Sizing of extraction ventilation system and air leakage calculations for SR99 tunnel fire scenarios

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Abstract

Extraction ventilation system design for fire hazard mitigation design in roadway tunnels requires unique considerations for proper sizing of fan equipment capacity and operating pressure. SR99 bore tunnel facility extraction ventilation system sizing includes the following factors that increase the ventilation fan capacity requirement: common exhaust duct for incident and non-incident exhaust duct networks, damper leakage, structural joint leakage. This paper describes fluid mechanic relationships utilized in determining leakage flows along with numerical calculation procedures using Subway Environmental Simulation (SES) program to determine ventilation plant equipment sizes. The objective is to ensure the duct leakage is properly estimated in long tunnels to allow optimization of minimum required tunnel diameter and ventilation plant sizing capacity requirement.

1 INTRODUCTION

The world's largest-diameter tunneling machine began a historic journey beneath downtown Seattle in summer 2015. This 3-km long tunnel, the State Route 99 (SR99) highway tunnel, will run along the waterfront of Seattle between Sodo and Battery Street, it will replace the existing Alaskan Way Viaduct which has been damaged by the earthquake. This single bored tunnel with northbound and southbound traffic roadways is shown in Figure 1.

The SR 99 Tunnel road ways have a cross section area of 671 SF and 578 SF for the southbound and northbound roadways, the tunnel's fire emergency smoke extraction system is a negative pressure system. The negative pressure is developed by the tunnel extraction fans that are housed in the two tunnel ventilation exhaust fan plants located in South Operations Building and North Operations Building. These fan plants create negative pressure in the extraction duct to draw smoke away from the tunnel with the damper openings local to the fire. The smoke is drawn through the extraction duct and discharged through the stacks on top of the Operations Buildings.

When operating the emergency tunnel ventilation system, air will leak into the extraction exhaust duct from the roadways during a fire event because of the pressure differential between the roadway and the duct. This leakage would be through closed dampers, and concrete construction and expansion/shrinkage joints between the roadways and the extraction duct. The size of the tunnel extraction fans should consider various factors including the air leakage into the extraction duct. Figure 1 shows the tunnel cross section with southbound and northbound roadways, and egress corridors and the smoke duct. Figure 2 shows the arrangement of fan plants at each end of the extraction duct and illustrates the distributed nature of the leakage with flows dependent on localized pressure differential between extraction duct and roadway. The exhaust fans are sized to overcome this leakage and to provide the desired exhaust rate at the fire location.

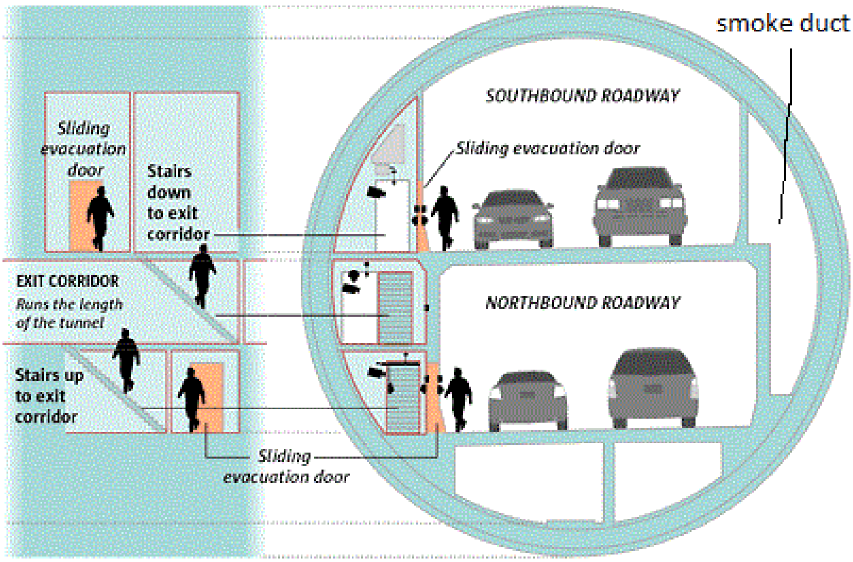

Figure 1: SR99 Tunnel cross section with southbound and northbound roadways (Source: Washington State Department of Transportation, WSDOT)

The following calculations validate the size of the extraction fans. They are based on an effective extraction rate of 283.2 m^3/s at the fire site. This extraction rate has been confirmed with detailed CFD analysis. Refined SES calculations performed for six fire locations along the northbound tunnel confirmed that the modified fan curve with seven of the 373 kW tunnel exhaust fans, which considered approximately 10% reduction in flow, satisfied the smoke extraction requirements.

