Table F.2

TWH AIR CURTAIN DATA

Location of Air Curtain		WPV	EPV
Type of Air Curtain		Single Nozzle	Single Nozzle
Nozzle Discharge Velocity, w	m/s fpm	21.41 4215	21.44 4220
Nozzle Slot Width, s	mm ft	300 0.98	300 0.98
Nozzle Slot Height, d	mm ft	5200 17.06	5800 19.03
Air Flow Through Nozzle (In One Tunnel)	m^3/s cfm	33.4 70 768	37.3 79 031
Effective Tunnel Width, b	mm ft	4000 13.12	4000 13.12
Nozzle Orientation Angle, β	deg	30	30
Air Curtain Strength,* c	m^2/s^2 ft^2/s^2	103.055 1109.247	103.310 1111.997
Recovery Time, t_o	s	4	4
Air Curtain Fan Total Pressure at Anticipated Density	Pa in. wg	741.7 2.98	805.8 3.24
Air Curtain Fan Power (Brake) Per Fan at 80% Efficiency	kW bhp	30.9 41.5	37.5 50.3

* Simulations done using 103.143 m^2/s^2 (1110.196 ft^2/s^2).

of the tunnel. The purpose of the baffles is to prevent backflow of the air curtain air into the tunnel by deflecting it out the portal, and to prevent the air curtain from inducing flow out of the tunnel. The optimal locations of the baffles are chosen by field adjustments within the limits shown on Figure F.7. The theoretical optimal location is about 1000 mm towards TWH from the intersection of the extended centerline of the nozzle with the tunnel wall.

The air curtain inlets are located on the roof of the WPV.

F.4 AIR CURTAIN MODELING

F.4.1 INTRODUCTION

As part of the TWE design analysis effort, the SES computer program was modified to incorporate the effect of air curtains similar to those described above on airflows and thus on system convective heat gains. By resisting the flow of air in a section, the air curtains cause a pressure loss. As outlined in Appendix A, and thoroughly explained in Reference 4, the SES program includes an aerodynamic subprogram which computes the net imbalances of the system pressure gains caused by trains and fans and the system pressure losses caused by friction at the tunnel walls and expansion, contraction and turning losses. These net imbalances are then used to compute the acceleration or deceleration of the flows in the various sections of the system. These rates of change of flow are used to compute the air velocities and flow rates in the system. Using an air curtain model previously developed by Abramovich (Ref. 2), equations were derived to calculate the pressure loss caused by an air curtain. These equations were programmed into the SES and a series of tests was conducted to validate their performance.

F.4.2 DERIVATION OF GOVERNING EQUATIONS

F.4.2.1 Abramovich Model

The phenomenological aspects of air curtains are discussed in Reference 2 and by Abramovich in Reference 1. The resistance of the air curtain to airflow is dependent on fixed parameters such as the nozzle width, angle, and discharge velocity, and by transient parameters such as the tunnel air velocity and the time elapsed since a train passed through the air curtain. An air curtain model should include all these parameters.

Figure F.9 shows the Abramovich air curtain model. The governing equations are derived from this model, using algebraic nomenclature which is also shown in Figure F.9. In this figure, the quantity of air entering the tunnel is being reduced by an air curtain formed by the discharge of air from a nozzle. The discharge initially has a velocity component against that of the air entering the tunnel. The air entering the tunnel turns the discharge until it crosses the plane of the portal. This intersection defines the height or range of the air curtain. Abramovich assumes that beyond this intersection the air enters the tunnel essentially undisturbed. If the range of the air curtain, h, is greater than the span of the tunnel, b, then little or no air can enter the tunnel, a condition in which the air curtain is said to be "up." If h equals zero, then the flow of air into the tunnel is not restricted, and the air curtain is said to be "down." Abramovich also assumes that the air curtain is effective over the entire depth of the tunnel; thus there is no significant leakage at the tunnel floor or ceiling caused by edge effects.

