENTRANCE BARRIER CONCEPTUAL LAYOUT

- fan Capacity,
- fan Operating Direction,
- time Length of Simulation, and
- head Loss Coefficients at points of blockage (tunnels and stations) representing blockage.

Fan capacity in the supply mode was established as 70% of capacity in the exhaust mode. Increased individual tunnel fan capacity was limited to the 60,000 CFM obtainable by increasing the speed of the WMATA standard 50,000 CFM fan from 870 RPM to 1170 RPM and increasing horsepower from 20 to 30. These modifications do not require a change in the physical dimensions of the fan.

VIII. COMPUTER SIMULATION PROCEDURE

Computer simulations were run on the following basis:

- Train and fire locations were selected to produce apparent worst-case situations. In general, this required situating the train in a tunnel segment with a relatively steep grade.
- Evacuation was conducted in the direction which appeared to offer the safest path away from the fire for the majority of patrons. The desired direction of air flow was then established as being in the opposite direction, i.e., into the faces of the evacuating patrons.
- The first run on a particular route was performed with existing fan capacities and no tunnel blockage. Run results were then compared with criteria.
- A second run, if necessary, was performed with existing fan capacities plus tunnel blockage.
- Further runs were performed as required with various combinations of fan capacities and tunnel blockage schemes.
- Upon meeting the criteria, the train and fire were repositioned. The process described above was then repeated until all selected train and fire locations had been simulated, and a means of meeting or exceeding critical air velocity criteria had been found.
- Any increase in fan capacity found necessary in a run was treated as a minimum requirement for all runs which followed.

IX. SIMULATION OUTPUT

Narrative descriptions of conditions during each simulation along with final results follow. Simulation results are further illustrated on the attached sketches as plots of air velocity versus simulation time. The term air velocity as used in the descriptions refers to the air velocity through the clear area of the occupied tunnel.

A simulation time of 500 seconds was used as it appeared to allow a sufficient period for the air velocity to stabilize after the introduction of the fire source. The first portion (20 to 40 seconds) of each plot reflects fan start up, and is also influenced by the sudden introduction of the fire source at full intensity. The SES program is not capable of simulating an increasing fire intensity. Determination of compliance with criteria was therefore made at the point at which tunnel air velocity had stabilized and either equalled or exceeded the critical velocity.

To reduce costs associated with the computer runs, most runs were limited to 200-second simulation times and extrapolated out to 500 seconds. Simulation times of 500 seconds were, however, employed on all E Route runs since computer central processing unit (CPU) times were relatively small. Some runs on the B and F Routes were also run for the full 500 seconds in order to gauge system performance. In cases where extrapolated plots are shown, they represent approximations based on behavior exhibited during the longer runs.

E Route (Sta. 509+15 to 576+00) (Reference Sketch SCS-E8-1)

- General

  All E route runs were conducted with the train located on a four percent grade between the fan shaft at STA 525+00 (FE-1) and the vent shaft at STA 550+00. This placed the rear of the train approximately 600 feet outbound from FE-1. Since this portion of the E route is essentially symmetrical around the vent shaft at STA 550+00, the results would also be applicable to a situation in which the train is located in the vicinity of the fan shaft at 565+00 (FE-2). As the alignment and other features of the E Route have not been finalized, the fan shaft identification numbers are temporary and assigned only for use in this study.

- Run No. 1

  In this scenario, the disabled train was located outbound of EF-1 (Train Location 1) with the fire at the front end of the train. FE-1 was selected as the point of exit from the system. Therefore, the desired direction of air flow was outbound, and the fans in FE-1 were placed in the supply mode while the fans in FE-2 were placed in the exhaust mode. Fan capacities were unchanged from the original design (100,000 CFM per shaft) and blockage was not used. The results indicate that after approximately 160 seconds, the tunnel air flow reversed direction becoming opposite to the direction of flow the tunnel ventilation fans were attempting to establish. See Graph No. 1.

- Run No. 2

  This run was conducted under circumstances identical to those used for Run No. 1 with the exception that blockage devices were placed at the base of FE-1. This action eliminated the reversal of air flow found in Run No. 1, however, the air velocity of approximately 60 FPM was far short of criteria. See Graph No. 1.

- Run No. 3

  For this run, total nominal fan capacities at each shaft were increased from 100,000 CFM to 200,000 CFM. All other conditions remained unchanged from Run No. 2. While the additional capacity resulted in a significant improvement, the final air velocity of approximately 180 FPM failed to meet criteria. See Graph No. 1.

- Run No. 4

  Run No. 4 was made with total nominal fan capacities of 300,000 CFM at each shaft. The other pertinent conditions remained unchanged from Run No. 3. Again, the increased capacities resulted in a significant improvement. However, the approximately 280 FPM final velocity was still short of criteria. See Graph No. 1.

- Run No. 5

  This run was conducted with conditions identical to those used during Run No. 4 except that blockage devices were placed at the base of EF-2. Introduction of the additional blockage resulted in a simulated air velocity of approximately 390 FPM which exceeds criteria by four percent. See Graph No. 1.

- Run No. 6

  In order to ascertain the degree to which blockage schemes effect tunnel air velocities, the conditions in Run No. 5 were modified for Run No. 6 to reflect total nominal fan capacities of 200,000 CFM in lieu of 300,000 CFM in each shaft. The results of this run indicate a final air velocity of 260 FPM. See Graph No. 1. A partial blockage situation (at only one shaft) with 300,000 CFM fan capacities such as that illustrated by Run No. 4 produced results similar to those of this run. It appears that placing blockage devices at the base of each of the fan shafts is roughly equivalent to increasing total fan capacities by 100,000 CFM per shaft.

- Run No. 7

  Without shifting the location of the train, the fire was repositioned to the rear of the train. Consistent with previously established procedures to evacuate patrons in the direction which placed the majority of patrons away from the fire, the exit path was changed so that the vent shaft at Sta. 550+00 became the point of exit. Correspondingly, the fans in FE-1 were operated in exhaust, while the fans in FE-2 were operated in supply. Total nominal fan capacities were returned to the original 100,000 CFM per shaft and no blockage was used. The resulting tunnel air velocity was approximately 130 FPM. See Graph No. 2. Unlike the basically similar Run No. 1, reversal of fan-induced air flow did not occur since the air flow resulting from buoyant effects coincided with and supplemented the fan-induced air flow.

o **Run No. 8**

Run No. 8 was similar to Run No. 7 except that blockage was provided at the base of each fan shaft. The resultant air velocity was 180 FPM. See Graph No. 2. Assuming that the fan capacities (300,000 CFM each shaft) and blockage device locations (at both shafts) as described for Run No. 5 would also produce sufficient air velocity in this case, no further runs were made.

o **Summary, E Route Runs**

In order to meet critical air velocity criteria, it is necessary to provide tunnel blockage devices at both FE-1 and FE-2, and to also increase total nominal fan capacities at each shaft as follows:

	EXISTING	REQUIRED
FE-1	2 at 50,000 CFM each	6 at 50,000 CFM each
FE-2	2 at 50,000 CFM each	6 at 50,000 CFM each

The wide difference in existing and required fan capacities can be accounted for by the fact that the existing fan shafts were sized based on ventilation required to remove heat rejected by the train during normal operations. In this particular section of the system, there is no station, consequently, the train does little braking, greatly reducing the major source of heat.

F ROUTE (Sta. 52+66 to 204+17) (Reference Sketches SCS-F2-1 and SCS-F2-2)

o **Run No. 1**

For the initial run, the train was located on a 3.96 percent grade between FF-5 and Navy Yard Station (Train Location No. 1). The selected point of exit from the system was Navy Yard Station, so fans in FL-1, FF-3, FF-4, Water Front and Navy Yard were operated in supply while fans in FF-5, FF-6 and Anacostia were operated in exhaust. Fan capacities were in accordance with the original design and no blockage was used. The final tunnel air velocity was approximately 50 FPM. See Graph No. 1.

o **Run No. 2**

For this run, the train location, evacuation route, fan capacities and fan operating modes remained identical to those used for Run No. 1. However, blockage devices were placed at the extreme ends of the system in the vicinity of FF3 and FF6. The final tunnel air velocity for this run slightly exceeded 50 FPM. See Graph No. 1. Since this represents only a minimal improvement over the results of Run No. 1, this blocking strategy is ineffective. Apparently there is too much leakage of air into and out of the tunnels between the blockage points and the disabled train.

- Run No. 3

  The tunnel blockage scheme was revised for this run by moving the blockage devices to the bases of FF-4 and FF-5. Other conditions remained unchanged from Runs No. 1 and No. 2. This action resulted in a significant increase in tunnel air velocity to approximately 280 FPM. See Graph No. 1.

- Run No. 4

  Again, the tunnel blockage scheme was revised with other conditions remaining unchanged from the preceding runs. The blockage devices placed at FF-4 and FF-5 were retained with partial blockage also provided in both entrances to Navy Yard Station. This strategy resulted in an approximate tunnel air velocity of 300 FPM, or an improvement of 7 percent over the results of Run No. 3. See Graph No. 1.

- Run No. 5

  Since it was not possible to achieve the required air velocities with blockage strategies only, increases were then made in fan capacities. The nominal capacities of individual tunnel ventilation fans were increased from 50,000 CFM to 60,000 CFM. Therefore, the resulting total capacities were 120,000 CFM at FL-1, 240,000 CFM at FF-3, 180,000 CFM at FF-4, 240,000 CFM at FF-5 and 120,000 CFM at FF-6. The train remained on the 3.96 percent grade between FF-5 and Navy Yard, and Navy Yard Station also remained as the point of exit. Fans in FL-1, FF-3, FF-4, Waterfront and Navy Yard were operated in supply and fans in FF-5, FF-6 and Anacostia were operated in exhaust. Blockage was provided at FF-4 and FF-5. The resulting tunnel air velocity was approximately 360 FPM. See Graph No. 1.

- Run No. 6

  Since the results of Run No. 4 demonstrated the improvement possible by partial entrance blockage, Run No. 6 was set up in a similar fashion. The train location, exit path, fan operating modes and fan capacities remained unchanged from Run No. 5, but in addition to blockage at FF-4 and FF-5, the entrances at Navy Yard Station were also partially blocked. The resulting air velocity was approximately 380 FPM, meeting the criteria. See Graph No. 1.

- Summation, Runs No. 1 through No. 6

  It was necessary to provide an overall increase in fan capacities and deploy blocking devices at the Navy Yard Station entrances in addition to blocking devices at FF-4 and FF-5. Since the highest air velocity achieved (380 FPM) represents only a 1.3 percent increase over criteria, it appears that fan capacity reductions in FF-3 and FF-6 would result in a system which could not meet criteria. Consequently, it is required that all tunnel fans in the simulated section (FL-1, FF-3, FF-4, FF-5, and FF-6) be increased from 50,000 CFM to 60,000 CFM, each.