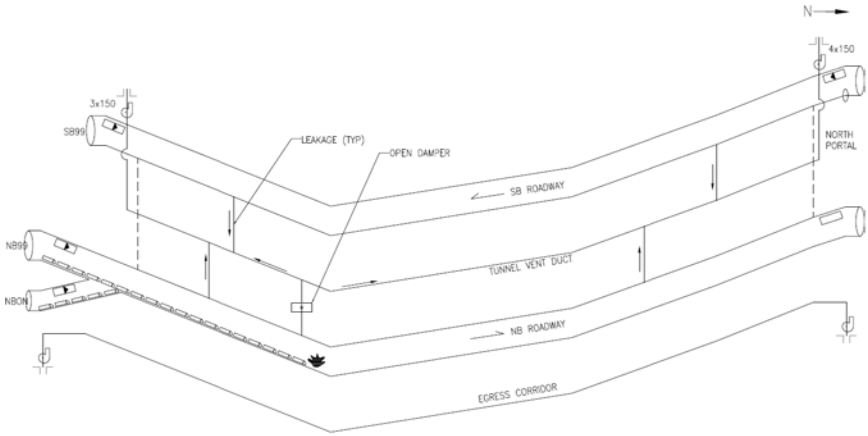

Figure 2: SR99 System Configuration

2 CHALLENGE

There are several challenges for this project.

The northbound and southbound roadways are stacked in one bored tunnel and a single extraction duct is shared by the south bound and north bound traffic. When the fans are running the extraction duct has a much lower pressure (up to -3.0 kPa) than the two roadways. Air will leak into the extraction duct from both roadways, even though the ventilation dampers are closed in non-incident roadway. The fans need to be sized to provide the desired exhaust rate through the opened dampers at the fire location while overcoming the air leakage from two roadways.

The tunnel ventilation dampers are placed vertically in the wall between the roadway and the extraction duct. The vertical dampers are spaced at 33 m on center, which is a quite densely distributed spacing. This increased the total number of dampers, therefore increased the leakage.

The fire event air flow into the tunnel roadways will be supplemented with jet fans. The jet fans are located in the cut and cover sections at each end of the bored tunnel, because the cut and cover sections have greater vertical and horizontal clearances than the bored tunnel. There are no jet fans between the two sets of the portal jet fans. The roadway airflow leaks into the extraction duct making maintenance of the modified critical velocity airflow along the tunnel roadways difficult. Exit portal jet fans will also be activated to blow out of the tunnel. This will prevent excessive air flow in from exit portal, which could interfere with upstream fire event air flow into the dampers.

3 STRATEGY

The tunnel leakage assumptions and assumed values for the surface roughness of the extraction duct are listed below:

- Leakage around the dampers: The damper frames will be embedded in the tunnel concrete walls. Any joints between the frame and the concrete are sealed. All slight unavoidable spaces between the frame and the structure are properly filled, so that the leakage area at the damper frame through the sealing joints is no more than that for the windows frame, where ASHRAE's best estimation is $1.667x10^{-4}$ leakage crack area / window area[3].

- The specifications also required testing of the damper leakage during commissioning. "Leakage test: The damper manufacturer shall conduct a field test to measure the air leakage through each of the composite damper units installed along the roadway. Composite dampers units that fail the field test shall be adjusted and retested. Composite dampers units that do not pass the field leakage test will be removed and replaced with composite dampers units that pass."
- Structural Leakage is the leakage through the thermal expansion and construction joints. This leakage depends on the construction methods used, the concrete mix, curing, workmanship and quality control. Thermal expansion joints will be sealed and its leakage area is no more than $8.47x10^{-5}$ m^2 per linear meter of its length[2]. The design leakage rate through the joints should not exceed 10% of the designed exhaust rate. This has to be verified by explicitly calculating the K factor based on the leakage area and the pressure.
- Damper leakage due to long term maintenance and slight variations in damper size: Project specifications normally are according to UL555S Class 1, and require that "The damper manufacturer shall test and certify that, when the dampers are fully closed and holding against a differential pressure of plus or minus 3 kPa, leakage through the damper assembly will not exceed 14 cfm per square foot (0.07112 m^3/s per m^2)." This analysis increased this leakage to 28 cfm per square foot (0.1422 m^3/s per m^2) to account for up to a 10% increase in the size of the damper, and to account for long term accumulation of dirt and debris on the dampers.
- The inner surface of the extraction duct wall will be either the inside face of the tunnel liner or the inside of the cast in place concrete wall between the roadway and the extraction duct. The inside of the tunnel liner will be cast against the liner mold. This surface will be close to smooth. The inner face of the concrete wall between the roadway and the duct will also be the side cast against the formwork and will also be close to smooth. Wall friction factor of 0.03 for SES input has been used to model extraction duct roughness calculations to reflect the actual surface roughness of the formed concrete.

These factors are combined to result in an aggregate air leakage into the extraction duct to no more than 40% of the total extraction rate.

4 DESIGN PARAMETERS AND ANALYSIS METHODOLOGY

This ventilation design is based on the test data, previous project experiences and the regulatory guidelines. The following parameters have been used in the analysis.

