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SSC TUNNEL AIR CONDITIONING

(Heating/Cooling and Dehumidifying)

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The great distances between penetrations to the SSC tunnel create difficulties in ventilating and air conditioning the tunnel. Major penetrations were assumed for these calculations to be 8000 meters apart (one per sector) into an 8 foot diameter tunnel. The result of this large length to diameter ratio is that one cannot heat or dehumidify only from one end of the sector. Increasing the tunnel diameter to 9 feet does not affect this study; the area actually available for air flow depends on the floor design and space taken up by magnets and other equipment. For the 8 foot diameter tunnel this air flow area is taken to be 50 ft^2, the full tunnel cross sectional area.

Ventilation requirements for the SSC tunnel depend not only on protecting equipment from excessive humidity but also on safety and comfort for personnel during accesses to the tunnel. We have used Cern's requirement that air is changed at a rate of 30 m^3/hr per person in its tunnels. The temperature should stay within an acceptable range for workers, e.g., 65° to 80°F. The dew point should remain less than the temperature of the coldest surface (except, of course, for possible cold spots on cryogenic equipment with vacuum leaks, etc.) A maximum dew point of 57°F was selected (corresponding to 75% relative humidity at 65°F), and calculations were done for dehumidification to a 53°F dew point (corresponding to 65% relative humidity at 65°F).

Figure 1 shows a schematic of air flow through the completed tunnel. We want to be able to out-walk the gas from a cryogenic leak, hence we use a 3 mph maximum tunnel air flow rate. For the purposes of this study there is assumed to be 2 miles per hour of continuously circulating air flow around the tunnel. In addition to this circulating flow, 1 mile per hour of fresh air is injected into each sector, and 1 mile per hour of air is lost in total from each sector through various minor penetrations and to the outside at the end of the sector where the next 1 MPH unit is injecting air. Thus, there are 12 places (one for each sector) where outside air is introduced at a volume flow rate equivalent to 1 MPH of tunnel air flow.

For our 50 ft^2 of tunnel air flow area, one mile per hour is 7477 m^3 per hour of fresh air flow. (See Appendix 1 for details.) After mixing with 2 MPH of "stale" air from the previous sector and the loss of at most one mile per hour equivalent of this mixture through the sector, the end of the sector receives at least 2/3 x 7477 m^3 or 4985 m^3 per hour of fresh air. Thus, 4985 m^3 per hour would be the minimum amount of fresh air flowing anywhere in the tunnel. The number of people in each sector would be limited to 4985 m^3 per hour divided by 30 m^3 per hour per person, or 166 people per sector.

Dehumidifying 1 MPH of air from 100% relative humidity at 95°F to a humidity equivalent to 65% at 65°F requires the removal of 69 gallons of water per hour from the air. (See Appendix 1 for details.) The power to remove this water is approximately 90 KW per 1 MPH unit. It is not necessary to inject cool air into the tunnel after dehumidification. This unit may put the heat generated by the process back into the dry air.

In winter to heat -25°F air to 65°F would require 127 KW for a 1 MPH unit. (See Appendix 1 for details.) Thus, the maximum powers for winter and summer are each on the order of 100 KW for a 1 MPH unit. Twelve of these around the ring implies approximately 1200 KW for conditioning outside air.

The 2 miles per hour basic circulating flow, the minimum flow rate at any place in the tunnel, was used to calculate heat loss by convection from the tunnel air to the rock wall (Appendix 2) and moisture picked up by the air from the tunnel wall (Appendix 3). For convection to the tunnel wall it was assumed that the rock conducts the heat radially outward to a fixed 55°F at a 100 foot radius with a thermal conductivity of 3.5 W/m-K. Both the rock thermal conductivity and the radius at which the temperature is fixed are parameters which should be refined. For evaporation into the tunnel air a 5% wetted surface was assumed for the rock; this is also an important parameter which should be refined.

As is shown by Appendices 2 and 3, the tunnel cannot be heated or dehumidified just from one end of a sector. Distributed heating and dehumidification are necessary. Distributed heating might be provided incidentally by equipment in the tunnel. To see what the heating (or cooling) requirements are, a Tunnel Heat Table (Appendix 4) was assembled. It does appear that the operating system may dissipate enough power to heat the tunnel.

Appendix 3 contains an example of distributed dehumidification. Dehumidifiers spaced every 1000 meters could maintain tunnel humidity between 65% and 75%. The power required is approximately 16.4 KW per unit or 130 KW per sector. Fifty gallons of water per hour per sector are removed from the air.

A check of the fan required for pushing 1 mile per hour of air through the tunnel indicates that its power requirement is negligible. Calculating pressure drop like through a tube: three miles per hour of flow through a sector is about 0.83×10^{-2} psid per sector, or 0.23 inches of water per sector. For each 4400 ft^3 per minute (1 mile per hour of flow) through a 1/4 inch water pressure rise one would need a 3/4 HP fan. (See details in Appendix 5.)