In the case of Run No. 6, the increase in tunnel air velocity resulting from partial blockage of the Navy Yard Station entrances was sufficient to meet criteria.

- Run No. 7

  For this run, the train was positioned on a 0.35 percent grade between FF-4 and Navy Yard Station (Train Location No. 2) with the fire at the rear of the train. Navy Yard Station was again selected as the point of exit from the system. Fans in FL-1, FF-3, FF-4 and Waterfront were operated in exhaust and fans in FF-5, FF-6, Navy Yard and Anacostia were operated in supply. No blockage was used, and fan capacities remained at the levels established in earlier runs (60,000 CFM). The resulting air velocity was approximately 230 FPM. See Graph No. 2.

- Run No. 8

  Since criteria was not met in Run No. 7, blockage was provided at FF-4 and FF-5. All other conditions were consistent with Run No. 7. While the final tunnel velocity increased to approximately 330 FPM, the increase was not sufficient to meet criteria. See Graph No. 2.

- Run No. 9

  Since partial blockage of station entrances had been successfully used in Run No. 6, the same strategy was used for this run. Therefore, all conditions remained unchanged from Run No. 8 with the exception that blockage was added at both entrances to Navy Yard Station. The addition of partial entrance blockage resulted in a final tunnel air velocity of approximately 350 FPM. See Graph No. 2. The increase of 20 FPM caused by entrance blockage is consistent with the increase experienced in Run No. 6 under similar circumstances.

- Run No. 10

  Since tunnel and station entrance blockage did not result in sufficient air velocity, fan capacities were increased for this run. The train location, exit path, blockage scheme, and fan operating modes remained unchanged from Run No. 9. However, the number of fans at FF-4 was increased from three at a nominal capacity of 60,000 CFM each to four at 60,000 CFM each. This resulted in a total nominal capacity of 240,000 CFM at FF-4. The resulting tunnel air velocity was approximately 420 FPM. See Graph No. 2.

- Summation, Runs No. 7 through No. 10

  In order to produce a tunnel air flow which met or exceeded criteria, it was necessary to provide blockage at FF-4, FF-5 and Navy Yard Station entrances, increase all fans to 60,000 CFM, and increase the total number of fans at FF-4 from three to four.

o **Run No. 11**

For this run, the train was positioned on a four percent grade between FF-5 and emergency access shaft EF-1 at STA. 169+70 (Train Location No. 3.). EF-1 was also selected as the point of exit from the system. Fans at FL-1, FF-3, FF-4, FF-5, Waterfront and Navy Yard were operated in exhaust, while fans in FF-6 and Anacostia were operated in supply. Fan capacities were identical to these used during Run No. 10. Blockage was provided at FF-5, FF-6 and at both entrances to Anacostia Station. The final tunnel air velocity was approximately 360 FPM. See Graph No. 3.

o **Run No. 12**

For this run, the fan capacity at FF-6 was increased by the addition of two fans at 60,000 CFM each, resulting in a total of four fans and a total capacity of 240,000 CFM. All other conditions remained unchanged from Run No. 11. The final tunnel air velocity was approximately 380 FPM. See Graph No. 3.

o **Summation, Runs No. 11 and No. 12**

Compliance with criteria required blockage at FF-5, FF-6 and Anacostia Station entrance ways, increasing all fans to 60,000 CFM, and the addition of 2 fans at FF-6 and 1 at FF-4.

o **Summary, F Route Runs**

The final tunnel ventilation fan capacities resulting from all F Route runs are as follows:

	EXISTING	REQUIRED
FF-3	4 at 50,000 CFM	4 at 60,000 CFM
FF-4	3 at 50,000 CFM	4 at 60,000 CFM
FF-5	4 at 50,000 CFM	4 at 60,000 CFM
FF-6	2 at 50,000 CFM	4 at 60,000 CFM

Blockage was found to be necessary at all fan shafts on the F Route and also at Navy Yard and Anacostia Stations.

While FL-1 fan capacities were modified during the course of these runs, final recommendations regarding their capacity and blockage require runs specifically simulating the L route.

B Route (Sta. 480+30 to 1230+60) (Reference Sketches SCS-B9-1 and SCS-B9-2)

o **Run No. 1**

The initial simulation was made with the train between Emergency Egress

EB-1 (Sta 982+44) and Fan Shaft FB-5 (Sta 1017+20) (Train Location No. 1) on a 3.3 percent grade. The evacuation route was to EB-1, therefore, fans at FB-5, FB-6, FB-7, FB-8, FB-9, Forest Glen, Wheaton and Glenmont Stations were all placed in the exhaust mode. Fan capacities were in accordance with the original design and blockage was not used. The simulation indicated an air velocity of 670 FPM which greatly exceeded the critical velocity of 375 FPM. See Graph No. 1.

- Run No. 2

  While Run No. 1 indicated an air flow well above the criteria, there was concern that smoke would be drawn into Forest Glen Station with all fans in the exhaust mode. To explore this situation, Run No. 2 was made with the train location, exit path, and fan capacities unchanged from Run No. 1, the fans in FB-5 still in the exhaust mode, but with the fans in Forest Glen Station in the supply mode and all other fans turned off. Blockage was not used. This resulted in an air flow of only 200 FPM. See Graph No. 1.

- Run No. 3

  Since the conditions set up for Run No. 2 did not provide the required minimum velocity, the next step was to establish the minimum number of fans required to meet criteria. Run No. 3 was therefore made with the fans in FB-5, FB-6, FB-7 and Forest Glen Station in the exhaust mode, and all other fans off. The train location and exit path remained unchanged but blockage was provided at FB-7. Fan capacities at FB-6 and FB-7 had been increased for another run and were left at that capacity. This resulted in an air flow of 840 FPM which exceeded even that obtained in Run No. 1. See Graph No. 1.

- Run No. 4

  Because of the high air flow indicated by Run No. 3, one more run was made with the train in the same location. The fans in FB-5 were left in the exhaust mode, blockage was provided at FB-5, and all other fans were turned off. FB-5 fan capacities were in accordance with the original design. This resulted in an air flow of approximately 470 FPM, still well over the criteria. See Graph No. 1.

- Summation, Runs No. 1 through No. 4

  Because of the minimum resistance to air flow presented by the tunnel portal, the criteria for air flow around a stalled train in Location No. 1 can be met by placing all the existing fans in the exhaust mode with no blockage. However, running all the fans in exhaust could cause smoke to be drawn into Forest Glen Station and other sections of tunnel in addition to the un-needed use of electrical power. This can be prevented and the air flow criteria still met by placing blockage at FB-5 and running only those fans in FB-5 in exhaust.

- Run No. 5

  For this run, the train was located between FB-5 and Forest Glen Station (Train Location No. 2.) on a 0.35 percent grade. The evacuation route was now to Forest Glen Station, therefore, the fans at FB-5 were placed in exhaust mode with all other fans in the supply mode. Blockage of the open tunnels was provided at FB-5 and FB-6. Fan capacities remained unchanged from the original design. The final air velocity of 800 FPM greatly exceeded the criteria. See Graph No. 2.

- Run No. 6

  Since criteria was substantially exceeded during Run No. 5, all blockage was removed for this run so that the effect of blockage on the results could be determined. In addition, due to requirements resulting from other B Route runs, increased nominal fan capacities of 240,000 CFM, each, were simulated at FB-6, FB-7, FB-8 and FB-9 (See Run Nos. 8 and 15). Train location, evacuation route and fan operating modes remained unchanged from Run No. 5. The resulting air velocity was approximately 650 FPM. See Graph No. 2.

- Summation, Runs No. 5 and 6

  Blockage is not a necessity in this case since an air velocity of 650 FPM can be achieved without it. However, it should be recognized that the 650 FPM velocity does reflect increased fan capacities at FB-6, FB-7 FB-8 and FB-9.

- Run No. 7

  For Run No. 7, the train was moved to a location between FB-6 and FB-7 (Train Location No. 3) on a 4.0 percent grade. The evacuation route was to FB-7, therefore, the fans at FB-5, FB-6 and Forest Glen Station were placed in exhaust with all other fans in the supply mode. Blockage was provided at FB-6 and FB-7, and fan capacities were in accordance with the original design. The final air velocity was 370 FPM or approximately 1.3 percent below criteria. See Graph No. 3.

- Run No. 8

  Since air velocity criteria was not met during Run No. 7, individual fan capacities at FB-6, FB-7, FB-8 and FB-9 were increased from 50,000 to 60,000 CFM each. The criteria could have probably been met by increasing the fan capacities in FB-6 and FB-7 only, however, increased fan capacities in FB-8 and FB-9 were required under other conditions, reference Run No. 15. All other conditions remained unchanged. The resulting tunnel air velocity was approximately 440 FPM. See Graph No. 3.

- Run No. 9

  With blockage at the fan shafts on either side of the disabled train location, it would appear that fans beyond the blockage would have very limited effect on air flow between the blockage. Run No. 9 was made to check this. Run No. 9 differs from Run No. 8 only in having the fans outside the blockage (FB-5, Forest Glen Station, Wheaton Station, FB-8, FB-9 and Glenmont Station) turned off. The resulting tunnel air velocity was only approximately 200 FPM or less than one-half of that obtained in Run No. 8. See Graph No. 3.

- <u>Summation, Runs No. 7 through 9</u>

  In order to meet critical air velocity criteria, a combination of tunnel blockage and fan capacity increases were required. For this particular series of runs, nominal fan capacities at FB-6 and FB-7 were increased from 4 fans at 50,000 CFM each to 4 fans at 60,000 CFM each. The capacities of fans in FB-8 and FB-9 had already been increased to meet other conditions. No change was required to FB-5.

- <u>Run No. 10</u>

  This was the first in a series of runs simulating a train located between FB-7 and Wheaton Station (Train Location No. 4) on a four percent grade with Wheaton Station as the point of exit. Fans at FB-5, FB-6, FB-7 and Forest Glen Station were placed in exhaust, while fans at FB-8, FB-9, Wheaton and Glenmont were placed in supply. Since it was anticipated that meeting criteria would prove difficult, blockage devices were placed at FB-7 and FB-8. Fan capacities were in accordance with the original design. Final air velocity was approximately 660 FPM. See Graph No. 4.

- <u>Run No. 11</u>

  The train location, exit path, fan capacities and fan operating modes were identical to Run No. 10. However, the blockage provided at FB-7 and FB-8 was removed in order to gauge the effectiveness of this strategy. The final air velocity was reduced to 540 FPM. See Graph No. 4.

- <u>Run No. 12</u>

  Since data obtained in Run Nos. 10 and 11 indicated unexpectedly high air velocities, an additional run was performed to determine the extent to which certain factors influence the results. The train location and exit path were identical to those used for Run Nos. 10 and 11. However, fan operating modes were modified such that fans in FB-5, FB-6, FB-7 and Forest Glen operated in exhaust, and fans in FB-8, FB-9, and Glenmont Station operated in supply. Fan capacities remained unchanged from Run No. 11 and again, blockage was not provided. Wheaton station systems were not operated during this run in order to determine their effect. Under these conditions, final air velocity was approximately 430 FPM. See Graph No. 4.