Input design parameters:

- Leakage rate through the closed dampers is 2 x 0.07112 m^3/s per m^2 at 3 kPa.
- Face area per damper is 9.29 m^2(100 square feet)
- Leakage area from the damper frame of 0.024 square inch per square feet of face area based on 2001 ASHRAE Fundamentals Handbook(2)
- Damper spacing along the tunnel modeled at 33 meters measured center to center of the damper face.

- Structural leakage area of 0.04 square inch per linear feet length of the thermal expansion joints. This parameter represents a conservative input considering manufacturer claims of zero air infiltration based on testing according to ASTM E1966 and UL 2079.
- Extraction duct wall friction factor reduced from a maximum 0.04 to 0.03 (rounded up from the actual value of 0.0276, based on extraction duct roughness calculations) to represent the actual condition as discussed above.
- Fan curves with approximately 10% of reduction of in flow rate are given as per Table-1 and Table-2.

Table 1: Extraction Fan curves for 3 x 150 kcfm fans used in SES

Pressure – kPa	10% Reduction Flow Rate – m^3/s	Original Flow Rate - m^3/s
4.98	0.00	0.00
4.15	181.70	200.58
2.41	266.65	294.97
0.41	297.33	330.37

Table 2: Extraction Fan curves for 4 x 150kcfm fans used in SES

Pressure – kPa	10% Reduction Flow Rate – m^3/s	Original Flow Rate - m^3/s
4.98	0.00	0.00
4.15	254.85	283.17
2.41	339.80	377.56
0.41	382.28	424.76

Two sets of parameters were checked to ensure the system operability:

- The CFD modeling indicates that the target extraction rate at the fire location should be at least 283.2 m^3/s.
- The SES calculated leakage rate through the closed dampers and due to structural leakage is not less than the estimated value. The estimated value is based on sum of the structural and damper leakage for every 220 feet of tunnel length given in Table-4. Three different pressure locations were checked.

For the suitability of SES modeling, the structural leakage has also been added to the damper leakage. The tunnel has uniformly distributed wall dampers spaced at every 110 feet center to center. Every two dampers were grouped together and represented by one closed damper with a total leakage area of 3 square feet. So the target leakage rates given in Table-4 represents the leakage from two adjacent dampers and the other leakages including structural leakage, etc. It has been assumed that the total structural leakage rate is approximately 30% of the total damper leakage, this assumption has been confirmed by comparing the K factor back calculated based on this known leakage rate and the K factor calculated based on the structural installation and the ASHRAE Handbook[2]. The damper leakage given in Table 3 is used as the basis for leakage calculation.

Table-3: Damper leakage based on 28 cfm/square feet at 12 inch water

Pressure	1.00 kPa	1.99 kPa	2.99 kPa
Maximum Leakage rate	0.081 $m^3/s*m^2$	0.112 $m^3/s*m^2$	0.142 $m^3/s*m^2$

The damper leakage at pressures other than the pressure given in the project specification is calculated based on the leakage – pressure relationship[2]:

Leakage flow rate at pressure P = Leakage flow rate at 4 inch water gauge x $(P/4)^{0.55}$

Based on the estimated leakage flow for two dampers' leakage area of 3 square feet, the K factor has been back calculated into a consolidated value as summarized in Appendix A; its range is approximately 32 – 42 for pressure between 0.12 to 2.99 kPa.
For the same leakage pressure and leakage area, the lower the K factor, the more leakage will be. To add a safety factor of approximately 10%, a K factor of 26.55 was used in the SES calculation, which account for approximately 10% more leakage than that is calculated based on the project design criteria.
It can therefore be concluded that the SR99 tunnel design is conservative with a higher leakage flow rate than that has been calculated based on project specifications. Therefore, the design deemed to satisfy the acceptance criteria if the SES modeling can achieve the leakage rate as given in Table-4.

Table 4: Estimated leakage rate per 67m tunnel length as a function of pressure

Pressure – kPa	Damper + Structural leakage - m^3/s
0.12	0.48+0.14=0.63
0.25	0.70+0.21=0.92
0.50	1.03+0.31=1.34
0.75	1.29+0.39=1.68
1.00	1.51+0.45=1.96
1.25	1.63+0.49=2.12
1.49	1.81+0.54=2.35
1.74	1.96+0.59=2.55
1.99	2.08+0.62=2.70
2.24	2.26+0.68=2.93
2.49	2.39+0.72=3.11
2.74	2.52+0.76=3.27
2.99	2.64+0.79=3.44

5 SES ANALYSIS

5.1 Standard SES input:

As discussed in section 4, each damper in the SES model represents two adjacent dampers to reduce the complexity of the model, and the K factor for the leakage dampers also includes the structural leakages. The opened damper has a cross section area of 9.29 m^2, the closed damper is assumed to have an opening of 0.28 m^2 representing the leakage area of two closed dampers. This leakage area is a reference value for calculating the K factor only, as the actual leakage flow rate is controlled by the K factor and the corresponding leakage area at a fixed pressure. The SES input value for the K factor was estimated based on calculations in Appendix A. This value is adjusted based on the back check of the leakage rate to ensure the SES calculated leakage is not less than the desired leakage as specified in Table-4.