F.4.2.2 Pressure Loss Caused by Air Curtains

Both Abramovich (Ref. 1, p. 562) and Asker (Ref. 2, p. 57) state that the following is approximately true:

$$Q = V_1 d\,(b - h) \qquad \text{(F.1)}$$

Q may also be defined as follows:

$$Q = bdV_3 \qquad \text{(F.2)}$$

Equations F.1 and F.2 may be combined as follows:

$$V_3 = V_1\left(1 - \frac{h}{b}\right) \qquad \text{(F.3)}$$

From Abramovich (Ref. 1, p. 560):

$$h = \frac{ksw^2 \cos^2 \alpha \sin \alpha}{V_1^2} \qquad \text{(F.4)}$$

The air curtain recovery factor τ modifies h as follows:

$$h = \frac{\tau ksw^2 \cos^2 \alpha \sin \alpha}{V_1^2} \qquad \text{(F.5)}$$

τ is a dimensionless coefficient which reflects the transient nature of the air curtain recovery after a train has passed the air curtain. The function that describes τ should satisfy the following requirements:

1. If a considerable amount of time has elapsed since a train passed the air curtain, then $\tau = 1$ and the air curtain is "up."

2. If a train is passing the air curtain, then $\tau = 0$ and the air curtain is "down." The assumption behind this is that the air curtain has no effect when it is blocked by a train.

3. If a train has just passed the air curtain, the train wake effect predominates over the air curtain effect and τ should be slightly greater than zero.

4. As the train wake effect dissipates, τ should first increase rapidly and then increase asymptotically to 1.

Using these requirements, the following function was chosen for τ:

$$\tau = 1 - e^{-nt^2} \qquad \text{(F.6)}$$

where t is the time that has elapsed since the train passed the air curtain and n is a constant defined by the program user such that for a given recovery time t_0, $\tau = 0.9999$. For example,

b = The effective tunnel width (m).

c = The air curtain strength ($(m/s)^2$). It is defined by Equation F.7.

d = Depth of tunnel (m).

h = Range or height of air curtain (m).

H_A = Ambient total pressure head ($(m/s)^2$). Pressure head is the ambient pressure (Pa) divided by the ambient density (kg/m^3).

h_a = Ambient static pressure head ($(m/s)^2$).

k = A dimensionless numerical coefficient.

Q = Tunnel airflow (m^3/s).

S = Air curtain slot width (m).

t_o = Recovery time after train passage (s).

w = Air curtain discharge velocity (m/s).

V_A = Far-field ambient air velocity (wind) (m/s).

V_1 = Near-field ambient air velocity (wind plus induced) (m/s).

V_2 = Air velocity over the "top" of the air curtain (m/s).

V_3 = Tunnel air velocity (m/s).

α = Air curtain angle with respect to the positive tunnel axis (deg).

β = Air curtain discharge angle across the tunnel (deg).

ΔH = Increase in total pressure head across the air curtain. Measured when moving along the positive axis of the tunnel.

ρ = Mass density of air (kg/m^3).

τ = A dimensionless coefficient which reflects the transient nature of the air curtain recovery after the train has passed it.