- <u>Summation, Runs No. 10 through 12</u>

  Critical air velocity criteria was exceeded without increasing fan capacities or providing tunnel blockage devices. In addition, it was not necessary to operate the fans at Wheaton Station. However, in this situation, operation of Wheaton Station ventilation systems in the supply mode would provide additional insurance against smoke migration into the station.

- Run No. 13

  For this run, the train was located on a 3.95 percent grade between FB-8 and FB-9 (Train Location No. 5), with the evacuation route to FB-9. Fans in FB-5, FB-6, FB-7, FB-8, Forest Glen and Wheaton were operated in exhaust, while fans in FB-9 and Glenmont were operated in supply. No blockage was used and fan capacities remained unchanged from the original design. The resulting air velocity was approximately 280 FPM. See Graph No. 5.

- Run No. 14

  Since critical air velocity criteria was not met in Run No. 14, blockage was provided at FB-8 and FB-9. All other conditions remained unchanged from Run No. 13. The resulting air velocity was approximately 350 FPM. See Graph No. 5.

- Run No. 15

  Since blockage did not produce the necessary air velocity increase, individual fan capacities at FB-8 and FB-9 were increased from 50,000 CFM each to 60,000 CFM each. Train location, evacuation route, fan operating modes, and blockage strategies remained unchanged from Run No. 14. The resulting air velocity was approximately 400 FPM. See Graph No. 5.

- Summation, Runs No. 13 through 15

  In order to meet/exceed critical air velocity criteria, it is necessary to provide blockage and increase total nominal fan capacities from 200,000 to 240,000 CFM, each, at FB-8 and FB-9.

- Summary, B Route Runs

  While conditions at individual locations didn't necessarily require all fans to be increased in capacity, the summation of simulations at various locations resulted in requirements for increased fan capacities at all fan shafts except FB-5. In all cases, the increased capacity can be met by increasing individual fan capacity and not adding fans. Based on all B Route runs, the final fan capacities are as follows:

	EXISTING	REQUIRED
FB-5	6 at 50,000 CFM each	6 at 50,000 CFM each
FB-6	4 at 50,000 CFM each	4 at 60,000 CFM each
FB-7	4 at 50,000 CFM each	4 at 60,000 CFM each
FB-8	4 at 50,000 CFM each	4 at 60,000 CFM each
FB-9	4 at 50,000 CFM each	4 at 60,000 CFM each

Although tunnel blockage was not a necessity in every case simulated on the B Route, blockage was required at FB-5, FB-6, FB-7, FB-8 and FB-9 during various runs in order to insure compliance with criteria. Blockage of station entrances was not required.

X. CORRECTIVE ACTIONS

The program runs demonstrated the desirability of using blockage devices as a means of controlling tunnel air flows during an emergency situation. As a result, the use of these devices is recommended at all fan shafts contained in the tunnel sections simulated as part of this study. A description of the preferred blockage device is given in Section VI of this report.

In cases where it was not possible to meet criteria with blockage alone, an increase in fan capacity and/or fan quantities is necessary. Recommended actions are given in Table 1. Where a standard WMATA tunnel ventilation fan (Joy Mod. No. 60-26-870 or equivalent; 50,000 CFM @ 1.4" W G, 20 HP) is not sufficient, an appropriate alternate is identified.

Costs estimates given in Table 1 consist of order-of-magnitude figures associated with structural, electrical and mechanical modifications and illustrate the difference between the modified and originally conceived versions of the fan shafts. Exact costs will have to be determined following detailed redesign of the affected shafts, mechanical equipment and electrical distribution systems. Blockage device costs are given on Table 2, and consist of developmental and installation costs. Table 3 contains a summary of the cost data given on Tables 1 and 2.

TABLE 1

RECOMMENDED CORRECTIVE ACTIONS

FAN SHAFT	INITIAL CONDITION	PROPOSED ACTION	ESTIMATED COST
	E ROUTE		
FE-1	2 FANS AT 50,000 CFM, 20 HP EACH	ADD 4 FANS AT 50,000 CFM, 20 HP EACH	$182,900
FE-2	2 FANS AT 50,000 CFM, 20 HP EACH	ADD 4 FANS AT 50,000 CFM, 20 HP EACH	$302,900
		TOTAL	$485,800
	F ROUTE		
FF-3	4 FANS AT 50,000 CFM, 20 HP EACH	REPLACE WITH 4 FANS AT 60,000 CFM, 30 HP EACH	$19,000
FF-4	3 FANS AT 50,000 CFM, 20 HP EACH	REPLACE 3 FANS AND ADD 1 FAN, ALL AT 60,000 CFM, 30 HP EACH	$306,800
FF-5	4 FANS AT 50,000 CFM, 20 HP EACH	REPLACE WITH 4 FANS AT 60,000C FM, 30 HP EACH	$19,000
FF-6	2 FANS AT 50,000 CFM, 20 HP EACH	REPLACE 2 AND ADD 2 FANS AT 60,000 CFM, 30 HP EACH	$166,700
		TOTAL	$511,500
	B ROUTE		
FB-5	6 FANS AT 50,000 CFM, 20 HP EACH	NO CHANGE	$0
FB-6	4 FANS AT 50,000 CFM, 20 HP EACH	REPLACE WITH 4 FANS AT 60,000 CFM, 30 HP EACH	$19,200
FB-7	4 FANS AT 50,000 CFM, 20 HP EACH	REPLACE WITH 4 FANS AT 60,000 CFM, 30 HP EACH	$20,000
FB-8	4 FANS AT 50,000 CFM, 20 HP EACH	REPLACE WITH 4 FANS AT 60,000 CFM, 30 HP EACH	$21,000
FB-9	4 FANS AT 50,000 CFM, 20 HP EACH	REPLACE WITH 4 FANS AT 60,000 CFM, 30 HP EACH	$21,000
		TOTAL	$81,200

TABLE 2

BLOCKAGE DEVICE COSTS

ITEM		ESTIMATED COST
Development		- $70,000
E Route:		
Tunnel Blockage Devices, 8 total		- $40,000
F Route:		
Tunnel Blockage Devices, 16 total		- $80,000
Station Entrance Blockage Devices, 4 total*		- $40,000
	Total	- $120,000
B Route:		
Tunnel Blockage Devices, 20 total		- $100,000

*Note: Cost includes development and testing costs.

TABLE 3

COST SUMMARY

Tunnel Blockage Device Development:		- $70,000
E Route:		
Fan Shaft Modifications		- $485,000
Blockage Devices		- $40,000
	Total (E Route)	- $525,000
F Route:		
Fan Shaft Modifications		- $511,500
Blockage Devices		- $120,000
	Total (F Route)	- $631,500
B Route:		
Fan Shaft Modifications		- $81,200
Blockage Devices		- $100,000
	Total (B Route)	- $181,200
	Total	- $1,407,700

XI. GENERAL OBSERVATIONS

On the basis of the computer simulation results described in the preceding section, general observations regarding tunnel ventilation performance are as follows:

- The minimum acceptable fan shaft capacity appears to be 240,000 CFM when it is possible to reinforce the flows produced by the fan shafts closest to the fire with flows from additional fan shafts and station ventilation systems. This is the case on both the simulated sections of the B and F Routes. In the case of the E Route section, where it is not possible to reinforce the air flows produced by the closest fans, the minimum fan shaft capacity requirement was 300,000 CFM.

- Tunnel blockage and the simultaneous operation of additional fans located beyond the limits of the blockage initially appeared to be counter productive. For example, while operation of additional fans is intended to reinforce air flows produced by the fans closest to the fire, blockage would seem to have the opposite effect of minimizing the contribution of the reinforcing fans to flow past the train. However, as demonstrated by B Route Run No. 9, the effectiveness of tunnel blockage is enhanced by operation of reinforcing fans. To illustrate this, consider a typical scenario in which a fan shaft located on the in-bound side of a burning train is to be operated in exhaust and provided with blockage. Further, a fan shaft located beyond the blockage is also to be operated in exhaust as flow reinforcement. In this situation, the blockage devices are essentially located between both shafts. Since the fans in both shafts are operating in the exhaust mode, it can be seen that the flow across the blockage device produced by one fan shaft will be opposite in direction to the flow produced by the other fan shaft. As a result, the net flow across the blockage device would be reduced. Since zero leakage would be the result of a perfect blockage device, a reduction in flow across the device improves the apparent effectiveness of that device. The same situation exists with fans operating in supply.

- The location of the fire on board a train is a major factor in determining the most effective evacuation path. A fan operation and tunnel blockage scheme which will produce a safe evacuation path leading from one end of the train will also force smoke and heated gases to flow beyond the other end of the train. Since it may not be possible for patrons on one side of the fire to cross to the other, some patrons may be forced to use an evacuation path which is inundated with smoke and hot gases. Evacuation paths should therefore be selected to minimize the risk for the majority of patrons.

- In general, the tunnel ventilation systems on the B Route section performed much better than expected under certain circumstances. When compared to the F Route section, the B Route section is a relatively tighter system due to the reduced number of flow paths to the surface. Specifically, the B Route section consists of three stations but contains only two entrances which are open to the surface. While the F Route section contains the same number of stations, there are also a total of five entrances which are open to the surface. Therefore, there is a greater potential for air to "leak" out of the system on the simulated F Route section.

- Since the simulated section of the E Route did not contain any stations, the resulting performance levels could be expected to exceed those experienced during B Route runs. However, E Route run results indicated otherwise. This situation is a consequence of the total installed fan capacities for each Route. The E Route section will have a total nominal fan capacity of 600,000 CFM if recommendations are followed. By comparison, the B Route section will be equipped with a total nominal fan capacity of 1,710,000 CFM, or an increase of 285% over the E Route section. The B Route section installed capacity also exceeds the F Route section installed fan capacity of 1,320,000 CFM.

- Due to the difference in results obtained for each route, generalizations regarding fan capacities in terms of tunnel grades would only apply to the specific route and would not necessarily be valid for any other route.

- It appears that deployment of blockage devices is effective at increasing the influence of fan-induced flows and, consequently, diminishing the influence of buoyant effects. This conclusion is based on the observation that even though the results of runs without blockage appear to highly variable, runs made with blockage tend to indicate more predictable behavior.

- The condition illustrated by E Route Runs No. 7 and 8 is not a worst case situation since buoyancy causes the flow of heated gases and smoke to be in the same direction as the flow produced by the fans. While it is probably not necessary in this type of situation to achieve a 375 FPM air velocity for the purpose of maintaining a smoke free path, the modifications required to insure this capability in other situations will also make it possible to achieve this air velocity in this case.