SES model has been updated to reflect the changes based on the above discussion. Following parameters are updated:

- The maximum friction factor for the flow along the extraction duct has been revised from 0.04 to 0.03 (K factor reduced from 1.08 to 0.81). For a friction factor of 0.03, it has a safety factor of 1.08 based on the reference value of 0.0276.
- Structural leakage has been reduced to 10% of the extraction flow rate. This has been modeled by applying the K factor value of 26.55, which accounts for a higher leakage rate than using the calculated K factor values based on ASHRAE Handbook's best estimation for similar installations.
- Reduce fan curve flow by 10%, which is contributed by the reduction of friction factor along the smoke duct and the leakage reduction by applying sealing joints for damper frame and the thermal expansion joints.

Figure 3 shows the extent of detail incorporated into SES ventilation model to more accurately capture localized leakage conditions.

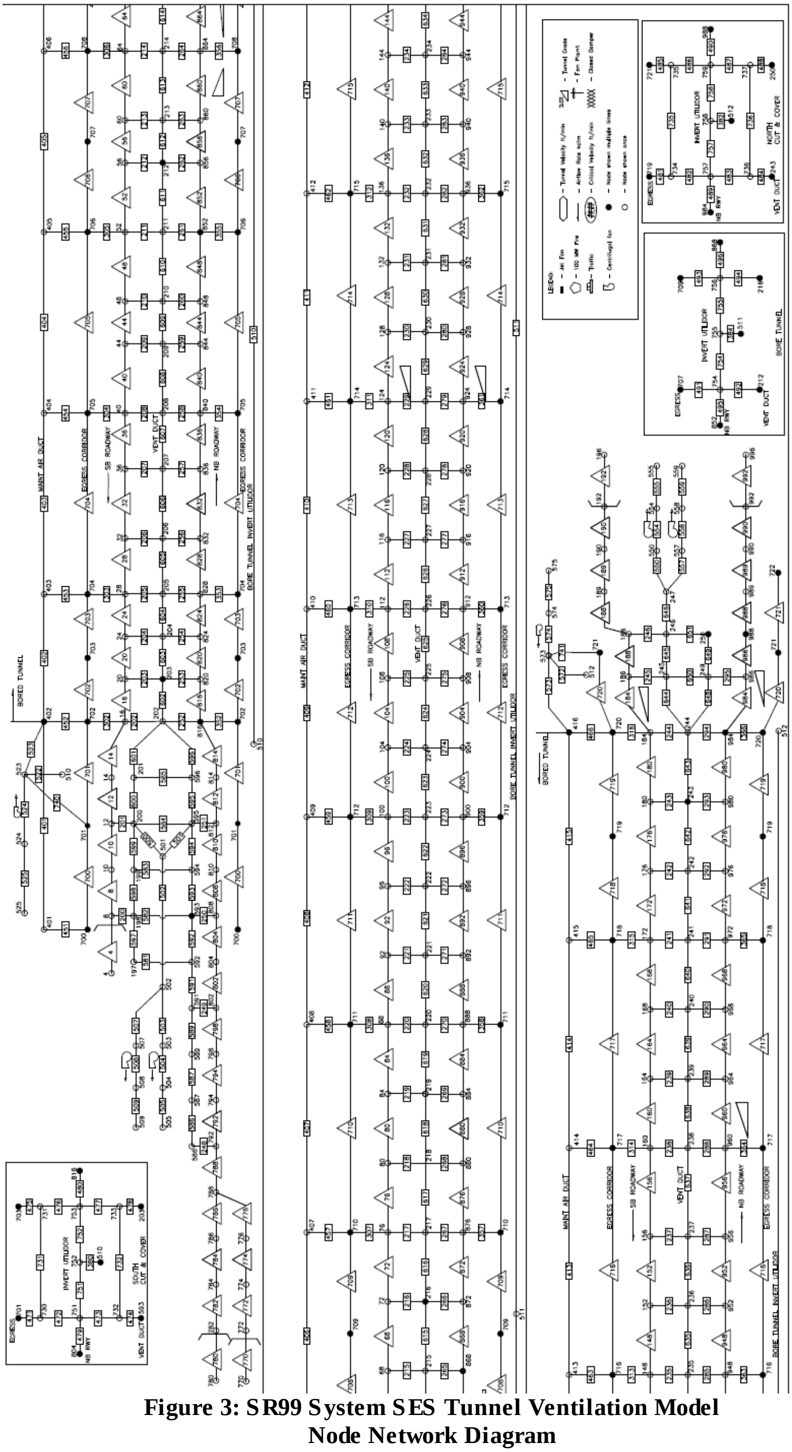

Figure 3: SR99 System SES Tunnel Ventilation Model Node Network Diagram

5.2 Analysis

SES modeling has been performed on six fire locations along the northbound roadway, named NB1 – NB6 as shown in Figure 4. The SES calculated pressure in the extraction duct and the leakage along the extraction duct are given in Figure 5 through Figure 10 in Appendix B.