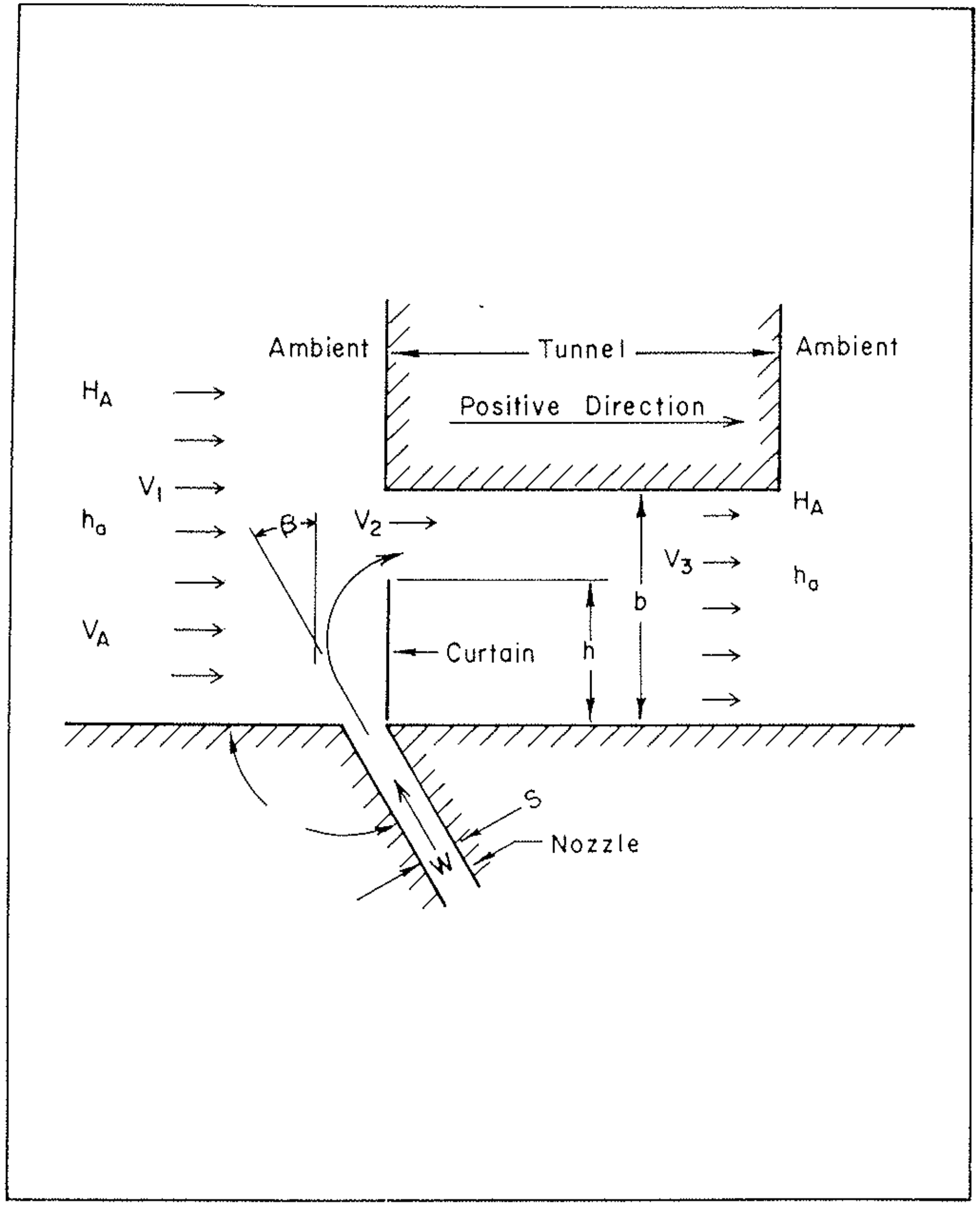

Figure F.9 - Air Curtain Nomenclature

This indicates that a minimum pressure is required before air leaks through the curtain.

The case of large values of V_3 or values approaching infinity shall now be considered. Equation F.18 may be manipulated to give:

$$\rho \Delta H = \frac{\rho V_3^2}{4} - \frac{\rho V_3^2}{4}\left(1 + \frac{4c\tau}{V_3^2}\right)^{1/2} - \frac{\rho c \tau}{2} \qquad (F.21)$$

The square root in equation F.21 may be approximated by a two-term binomial expansion:

$$\rho \Delta H = \frac{\rho V_3^2}{4} - \frac{\rho V_3^2}{4}\left(1 + \frac{2c\tau}{V_3^2}\right) - \frac{\rho c \tau}{2} \qquad (F.22)$$

By multiplying out:

$$\rho \Delta H = \frac{\rho V_3^2}{4} - \frac{\rho V_3^2}{4} - \frac{\rho c \tau}{2} - \frac{\rho c \tau}{2} \qquad (F.23)$$

Or:

$$\rho \Delta H = -\rho c \tau \qquad (F.24)$$

This indicates that the maximum pressure drop of the air leaking through the air curtain is limited to a fixed value which is twice the minimum pressure drop of equation F.20.

Equation F.7 may be substituted into equation F.20 to give:

$$\rho \Delta H = -\frac{\rho \tau k s w^2 \cos^2 \alpha \sin \alpha}{2b} \qquad (F.25)$$

Equation F.25 may be solved for k as follows:

$$k = -\frac{2b\Delta H}{\tau s w^2 \cos^2 \alpha \cos \alpha} \qquad (F.26)$$

Data from Reference 2 indicate that an air curtain with a discharge velocity of 6000 fpm (30.48 meters per second) and a width of 8 inches (203 mm) discharging across a tunnel 15 feet (4572 mm) wide at a 30 degree angle will prevent or stop a 2190 fpm (11.13 meters per second) wind from inducing airflow into a tunnel. (These data are similar to that supplied by other manufacturers.) Thus, appropri values for equation F.26 are:

w	=	6000 fpm	$\cos \alpha$	=	½
s	=	8 inches or 2/3 foot	$\sin \alpha$	=	$\sqrt{3}/2$
b	=	15 ft	ΔH	=	$-(2190)^2/2$
β	=	30 degrees	τ	=	1
α	=	120 degrees			

Solving for k:

$$k = \left(\frac{2 \times 15 \times 2190 \times 2190}{2}\right) \times \left(\frac{3 \times 2 \times 2 \times 2}{1 \times 2 \times 6000 \times 6000 \times 1 \times 1 \times \sqrt{3}}\right) = 13.845 \qquad (F.$$

Equation F.27 may be substituted into equation F.7 to give:

$$c = \frac{13.845\, s w^2 \cos^2 \alpha \sin \alpha}{b} \qquad (F.2$$

With this value of c, equation F.18 may be used to calculate the pressure drop across an air curtain as a function of the tunnel air velocity. Figure F.11 shows the results for the two air curtains described in Table F.3; the case A air curtain is similar to the LAK air curtains and case B is similar to TWH.