XII. CONCLUSIONS AND RECOMMENDATIONS

Program run results indicate that present tunnel ventilation system capacities are generally not sufficient to produce the required critical air velocities. In some cases, the required critical air velocity can be achieved by the proper deployment of blockage devices. However, to insure that critical air velocities can be maintained at all points along a particular route, it is necessary to increase total fan shaft capacities in addition to providing blockage devices. Increases in total fan shaft capacities may be accomplished by increasing individual fan capacities, providing additional fans in selected shafts, or a combination thereof. Increases in station dome and underplatform exhaust system capacities were not considered in this study. While capacity increases in these systems may prove beneficial, the potential for negative impact on station environmental systems intended for normal operations and the necessary structural modifications would require detailed study prior to the development of any scheme.

In addition to the need for modifications to the existing tunnel ventilation concept, program results also illustrated the necessity for computerized, preplanned responses to tunnel fire situations. In the case of a burning train disabled in a tunnel, OCC personnel will be obliged to determine the safest patron evacuation route on the basis of the actual location of the fire and the available points of exit from the system. When this step is completed, it will then be necessary to determine correct fan operating modes and blockage device deployment. As shown on the sketches, the steps necessary to produce conditions which are in conformance with criteria can be relatively complex and may not necessarily be immediately obvious. A preplanned procedure would prove advantageous by reducing response time to fire situations through the elimination of unnecessary decision-making by OCC personnel, and by providing some guarantee that the response will be proper.

In cases where ventilation system performance as predicted by SES program runs only minimally exceeds criteria, field tests should be conducted to verify program results. In order to fully assess the performance of any system modifications, it will be necessary to develop a means of reasonably approximating the buoyant effects produced by a tunnel fire. Tests would then be conducted employing fan operating modes, tunnel blockage schemes, and fire locations consistent with previous computer runs. This procedure would allow direct comparisons between measured and computer-generated results and would also serve to validate, to some degree, Version 3 of the SES program. This version of the SES program is relatively recent and has yet to be released by the Department of Transportation for general use.

On the basis of the preceding discussions, the following actions are recommended:

1) Provide blockage devices at the base of each fan shaft covered under this study,

2) Increase fan capacities and quantities as specified in Table 1,

3) Proceed with detailed design and prototype testing of blockage devices,

4) Expand existing tunnel ventilation control systems to provide for both remote and over-riding local activation of blockage devices,

5) Devise and execute field tests designed to verify SES computer run results in cases where program results only minimally exceed criteria, and

6) Proceed with a program designed to establish a standard operating procedure for OCC personnel to follow in the event of tunnel fire. This procedure would apply to the entire system and would specify fan and blockage device activation strategies in accordance with incident train and fire locations.

BIBLIOGRAPHY

1. Raymond Kaiser Engineers, "Metrorail Ventilation System Improvements and Vehicle Fire Hardening."

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

3. 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.

APPENDIX A

CRITICAL VELOCITY CALCULATIONS

Critical Velocity

Critical velocity is determined from the following coupled equations given in the SES Version III, User's Manual:

$$V_c = K_g \times K \left(\frac{g \times H \times Q}{\rho_\infty \times C_p \times A \times T_f} \right)^{1/3}$$

$$T_f = \frac{Q}{\rho_\infty \times C_p \times A \times V_c} + T_\infty$$

where:

V_c	=	critical velocity, ft/sec = unknown
g	=	acceleration due to gravity, ft/sec^2 = 32.2
H	=	tunnel height, ft = 13
Q	=	fire heat release rate, BTu/sec = 5555.555 = 20x10^6 BTUH
ρ_∞	=	ambient air density, 1bm/ft^3 = 0.075
C_p	=	specific heat of air at constant pressure, Btu/1bm-deg R = 0.244
A	=	net cross-sectional area of tunnel, ft^2 = 200
T_f	=	hot gas temperature, deg R = unknown
K	=	0.61 (dimensionless)
K_g	=	grade correction factor (dimensionless), from Fig. 16-3
T_∞	=	ambient temperature, deg R = 555 deg R = 95°F.

$$V_c = K_g \times K \left[\frac{g \times H \times Q}{\rho_\infty \times c_p \times A \times T_f} \right]^{1/3} \quad (1)$$

$$T_f = \frac{Q}{\rho_\infty \times C_p \times A \times V_c} + T_\infty \quad (2)$$

By solving equation (1) and (2) we can find V_c and T_f

By substitute equation (2) in equation (1) we get

$$V_c = K_g \times K \left[\frac{g \times H \times Q}{\rho_\infty \times c_p \times A \times \left[\frac{Q}{\rho_\infty \times c_p \times A \times V_c} + T_\infty \right]} \right]^{1/3}$$

$$V_c = K_g \times K \left[\frac{g \times H \times Q}{\frac{\rho_\infty \times c_p \times A \times Q}{\rho_\infty \times c_p \times A \times V_c} + \rho_\infty \times c_p \times A \times T_\infty} \right]^{1/3}$$

$$V_c = K_g \times K \left[\frac{g \times H \times Q}{\frac{Q}{V_c} + \rho_\infty \times c_p \times A \times T_\infty} \right]^{1/3}$$

$$\frac{V_c}{K_g \times K} = \left[\frac{g \times H \times Q}{\frac{Q}{V_c} + \rho_\infty \times c_p \times A \times T_\infty} \right]^{1/3}$$

$$\frac{V_c^3}{K_g^3 \times K^3} = \frac{g \times H \times Q}{\frac{Q}{V_c} + \rho_\infty \times c_p \times A \times T_\infty}$$

DeLEUW CATHER
De Leuw, Cather & Company
Engineers and Planners
SUBJECT ______ JOB NO. ______
SHEET NO. 3 OF 16
MADE BY Osama K. DATE 8/85 CHECKED BY [signature] DATE 9/10/85

$$\frac{V_c^3}{K_g^3 \times K^3} = \frac{g \times H \times Q}{\frac{Q}{V_c} + \frac{\rho_\infty \times c_p \times A \times T_\infty \times V_c}{V_c}}$$

$$\frac{V_c^3}{K_g^3 \times K^3} = \frac{g \times H \times Q \times V_c}{Q + \rho_\infty \times c_p \times A \times T_\infty \times V_c}$$

$$Q\,V_c^3 + \rho_\infty \times c_p \times A \times T_\infty \times V_c^4 = K_g^3 \times K^3 \times g \times H \times Q \times V_c$$

$$Q\,V_c^3 + \rho_\infty \times c_p \times A \times T_\infty \times V_c^4 - K_g^3 \times K^3 \times g \times H \times Q \times V_c = 0$$

$$V_c\,(\rho_\infty \times c_p \times A \times T_\infty \times V_c^3 + Q\,V_c^2 - K_g^3 \times K^3 \times g \times H \times Q) = 0$$

To solve this equation, we should use the method which is used in algebra to solve equations of higher degree

either $V_c = 0$

or $\underbrace{\rho_\infty \times c_p \times A \times T_\infty}_{a} \times V_c^3 + \underbrace{Q}_{b} V_c^2 \underbrace{- K_g^3 \times K^3 \times g \times H \times Q}_{d} = 0$

So we have this kind of equation

$$a\,V_c^3 + b\,V_c^2 + c\,V_c + d = 0$$

$a = \rho_\infty \times c_p \times A \times T_\infty$

$b = Q$

$c = 0$

$d = -K_g^3 \times K^3 \times g \times H \times Q$

DCO 16-45

$a = \rho_\infty \times c_p \times A \times T_\infty$

$= 0.075 \times 0.244 \times 200 \times 555 = 2031.3$

$\underline{a} = \underline{2031.3}$

$\underline{b} = Q = \underline{5555.555}$

$\underline{c} = \underline{0}$

$d = -K_g^3 \times K^3 \times g \times H \times Q$

$d = -(1.113)^3 \times (0.61)^3 \times 32.2 \times 13 \times 5555.555$

$\underline{d} = \underline{-727782.6088}$

From algebra:

$$a V_c^3 + b V_c^2 + c V_c + d = 0 \qquad (3)$$

This reduces by the substitution

$$(4) \quad V_c = Y - \frac{b}{3a} \quad \text{to} \quad Y^3 + pY + q = 0$$

where

$$p = \frac{1}{3}\left[3\left(\frac{c}{a}\right) - \left(\frac{b}{a}\right)^2\right]$$

$$q = \frac{1}{27}\left[2\left(\frac{b}{a}\right)^3 - 9\left(\frac{b}{a}\right)\left(\frac{c}{a}\right) + 27\left(\frac{d}{a}\right)\right]$$

$$D = \left(\frac{p}{3}\right)^3 + \left(\frac{q}{2}\right)^2$$

$$u = \sqrt{-\frac{q}{2} + \sqrt{D}} \quad , \quad v = \sqrt[3]{-\frac{q}{2} - \sqrt{D}}$$

$$P = \frac{1}{3}\left[3\left(\frac{c}{a}\right) - \left(\frac{b}{a}\right)^2\right]$$

$$P = \frac{1}{3}\left[3\left(\frac{0}{2031.3}\right) - \left(\frac{5555.555}{2031.3}\right)^2\right]$$

$$\underline{P = -2.493}$$

$$q = \frac{1}{27}\left[2\left(\frac{b}{a}\right)^3 - 9\left(\frac{b}{a}\right)\left(\frac{c}{a}\right) + 27\left(\frac{d}{a}\right)\right]$$

$$q = \frac{1}{27}\left[2\left(\frac{5555.555}{2031.3}\right)^3 - 9\left(\frac{5555.555}{2031.3}\right)\left(\frac{0}{2031.3}\right) + 27\left(\frac{-727782.6088}{2031.3}\right)\right]$$

$$q = \frac{1}{27}\left[2 \times 20.4578 - 0 - 27 \times 358.2841\right]$$

$$q = 1.5154 - 358.2841$$

$$\underline{q = -356.7687}$$

$$D = \left(\frac{P}{3}\right)^3 + \left(\frac{q}{2}\right)^2$$

$$D = \left(\frac{-2.493}{3}\right)^3 + \left(\frac{-356.7687}{2}\right)^2$$

$$D = -0.5739 + 31820.9763$$

$$\underline{D = 31820.4024} \quad > 0$$

$$\underline{\sqrt{D} = 178.3827}$$

From algebra:

If a, b, c, d are real and if

D > 0 there are one real and two conjugate imaginary roots:

$$Y_1 = u + v$$

$$Y_2 = -\frac{u+v}{2} + \frac{u-v}{2} i\sqrt{3}$$

$$Y_3 = -\frac{u+v}{2} - \frac{u-v}{2} i\sqrt{3}$$

$$u = \sqrt[3]{-\frac{q}{2} + \sqrt{D}}$$

$$u = \sqrt[3]{\frac{-(-356.7687)}{2} + 178.3827}$$

$$u = \sqrt[3]{178.38 + 178.38} = \sqrt[3]{356.76}$$

$$\underline{u = 7.092}$$

$$v = \sqrt[3]{-\frac{q}{2} - \sqrt{D}}$$

$$v = \sqrt{178.38 - 178.38} = \sqrt{0} = 0$$

$$\underline{v = 0}$$

DeLEUW CATHER
De Leuw, Cather & Company
Engineers and Planners
SUBJECT ______ JOB NO. ______
SHEET NO. 7 OF 16
MADE BY Osama K. DATE 8/85 CHECKED BY [illegible] DATE 9/10/85

$$Y_1 = u + v$$

$$Y_1 = 7.092 + 0$$

$$\underline{Y_1 = 7.092}$$

$$Y_2 = -\frac{u+v}{2} + \frac{u-v}{2} i\sqrt{3}$$

$$Y_2 = -3.546 + 3.546\, i\sqrt{3}$$

$$Y_2 = -3.546 + 6.1419\, i$$

$$Y_3 = -\frac{u+v}{2} - \frac{u-v}{2} i\sqrt{3}$$

$$Y_3 = -3.546 - 3.546\, i\sqrt{3}$$

$$Y_3 = -3.546 + 6.1419\, i$$

by substituting y_1 in equation (4)

$$V_c = Y - \frac{b}{3a}$$

$$V_c = 7.092 - \frac{5555.555}{3(2031.3)}$$

$$V_c = 7.092 - 0.9117$$

$$V_c = 6.18 \quad ft/sec$$

$$\boxed{V_c = 370.818 \quad ft/min}$$

by substituting the value of V_c in equation (2)

$$T_f = \frac{Q}{\rho_\infty \times c_p \times A \times V_c} + T_\infty$$

$$T_f = \frac{5555.555}{0.075 \times .244 \times 200 \times 6.18} + 555$$

$$T_f = 245.6167 + 555 =$$

$$\boxed{T_f = 800.6167^\circ \ R}$$

Now we want to see if we change the grade percentage what will happen to the Velocity (V_c)

In the other words, we want to plot a curve showing the relationship between the Velocity and grade percentage.

From figure 16-3

Grade (Percentage)	Kg
1.%	1.0375
2.%	1.065
3.%	1.09
4%	1.113
5%	1.135
6%	1.155

Finding the Velocity (Vc) depending on the value of Grade (percentage)

1- Grade (percentage) = 1 % From fig 16.3 ⇒ $K_g = 1.0375$

$a = 2031.3$

$b = 5555.555$

$c = 0$

$d = -(1.0375)^3 \times (061)^3 \times 32.2 \times 13 \times 5555.555$

$d = -589495.50$

$P = -2.493$

$q = 1.5154 - 290.206$

$q = -288.69$

$D = -0.5739 + 20835.569$

$D = 20834.995$

$\sqrt{D} = 144.34$

$u = \sqrt[3]{144.34 + 144.34}$

$u = 6.609 \quad , \quad v = 0$

$Y_1 = 6.609$

$V_c = Y_1 - \frac{b}{3a} = 6.609 - 0.9117$

$V_c = 5.6974$ ft/sec

$V_c = 341.845$ ft/min

DCO 16-45

2 - Grade (percentage) = 2 % From fig 16.3 ⟹ $K_g = 1.065$

$a = 2031.3$

$b = 5555.555$

$c = 0$

$d = -(1.065)^3 \times (0.61)^3 \times 32.2 \times 13 \times 5555.555$

$d = -637624.5114$

$P = -2.493$

$q = 1.5154 - 313.8997$

$q = -312.38$

$D = -0.5739 + 24395.9916$

$D = 24395.4177$

$\sqrt{D} = 156.19$

$u = \sqrt[3]{156.19 + 156.19}$

$u = 6.785$, $v = 0$

$Y_1 = 6.785$

$V_c = Y_1 - \frac{b}{3a} = 6.785 - 0.9117$

$V_c = 5.873$ ft/sec

$V_c = 352.41$ ft/min

3- Grade percentage = 3% From fig 16.3 ⇒ $K_g = 1.09$

$a = 2031.3$

$b = 5555.555$

$c = 0$

$d = -(1.09)^3 \times (0.61)^3 \times 32.2 \times 13 \times 5555.555$

$d = -683589.958$

$p = -2.493$

$q = 1.5154 - 336.5283$

$q = -335.01$

$D = -0.5239 + 28058.4126$

$D = 28057.83$

$\sqrt{D} = 167.50$

$u = \sqrt[3]{167.5 + 167.5}$

$u = 6.9451$, $v = 0$

$Y_1 = 6.9451$

$V_c = Y_1 - \frac{b}{3a} = 6.9451 - 0.9117$

$V_c = 6.0334$ ft / sec

$V_c = 362.0069$ ft / min

4- Grade percentage = 4% from fig 16.3 ⇒ $K_g = 1.113$

V_c is already found

$V_c = 370.818$

ft / min , $V_c = 6.18$ ft/sec

5- Grade percentage = 5% From fig 16.3 ⇒ $K_g = 1.135$

$a = 2031.3$

$b = 5555.555$

$C = 0$

$d = -(1.135)^3 \times (0.61)^3 \times 32.2 \times 13 \times 5555.555$

$d = -771798.2065$

$P = -2.493$

$q = 1.5154 - 379.9528$

$q = -378.4374$

$D = -0.5739 + 35803.7242$

$D = 5803.15$

$\sqrt{D} = 189.21$

$u = \sqrt[3]{189.21 + 189.21}$

$u = 7.2331$, $v = 0$

$Y_1 = 7.2331$

$V_c = Y_1 - \frac{b}{3a} = 7.2331 - 0.9117$

$V_c = 6.3214$ ft / sec

$V_c = 379.2842$ ft /min

6- Grade Percentage = 6 % From fig 16.3 ⇒ $K_g = 1.155$

$a = 2031.3$

$b = 5555.555$

$c = 0$

$d = -(1.155)^3 \times (0.61)^3 \times 32.2 \times 13 \times 5555.555$

$d = -813321.2756$

$P = -2.493$

$q = 1.5154 - 400.394$

$q = -398.87$

$D = -0.5739 + 39776.127$

$D = 39775.55$

$\sqrt{D} = 199.43$

$u = \sqrt[3]{199.43 + 199.43}$

$u = 7.361 \qquad v = 0$

$Y_1 = 7.361$

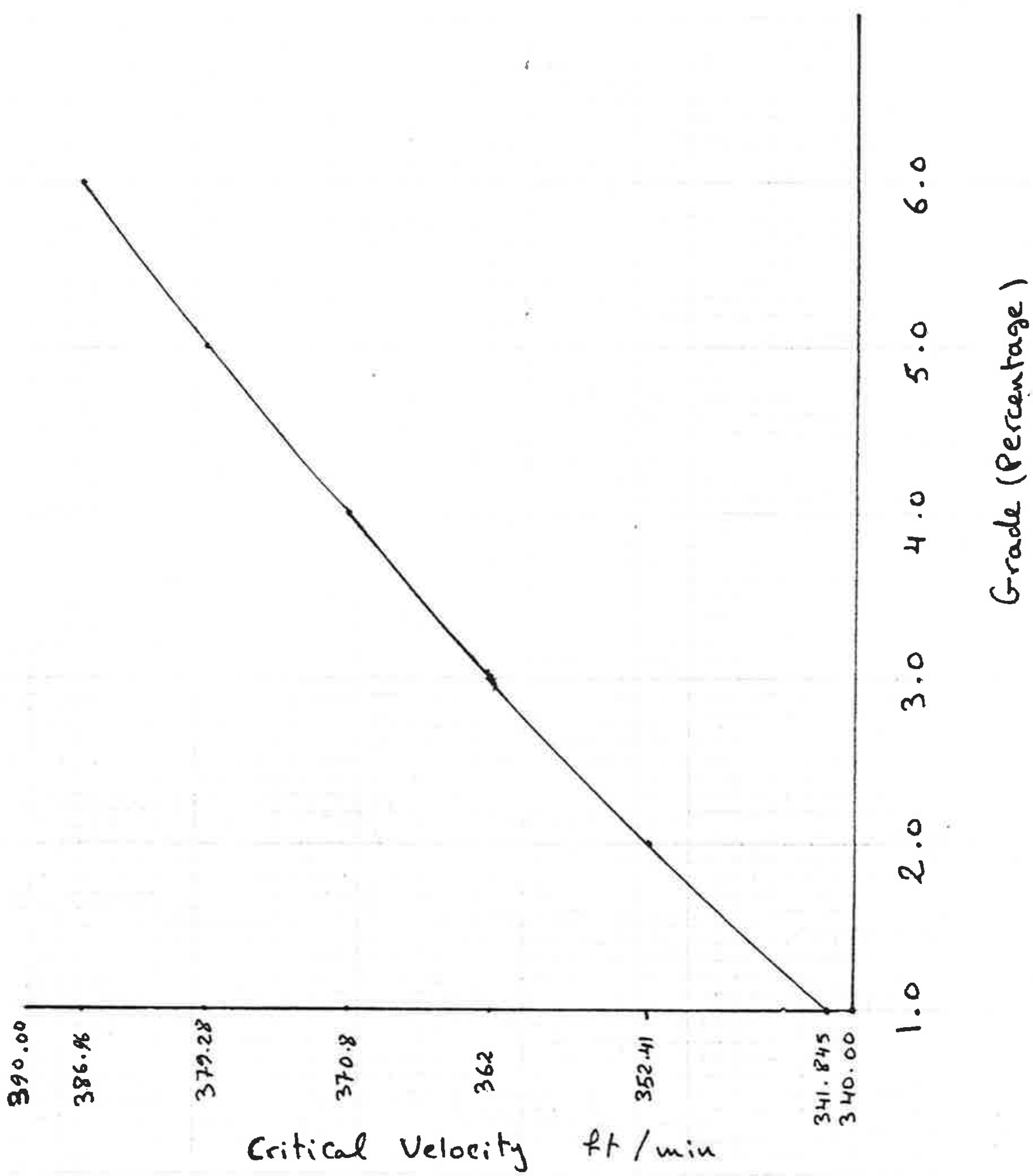
$V_c = Y_1 - \frac{b}{3a} = 7.361 - 0.9117$

$V_c = 6.4493$ ft / sec

$V_c = 386.9614$ ft / min

DeLEUW CATHER
De Leuw, Cather & Company
Engineers and Planners

SUBJECT ______ JOB NO. ______
SHEET NO. 15 OF 16
MADE BY Osama K. DATE 8/85 CHECKED BY [signature] DATE 7/10/85



Note: This curve has been adapted from data presented in, "Methane Roof Layers" by Bakke and Leach, S.M.R.E. Research Report No. 195, Sheffield, 1960.