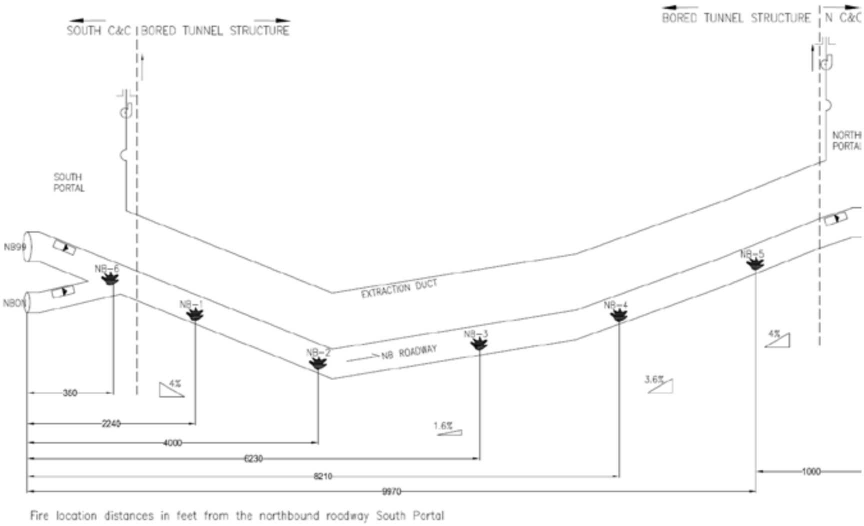

Figure 4: Fire locations

The following steps were completed.

1. While performing SES runs, the leakage rate from each SES damper was checked to ensure it is not less than the estimated rate in Table-4 for each pressure differential.
2. The next step confirms that the flow rate through the opened damper achieves a minimum of 283.2 m^3/s. Table-5 gives a summary of the total leakage rate and exhaust rate achieved at the fire locations for cases NB1 – NB6. For each of these fire scenarios, the total extraction rate at the South and North Operations Buildings is given in Table-5.

Table 5: SES Modeling Results

Case ID	Total Extraction at the Operations Buildings (m^3/s)	Leakage Flow Rate (m^3/s)	Exhaust Flow Rate achieved at the Fire Location (m^3/s)
NB-1	495.00	163.00	332.00
NB-2	518.00	189.00	329.00
NB-3	503.00	193.00	310.00
NB-4	525.00	187.00	338.00
NB-5	511.00	175.00	336.00
NB-6	478.00	143.00	335.00

3. Calculate the horse power required for the tunnel ventilation fans. A summary of fan duty points at the South and North Operations Buildings are given in Table-6. These extraction fan duty points are capable of delivering the target exhaust flow rate at the fire site. The motor power for each individual fan does not exceed 373 kW. Fan brake power is calculated based on the efficiency coefficient of 0.8 and the density at standard temperature.

Table 6: Fan Duty Point and Motor HP

Case ID	Exhaust Fan Flow Rate at South Operations Building (m^3/s)	Pressure at South Operations Building (kPa)	Exhaust Fan Flow Rate at North Operations Building (m^3/s)	Pressure at North Operations Building (kPa)	Maximum Power Required (kW)
NB-1	3 fans x 82 = 246	2.07	4 fans x 63 = 252	3.33	261
NB-2	3 fans x 83 = 250	2.77	4 fans x 67 = 268	4.05	338
NB-3	4 fans x 59 = 236	4.00	3 fans x 89 = 268	3.34	371
NB-4	4 fans x 62 = 250	3.91	3 fans x 92 = 275	2.79	321
NB-5	4 fans x 69 = 277	3.90	3 fans x 78 = 234	1.57	336
NB-6	3 fans x 81 = 241	1.33	4 fans x 59 = 237	3.38	249

6 CONCLUSION

Five of 500 horse power (373 kW) extraction fans will provide the effective extraction rate of 283.2 m^3/s. This assumes the following:

- Damper face leakage is controlled not exceeding 0.142 $m^3/s*m^2$ at 2.99 kPa as per best estimate for the caulked joints,
- Damper frame leakage area not exceeding $1.667x10^{-4}$ m^2 (leakage area)/m^2 as per the window frame,
- The smoke duct structure is properly sealed,
- The smoke duct wall roughness is controlled to achieve a wall friction factor of 0.03, and
- A flow reduction rate of 10% for the fan curve.

7 ACKNOWLEDGEMENT

We appreciate the partnerships between Washington State Department of Transportation (WSDOT), HNTB Corporation and Seattle Tunnel Partners during the development of tunnel ventilation operating modes and the preparation of this paper.