As shown in Figure F.11, equation F.17 predicts a pressure change across the air curtain when the tunnel air velocity V_3 is equal to zero. If the SES aerodynamic subprogram encounters such a circumstance, it tends to predict movement of air caused by this pressure change. Since this movement does not in fact occur, a separate equation

Table F.3

AIR CURTAIN PRESSURE LOSS CALCULATIONS

Type of Data		Case A (LAK)	Case B (TWH)
Nozzle Discharge Velocity, w	m/s	20.6	21.4
Nozzle Slot Width, s	m	0.25	0.30
Tunnel Width, b	m	4.0	4.0
Nozzle Angle, β	deg	20	30
Nozzle Angle, a	deg	110	120
Air Curtain Strength, c	$(m/s)^2$	40.36	102.96
τ	—	1	1
Air Density	kg/m^3	1.163	1.163
Minimum Pressure Drop (Equation F.20)	Pa	23.5	59.9
Maximum Pressure Drop (Equation F.24)	Pa	47.0	119.7

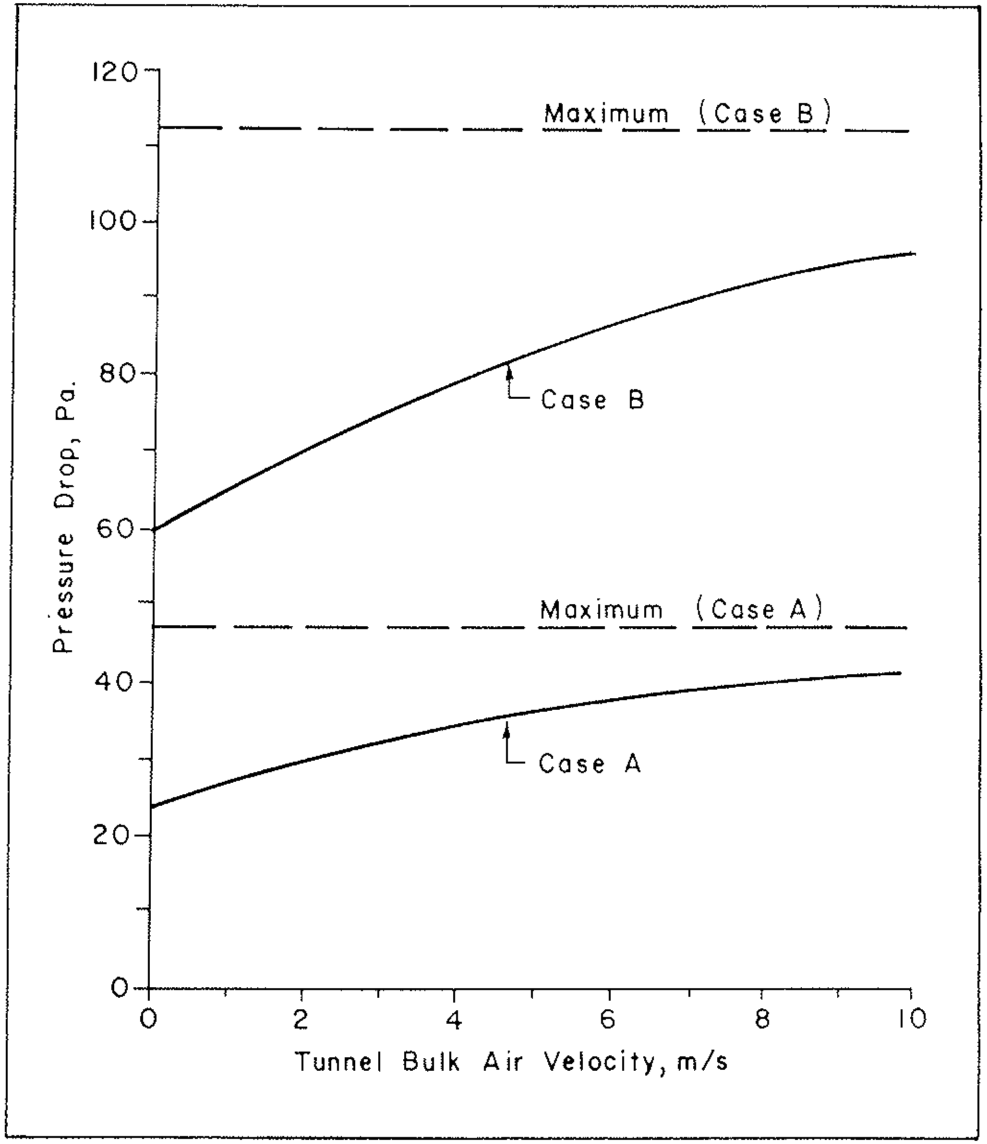

Figure F.11 - Air Curtain Performance Curve was postulated for small or zero values of V_3. For these values the air curtain pressure change is computed as:

$$\Delta H = -\frac{JV_3^2}{2} \qquad \text{(F.29)}$$

where J is the maximum head loss coefficient of the air curtain. (A value of 1000 was used in the simulations.) The program chooses the lower of the two values of pressure change resulting from equation F.29 and equation F.17.

The SES computer program does not have the ability to simulate the effect of wind pressure at a portal on tunnel ventilation. Equation F.17 may be modified to include the effect of wind in the direction shown in Figure F.9 as a term independent of the air curtain. The modified equation is as follows:

$$\Delta H = -\frac{V_3\left(-V_3+\sqrt{V_3^2+4c\tau}\right)+2c\tau}{4} + \frac{V_A^2}{2} \qquad \text{(F.30)}$$

Equation F.30 is not the impact of the wind on the air curtain; rather, it is the pressure change caused by the separate effects of the air curtain and the wind added together.

F.4.2.3 Additional Assumptions

A number of assumptions must be made to use the above equations to simulate air curtain performance. The first assumption is that recirculation neither helps nor hinders air curtain performance. Discussions with an air curtain manufacturer (Ref. 3) indicated that recirculation will improve performance when the air curtain is "up," i.e. when $h \geq b$, since the suction of the return inlet will attract the nozzle discharge with little entrainment of the tunnel air. With the air curtain "down," however, the air