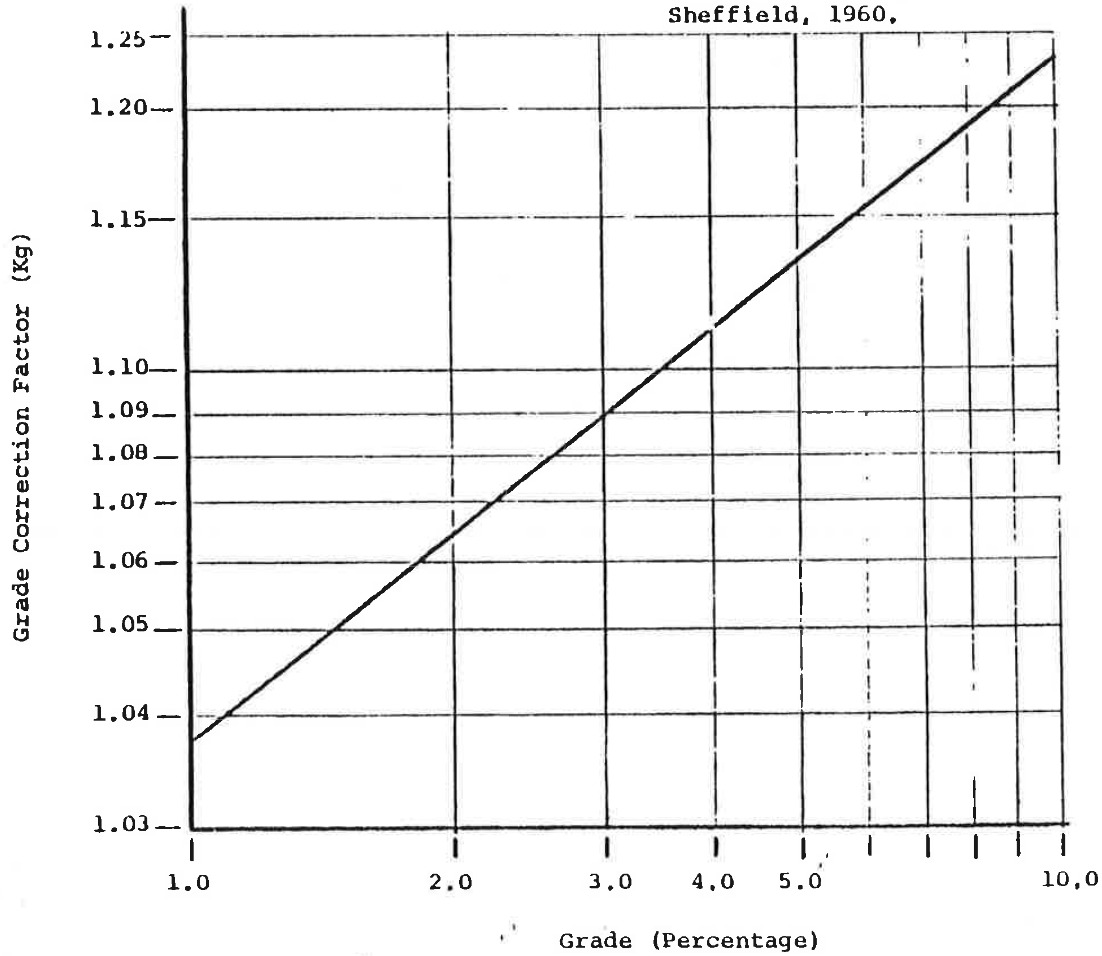


FIGURE 16-3 GRADE CORRECTION FACTOR

16 OF 16

APPENDIX B

PROPOSAL DEVELOPMENT OF TUNNEL BLOCKAGE DEVICE

Sheldahl

July 31, 1985

Mr. John Bumanis
DeLeuw, Cather and Company
600 Fifth Street Northwest
Washington, D.C. 20001

SUBJECT: Proposed Air Block Development

Dear John:

We are pleased to provide our preliminary proposal for development of inflatable air blocks for use in the Washington, D.C. subway system. We have based our proposal on information you have supplied, previous work related to new concepts for air blocks in underground mines and an extensive background with inflatables in which flexible composites have been used for structural purposes.

The Sheldahl Company has provided development and manufacturing services to the aerospace industry and commercial sector for nearly thirty years. We are one-of-a-kind in that we can provide a comprehensive variety of composite materials, internal processing capability to manufacture those materials, and specialized fabrication expertise for use of them. We work with all types of plastic films and fabrics, metal foils, vapor deposits, elastomers and a variety of adhesives. Our expertise has been applied to inflatables ranging from a few inches to many hundreds of feet in size and to such diverse applications as space inflatables, nuclear power plants, electronic circuitry, oil pipeline insulation, computer peripheral components and balloons of many shapes and sizes.

As noted in our proposal, we believe that determination of the air block configuration and size will be somewhat of a trial and error effort. For that reason, we propose a front-end development effort involving concept development, preliminary design, trial deployment, detailed design and field demonstrations. We anticipate that we will build 4-foot long tunnel mock-ups (wood) for initial evaluations of shape and size at Sheldahl, but ultimately, deployments should be performed in the subway. We view those evaluations as the field demonstrations and expect that they might be performed in the early morning hours. For budgetary purposes, we expect that those costs (through field demonstrations) will total approximately $70,000.

Our preliminary estimate of costs for future deliverable units (once development is complete) has been based on supplying the inflatable system complete with container, manifold/valve unit for the gas supply and other hardware necessary for deployment. Unless desirable from the customer standpoint, we would not provide the compressed gas cylinders since the intent is to use commercially available units from local suppliers.

Northfield, Minnesota 55057 Tel. 507-663-8000 TWX: 910-565-2180 SHELDAHL NOLD

Given those ground rules, the components we would supply are similar in cost whether toroidal or spherical because the amounts of material and length of seams required are about the same in each case. Our budgetary estimate for these units is $5,000/unit, but final price will be a function of size, shape, complexity and quantity purchased. If for example, the configuration turns out to be similar to that proposed, and a significant quantity were purchased, costs could be reduced via tooling and repetitive assembly operations.

In terms of installed system costs, the total should be quite moderate since only the following costs would be incurred:

- o Anchoring of the air block package to the tunnel wall,
- o piping from the gas supply to the air block (1/2" - 1" tubing),
- o nitrogen cylinders which may be purchased for about $300 each,
- o wiring for package opening (2 wires, may be low voltage), and
- o wiring to the gas supply (2 wires, may be low voltage).

We hope you will find our preliminary proposal acceptable and look forward to working with you to develop the proposed concepts further. If you need additional information, or have questions about the materials supplied, please call me at 507/663-8298.

Sincerely,

A. J. Wendt
Senior Engineer
Business Development

dc

PROPOSED AIR BLOCK CONCEPTS
FOR USE IN
NATIONAL CAPITAL TRANSPORTATION AGENCY SUBWAY TUNNELS

As Proposed To

DE LEUW, CATHER AND COMPANY

Proposal No. SF 10715

July 29, 1985

Sheldahl

- o Once inflated, and with the tunnel air handlers on, the air block will be subjected to dynamic pressures up to 3 inches of water.

Given the above, concepts have been developed for toroidal and spherical inflatables based on the following criteria:

- o The outside circumference of the inflatable should be somewhat greater than that of the tunnel,
- o In the case of the toroid, the inside diameter should be less than that of an inscribed circle that avoids all obstructions (walkway, tracks and cable/piping runs),
- o The inflatable should operate at low pressure to provide a conformal final configuration
- o There must be adequate contact area between the tunnel walls and inflatable to provide a friction force greater than the force generated by the air handlers (inflatable O.D., pressure, dynamic pressure and material stresses all interact),
- o The inflatable must be sized to provide for a final position that may not be perfect (off vertical axis, not uniformly in-plane),
- o Material used for fabrication of the inflatable should be tough enough to withstand abuse of sliding over objects or surfaces in the tunnels (rails, walkways, etc.),

Sheldahl
PRECISION FOR THE LONG RUN

o Commercially available equipment should be used where-ever possible (inflation, gas supply, valving, piping, etc.),

TOROID INFLATABLE

This concept involves the use of an oversized torus to support a spherically domed membrane as shown in Drawings SD 2095 and SD 2096.

The torus outside surface will be adequately sized to conform to the tunnel wall and provide a bearing surface sufficient to offset pressure loads on the air block with tunnel air handlers in operation. Nominally, the torus outside diameter is such that a 2-foot wide flat should occur at the contact surfaces, which also permits a vertical misalignment of about 20-25 degrees.

The intent at this point is that the torus is to be pressurized to about 1 psig which yields a low stress level in the torus wall and, hopefully, make the system compliant enough to fill-in corners and fit over obstructions.

Similarly, the spherical membrane has been sized to obtain a low stress level in it and allow the torus to adjust as necessary.

Characteristics of the 2 toroid designs include:

	Rectangular Tunnel	Circular Tunnel
Outside Diameter	18.5 feet	18.5 feet
Inside Diameter	10 feet	12.25 feet
Spherical Radius	10 feet	10 feet
Weight	56 lbs.	45 lbs.
Packaged Volume	2.0 cubic feet	1.7 cubic feet
Inflatant Supply	690 std. cubic ft.	395 std. cubic ft.

Sheldahl
PRECISION FOR THE LONG RUN

SPHERICAL INFLATABLE

The spherical air block is omnidirectional and may offer advantages for deployment over other designs, but it is heavier, bulkier and requires more inflatant than the toroid approaches. Construction details would be similar to the toroids and, therefore, a drawing has not been included with this letter.

The sphere size suggested is 17'-2" which should provide a flat of about 3 feet when in contact with the tunnel wall. In this case, an internal pressure of 6 inches water should provide adequate resistance to the air handler load without losing the ability to adjust to tunnel obstructions.

Physical characteristics of the spherical air block are as follows:

Diameter	17'-2"
Weight	84 lbs.
Package Volume	2.9 cubic feet
Inflatant Requirements	2,640 std. cubic feet

FEATURES IN COMMON

The materials and construction details for either type of inflatable are identical and based on work we have done in developing new air block concepts for underground mines. The composite proposed for use in the inflatable walls is tough, lightweight and environmentally stable under the planned conditions of use. It has been endorsed by the U. S. Bureau of Mines and meets MSHA requirements for use in underground mines.

Sheldahl
PRECISION FOR THE LONG RUN

The package configurations shown in Drawings SD 2095 and SD 2096 should be viewed as representative rather than absolute. The shape may be varied in numerous ways, including irregular shapes, as long as the internal volumes are held constant. The package could also be soft; however, a rigid base is probably desirable since it may be used as a means to fix the inflatant relative to the tunnel. As shown, inflatable release may be effected remotely with a single electrical signal. Note that explosive bolts or other electromechanical devices may be used as well as the solenoid shown.

At this point, commercial pressure vessels for compressed gases appear to be a reasonable way to provide inflation of the air blocks (see Drawing SD 2097). Assuming that nitrogen at 2000 psig is to be used, the toroids will require 2 - 3 cylinders while the sphere will require 10 cylinders of the 250 standard cubic feet size. These may be manifolded together and held ready for use with a single solenoid valve, which may in turn be operated remotely with a single electrical signal.