8 REFERENCES

[1] Subway Environment Simulation Computer program – SES VERSION 4, Part I User's Manual, December 1997.
[2] ASHRAE Fundamentals Handbook Section 26.15, 2001.
[3] ASHRAE Fundamentals Handbook Section 26.16, 2001.
[4] ASHRAE Handbook HVAC Applications 52.5, 2007.

Appendix A: Calculation of K factor for leakage estimation

As one of the key input parameters for calculating the leakage through the closed dampers, thermal expansion joints and the other structural cracks, K factor is required to be estimated as accurate as possible. SES modeling can only input the K factor for the dampers, including both closed and open dampers. Therefore, the K factor reflecting the leakage through the structural cracks and thermal expansion joints has been added into the damper leakage K factor, so that the SES modeling can take into account of the leakage other than just the damper face leakage by simply applying the overall K factor to the dampers.

This appendix discusses the standard based on which the K factor is calculated, and gives quantitative criteria for specifying the sealing requirements of the dampers frames and thermal expansion joints to satisfy the leakage allowance and ensure the effective extraction rate can be achieved and the required fan motor power is not oversized.

This K calculation is based on the following parameters from the project design and the standard:

- Leakage area of the damper is 3 square feet for every two dampers, as the K factor is dependent on the leakage area
- Longitudinal thermal expansion joint all the way along the SB tunnel
- Transverse thermal expansion joints of 14.78 feet for the SB tunnel every 650 feet along the tunnel
- Transverse thermal expansion joints of 15 feet for the NB tunnel every 650 feet along the tunnel
- Damper frame leakage area is based on the best estimate for the windows frame of 0.024 square inch per square feet of face area [3]
- Leakage area of the thermal expansion joints is estimated based on the caulked joints of 0.04 square inch per linear feet of crack [2]
- Leakage flow rate is calculated based on 2007 ASHRAE Handbook HVAC Applications [4]

Leakage flow rate:

$$Q=2610*A*P^{1/2}$$

Where, A= leakage area, square feet;
P= leakage pressure, inch water gauge;
Q = flow rate, cfm

For a leakage area of 3 square feet, calculated K factor for the leakage from SB and NB tunnel into the extraction duct is 38.13 and 45.23 respectively.

To check acceptable K factor required to control the leakage to a level that is within a range that is comparable to the similar projects, the K factor is back calculated based on the damper manufacture data for the SES input.

Based on fluid mechanics equation:

$$\text{Pressure head} = K \times v^2/(2g)$$

Where v = leakage air flow velocity = flow rate/leakage cross section area

K = K factor

Based on the leakage area of 6 and 3 square feet for every two adjacent dampers, the K factor can be calculated using the input data listed in Table-4, where the total leakage and the pressure are specified in Table A-1 below.

Table A-1: Back calculated and consolidated K factor based on damper and structural joint leakage flow rates

Pressure - INWG	Leakage - cfm	K factor for A=6 SF	K factor for A=3 SF
0.5	1325	1.65E+02	41.25
1	1941	1.54E+02	38.50
2	2841	1.43E+02	35.75
3	3551	1.38E+02	34.50
4	4160	1.34E+02	33.50
5	4498	1.43E+02	35.75
6	4973	1.40E+02	35.00
7	5412	1.38E+02	34.50
8	5720	1.42E+02	35.50
9	6214	1.35E+02	33.75
10	6584	1.34E+02	33.50
11	6939	1.32E+02	33.00
12	7280	1.31E+02	32.75

Appendix B: Leakage Rates and Extraction Duct Pressure

Pressure differentials and the associated leakage into the extraction duct have been combined in to a single leakage value at each pair of dampers. The dampers located further away from the opened damper have a higher pressure differential and therefore have higher leakage.

All the six fire locations have been analyzed. Figure 5 through Figure give the extraction duct pressure and leakage rate.