curtain return would entrain outside air which would then be recirculated and would eventually enter the system. This would cause air curtain performance to drop. Although the air curtain is "up" most of the time, it was decided to use the compromise assumption that recirculation has no effect on air curtain performance. A similar assumption was made for the computation of the fan requirement for the recirculating air curtain. It was assumed that the discharge velocity pressure of the air curtain nozzle was completely dissipated as the air traveled from the nozzle to the return.

The second assumption is that the baffles shown in Figure F.7 neither help nor hinder air curtain performance. With the air curtain "up," a baffle would improve performance by deflecting all the air curtain discharge (which consists of outside air) out of the portal while reducing any tendency of the air curtain to induce airflow out of the system. However, with the air curtain partially or fully "down," the baffle might deflect outside air into the system. Therefore, the compromise assumption of no effect was used.

The third assumption is that with unidirectional air curtains only a slight pressure drop would occur if the tunnel air velocity V_3 was negative (i.e. out of the portal, as shown in Figure F.9). With small negative values of V_3 the air curtain would cause pressure drops quite similar to those for positive values of V_3; however, with large negative values, the air curtain would not cause a pressure drop and could induce additional airflows in the negative direction. Therefore, a compromise was reached which assumes that the pressure drops for negative values of V_3 are one-tenth of those for positive values of V_3.

The fourth assumption is that only one nozzle of the bidirectional air curtains affects tunnel airflows at any one time, i.e., one nozzle acts to resist only inflow and the other nozzle acts to resist only outflow.

F.4.3 SES PROGRAMMING AND TESTING

Figure F.12 shows the sign conventions used in programming the air curtain equations. The conventions were chosen for user convenience.

The following equations were programmed for the bidirectional air curtain:

$$\Delta H = \text{either} - \frac{|V_3|\left(-|V_3|+\sqrt{V_3^2+4c\tau}\right)+2c\tau}{4} + \frac{V_A^2}{2} \qquad \text{(F.31)}$$

$$\text{or} - \frac{J|V_3|V_3}{2} + \frac{V_A^2}{2}. \qquad \text{(F.32)}$$