UNKNOWNS

The technology exists for development of the air block inflatables, packaging/deployment approaches and inflation; however, it is difficult to predict sizes required to effectively block air flows in the tunnels. In the final analysis, it may be a trial and error situation in which variations in dimensions may have to be made along with trial inflations in order to arrive at a "best fit" design.

Sheldahl
PRECISION FOR THE LONG RUN

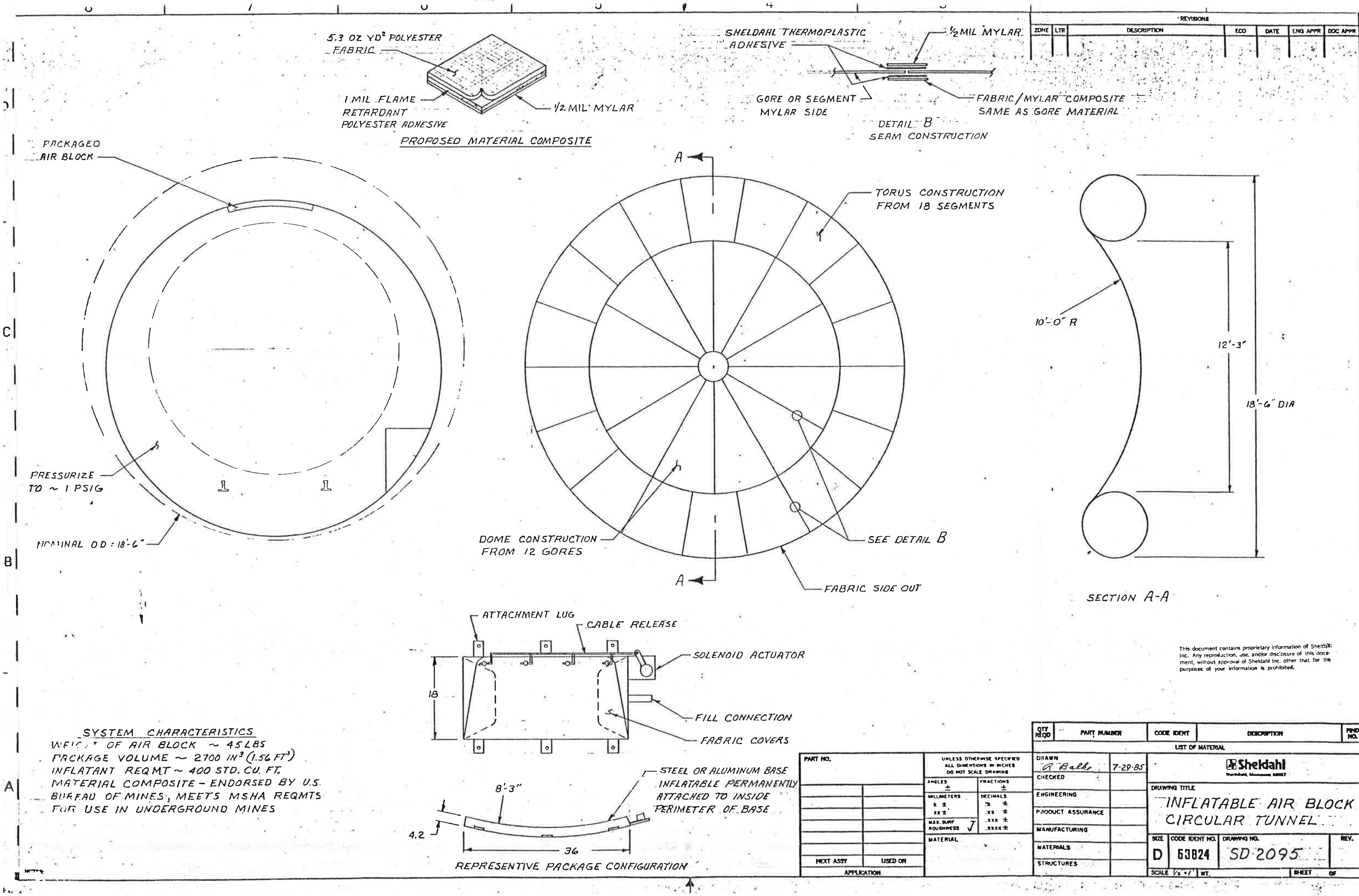
In addition, inflatable design may be more complex than shown if deployment must occur when air handlers in the tunnels are operating. It is possible that the designs shown, or slightly larger shapes, will adequately block-off the tunnels, but is also possible that additional deployment restraints may be necessary in that event.

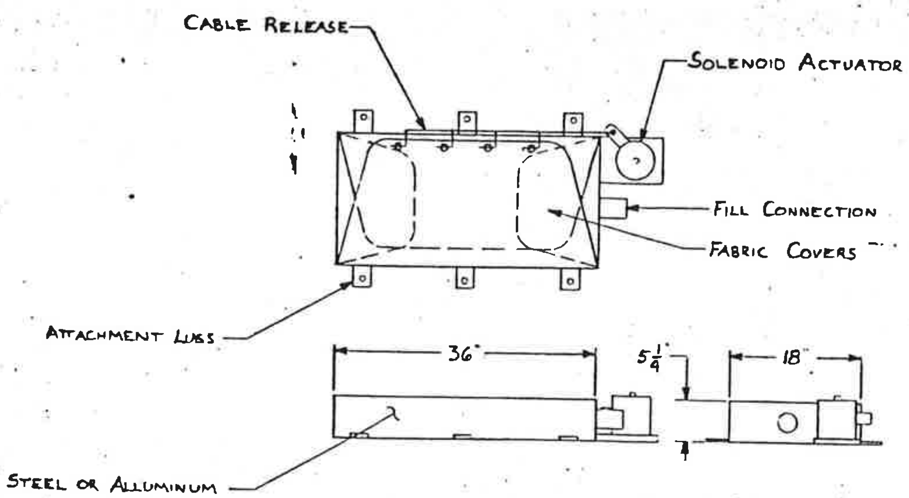
PROPOSED PLAN

We visualize that development of the proposed system would involve the following general tasks:

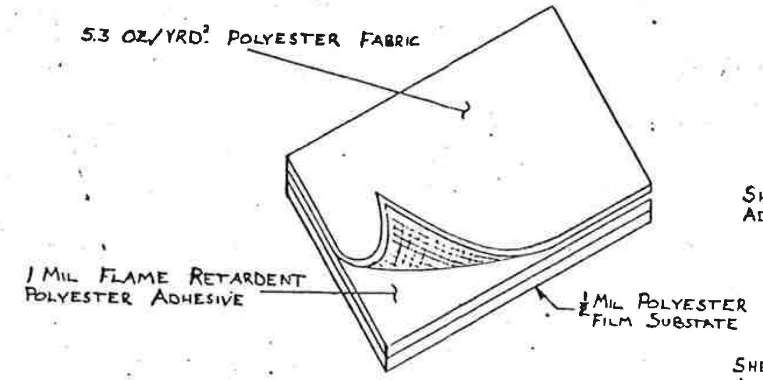
- o Concept Development
- o Preliminary Design
- o Trial Deployments
- o Detailed Design
- o Field Demonstrations
- o Final Design
- o Production

We are typically very responsive to customer needs in efforts of this sort and we can provide experienced design and field service personnel for work on the program.

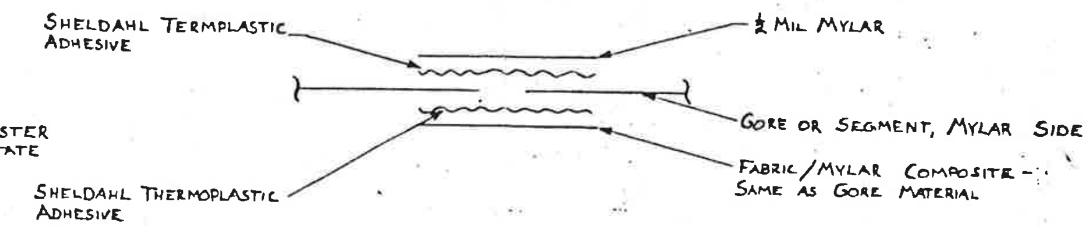

5.3 OZ YD² POLYESTER FABRIC
1 MIL FLAME RETARDANT POLYESTER ADHESIVE
1/2 MIL MYLAR
PROPOSED MATERIAL COMPOSITE
SHELDAHL THERMOPLASTIC ADHESIVE
1/2 MIL MYLAR
GORE OR SEGMENT MYLAR SIDE
FABRIC/MYLAR COMPOSITE SAME AS GORE MATERIAL
DETAIL B
SEAM CONSTRUCTION
PACKAGED AIR BLOCK
PRESSURIZE TO ~ 1 PSIG
NOMINAL OD = 18'-6"
A
TORUS CONSTRUCTION FROM 18 SEGMENTS
DOME CONSTRUCTION FROM 12 GORES
SEE DETAIL B
FABRIC SIDE OUT
A
10'-0" R
12'-3"
18'-6" DIA
SECTION A-A
ATTACHMENT LUG
CABLE RELEASE
SOLENOID ACTUATOR
18
FILL CONNECTION
FABRIC COVERS
8'-3"
STEEL OR ALUMINUM BASE INFLATABLE PERMANENTLY ATTACHED TO INSIDE PERIMETER OF BASE
4.2
36
REPRESENTIVE PACKAGE CONFIGURATION
SYSTEM CHARACTERISTICS
WEIGHT OF AIR BLOCK ~ 45 LBS
PACKAGE VOLUME ~ 2700 IN³ (1.56 FT³)
INFLATANT REQMT ~ 400 STD. CU. FT.
MATERIAL COMPOSITE - ENDORSED BY U.S. BUREAU OF MINES, MEETS MSHA REQMTS FOR USE IN UNDERGROUND MINES
This document contains proprietary information of Sheldahl Inc. Any reproduction, use, and/or disclosure of this document, without approval of Sheldahl Inc. other than for the purposes of your information is prohibited.
REVISIONS
ZONE LTR DESCRIPTION ECO DATE ENG APPR DOC APPR
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
MATERIAL
DRAWN 7-29-85
CHECKED
ENGINEERING
PRODUCT ASSURANCE
MANUFACTURING
MATERIALS
STRUCTURES
Sheldahl
DRAWING TITLE
INFLATABLE AIR BLOCK CIRCULAR TUNNEL
SIZE D
CODE IDENT NO. 63824
DRAWING NO. SD 2095
REV.
SCALE 1/2 = 1'
SHEET