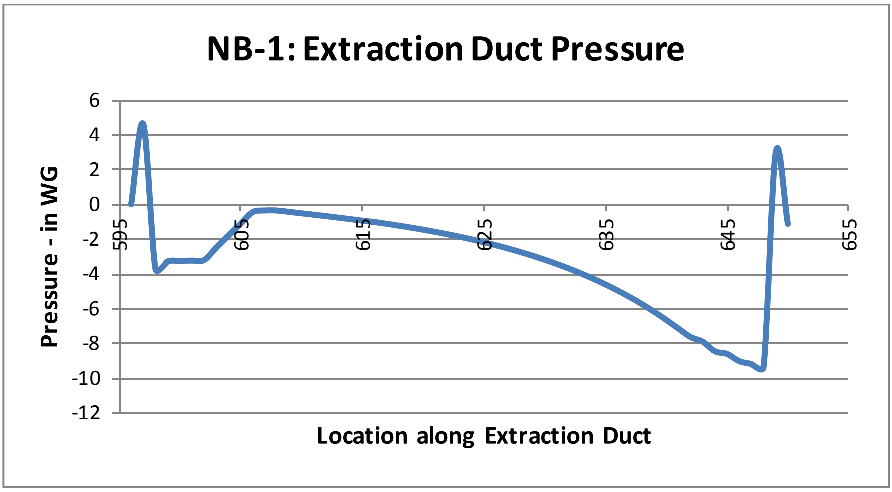

Figure 5: Extraction Duct Pressure for Case NB1

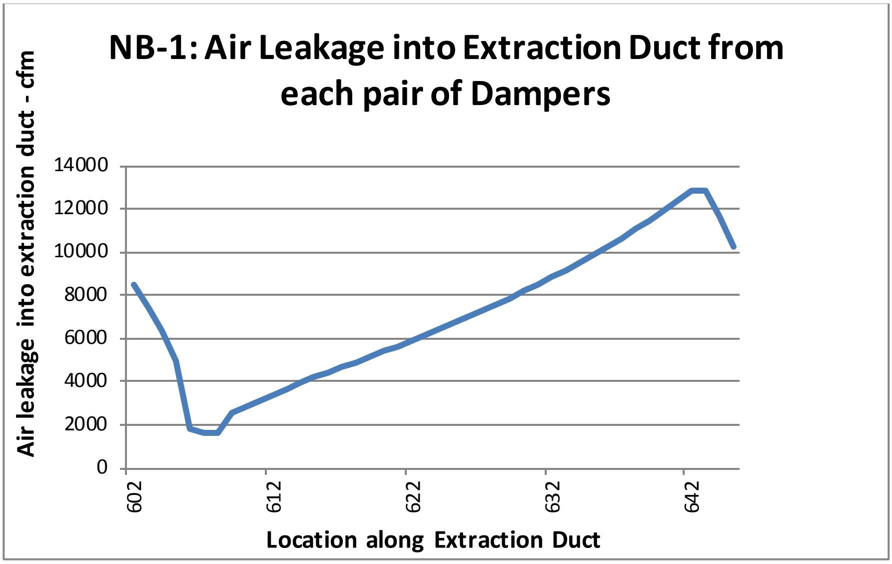

Figure 6: Air Leakage into the Extraction Duct for Case NB1

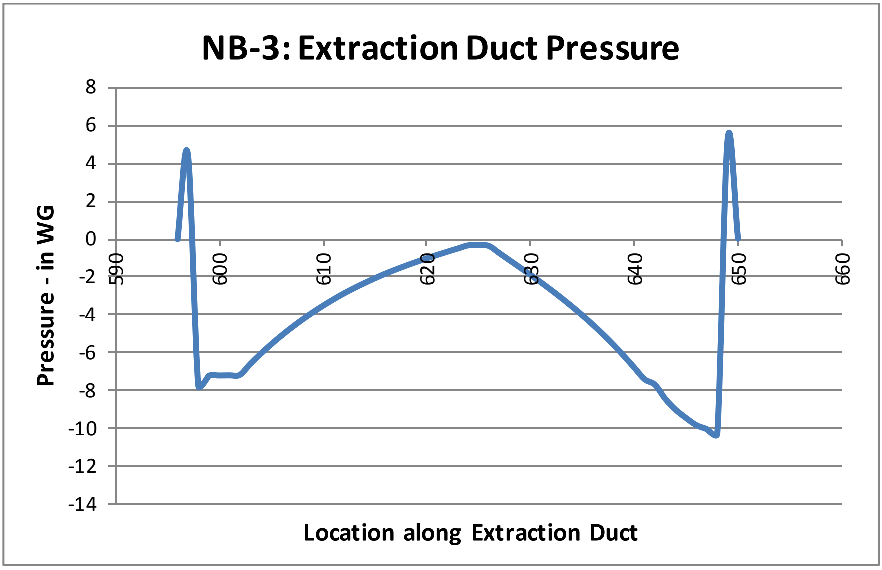

Figure 7: Extraction Duct Pressure for Case NB3

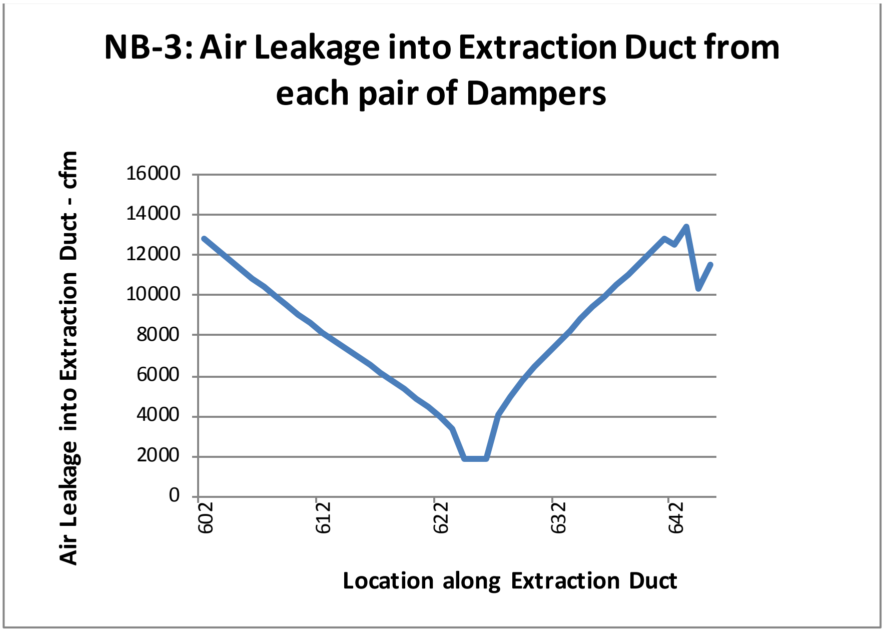

Figure 8: Air Leakage into the Extraction Duct for Case NB3

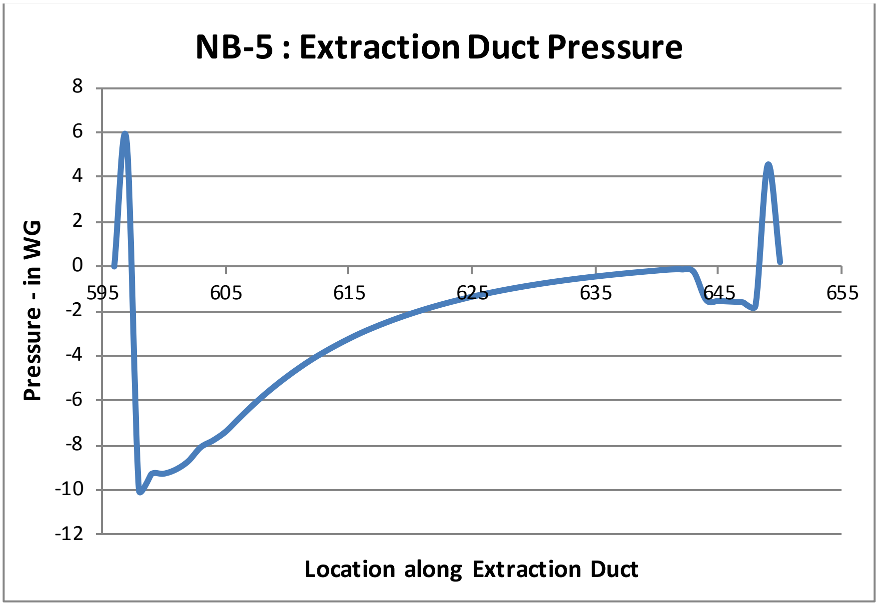

Figure 9: Extraction Duct Pressure for Case NB5

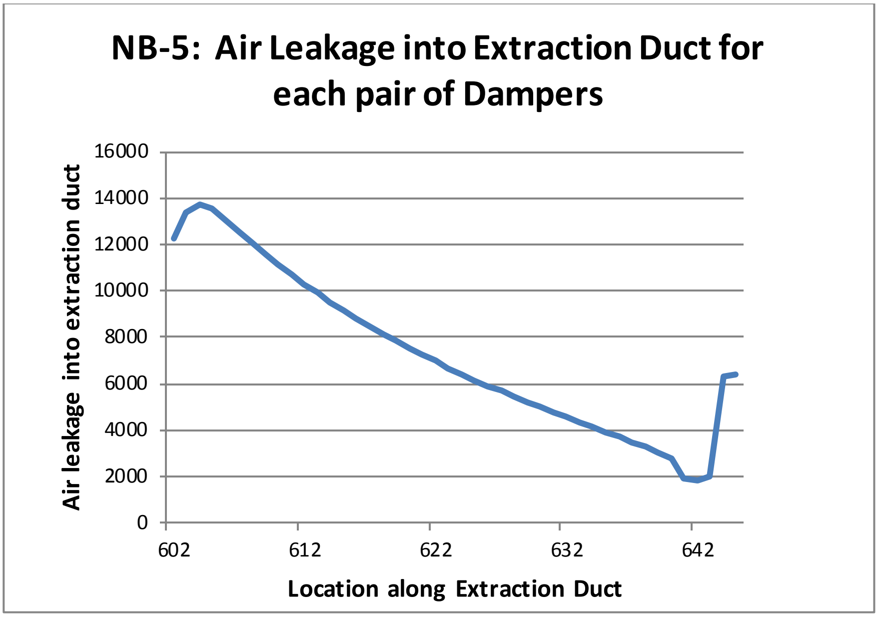

Figure 10: Air Leakage into the Extraction Duct for Case NB5