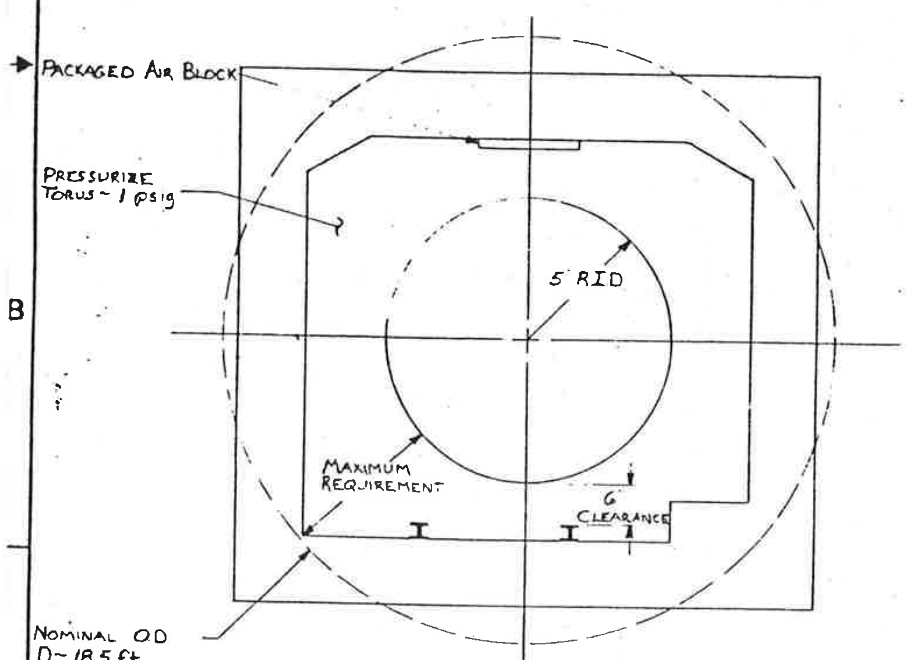
Representative Package Configuration



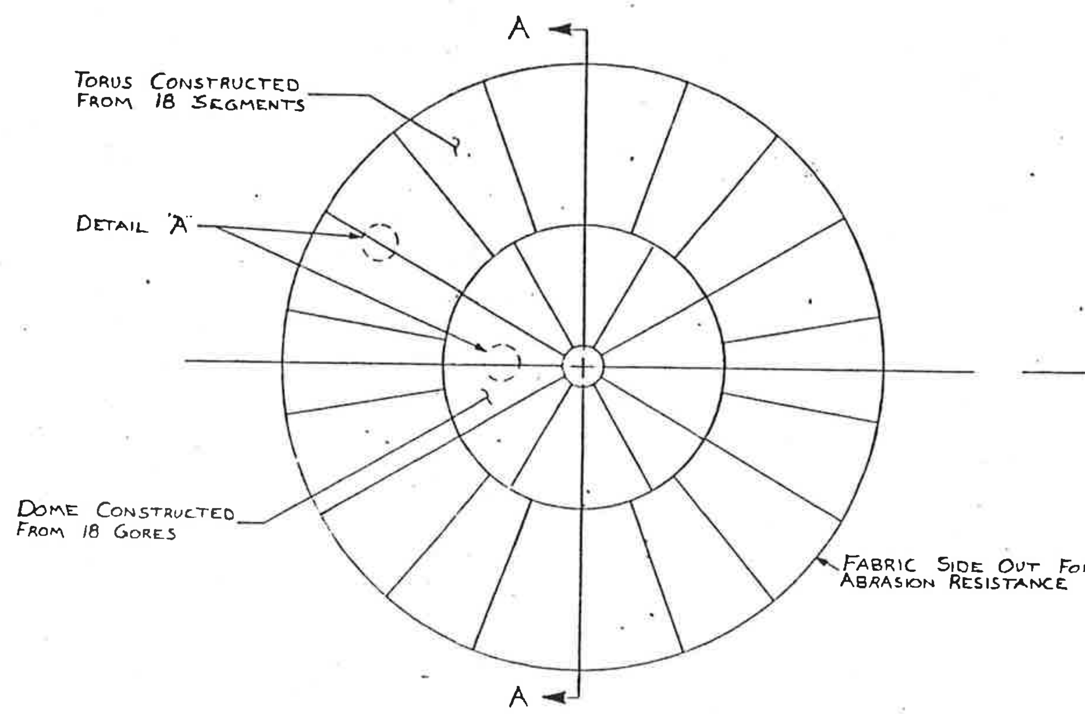
Proposed Material Composite



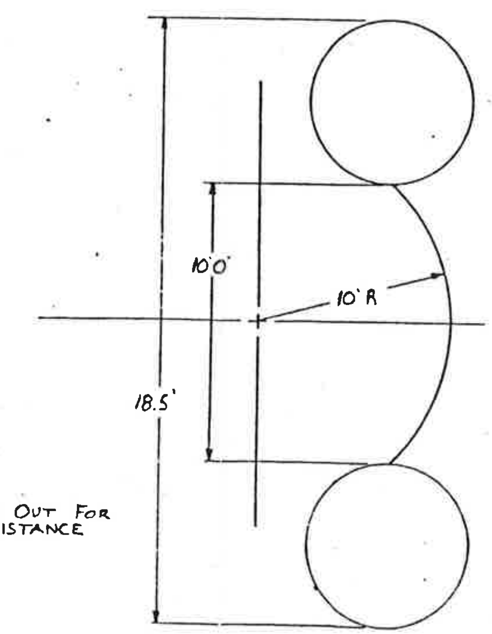
Detail "A" Seam Construction



Nominal Air Block Layout



Inflatable Configuration



Sect. A-A

System Characteristics

Weight of Air Block ~ 56 lbs.
Packaged Volume ~ 3375 in.³ (1.95 ft.³)
Inflatant Req'd. ~ 700 Std. Cu Ft.
Material Composite - Endorsed by U.S. Bureau of Mines, Meets MSHA Reqmts. for use in Underground Mines.

Notes:

Qty Req'd	Part Number	Code Ident	Description	Find No.

List of Material

Revisions: Zone | Ltr | Description | ECO | Date | Eng Appr | Doc Appr

Part No. — Next Assy — Used On — Application

Unless otherwise specified all dimensions in inches. Do not scale drawing. Angles ±; Fractions ±; Millimeters; Decimals .x ± .xx ± .xxx ± .xxxx ±; Max. surf roughness √; Material

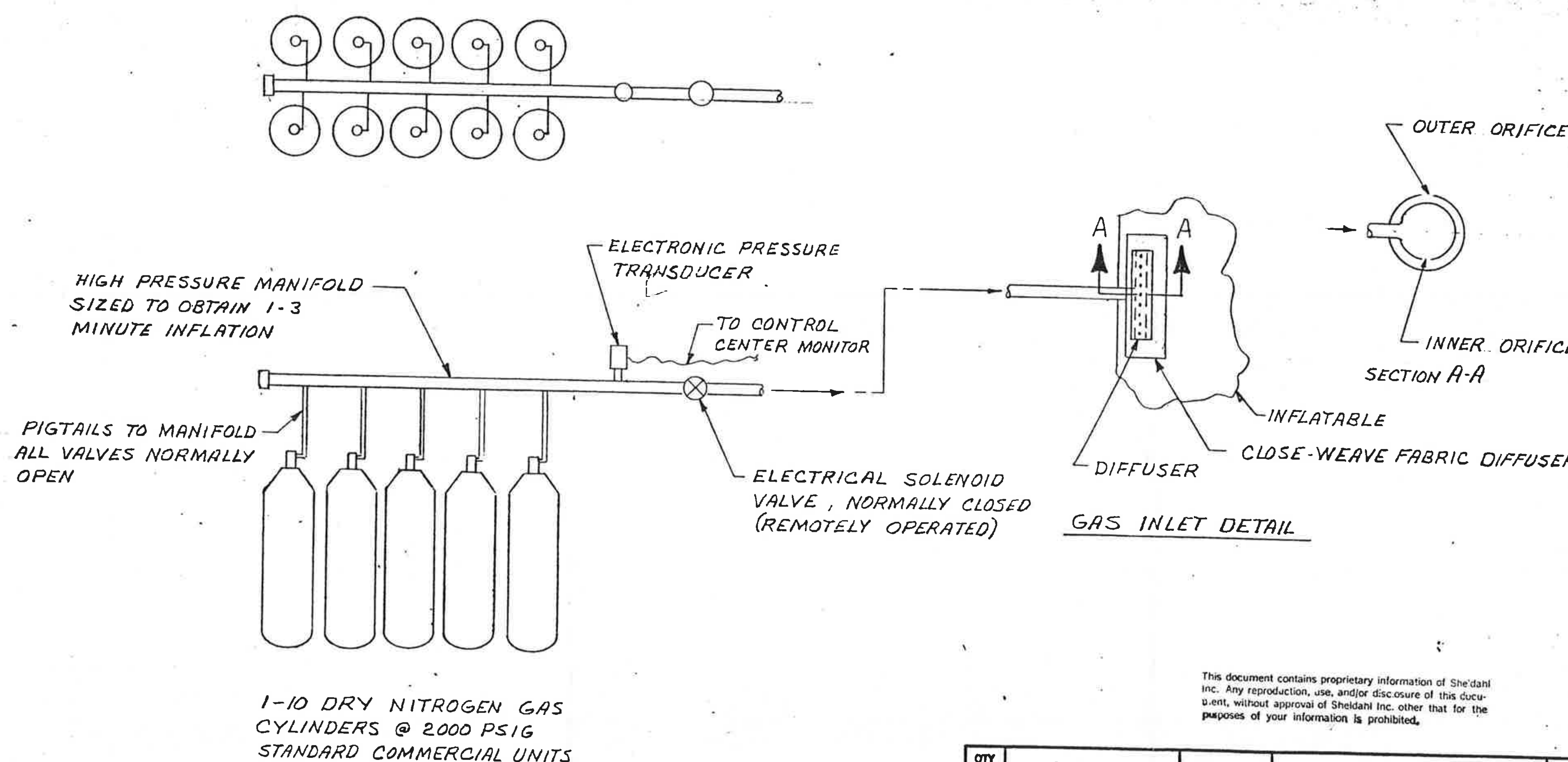
Drawn: [signature] 7-29-85
Checked
Engineering
Product Assurance
Manufacturing
Materials
Structures

Sheldahl — Northfield, Minnesota 55057

Drawing Title: Inflatable Air Block - Rectangular Tunnel

Size: D | Code Ident No.: 53824 | Drawing No.: SD 2096 | Rev.: A

Scale: None | Wt. | Sheet 1 of 1



REVISIONS

ZONE	LTR	DESCRIPTION	ECO	DATE	ENG APPR	DOC APPR

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

NOTES:

DRAWN A. Balk 7-29-85

CHECKED

ENGINEERING

PRODUCT ASSURANCE

MANUFACTURING

MATERIALS

STRUCTURES

Sheldahl
Northfield, Minnesota 55057

DRAWING TITLE
AIR BLOCK INFLATION SYSTEM SCHEMATIC

SIZE	CODE IDENT NO.	DRAWING NO.	REV.
C	53824	SD 2097	

SCALE | WT. | SHEET | OF

C SD2097