Only the completed tunnel has been discussed so far; construction poses special problems. Fig. 2 illustrates a possible arrangement for supplying air to the tunnel during construction. There is no circulating flow; all the air is conditioned outside air. Combinations of units which will provide outside air to the completed tunnel can provide air to the tunnel during construction. For example, with the tunnel incomplete in one sector, four 1 MPH units injecting air in one location can provide a flow of 2 MPH each way, with one 1 MPH unit for each sector supplementing the flow as in the case of the completed tunnel.

Also, the distributed tunnel heating and dehumidifying would have to be provided as for the completed tunnel. The dehumidifiers could be located in the tunnel in their final configuration during construction for use during installation, start-up, etc. Supplemental heaters may be required where other power consumption does not yet meet the heating requirements.

In conclusion, the length of the tunnel results in the necessity for distributed heating and dehumidification in the tunnel. Equipment may provide sufficient heating during operations, but there are some uncertainties. Among these are rock thermal conductivity. There must be introduction of outside air and removal of tunnel air. Skidded air intake units sized for 1 MPH of tunnel air flow, consuming about 100 KW each, can provide outside air during construction, when circulation of air is not possible, and during operation.

Among the important questions to be answered before detailed designs can be made are:

1. What will be the real percent wetted surface?

2. Will the percent wetted surface change over time?

3. What will be the rock thermal conductivity?

FIGURE 1

STEADY STATE AIR FLOW

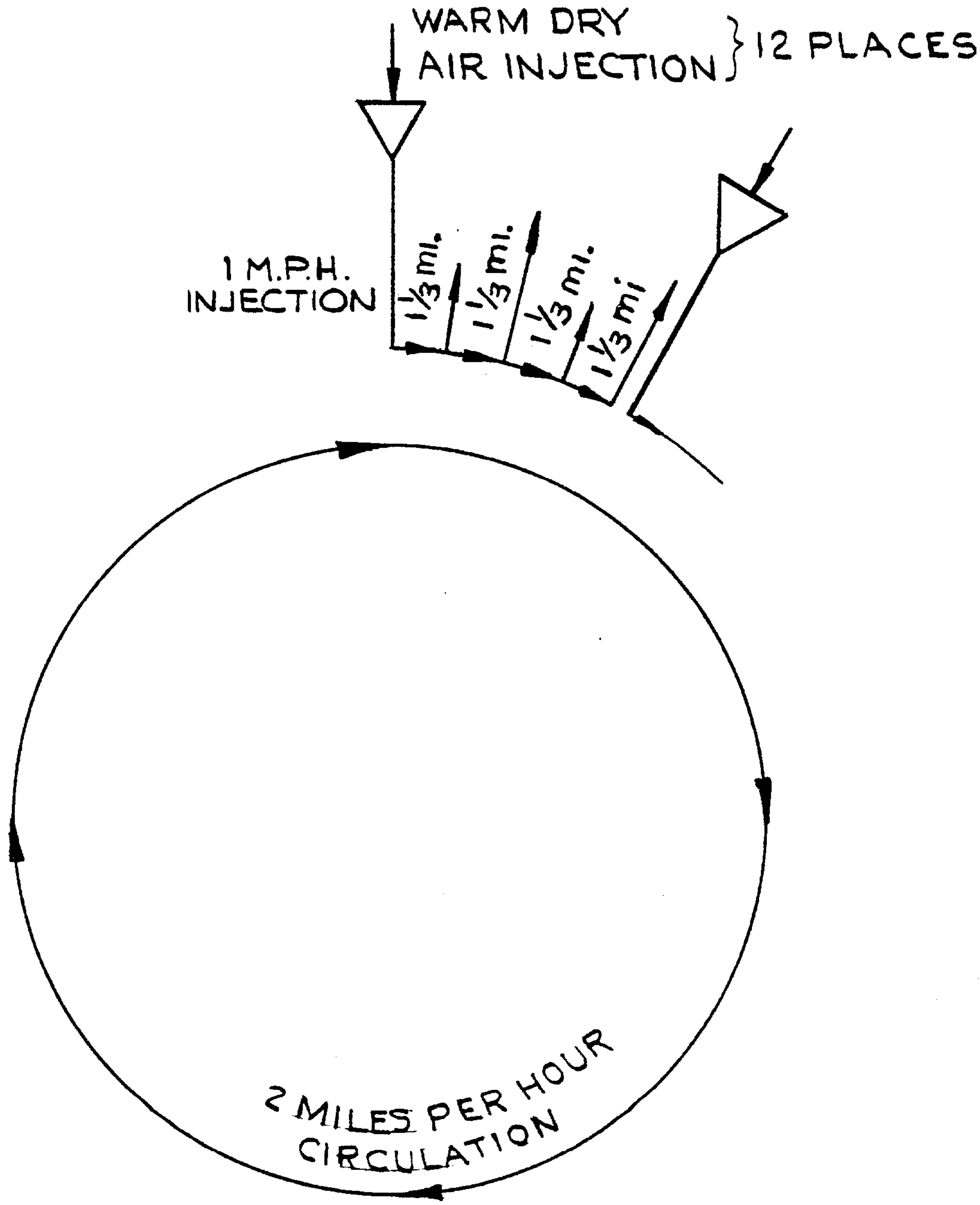
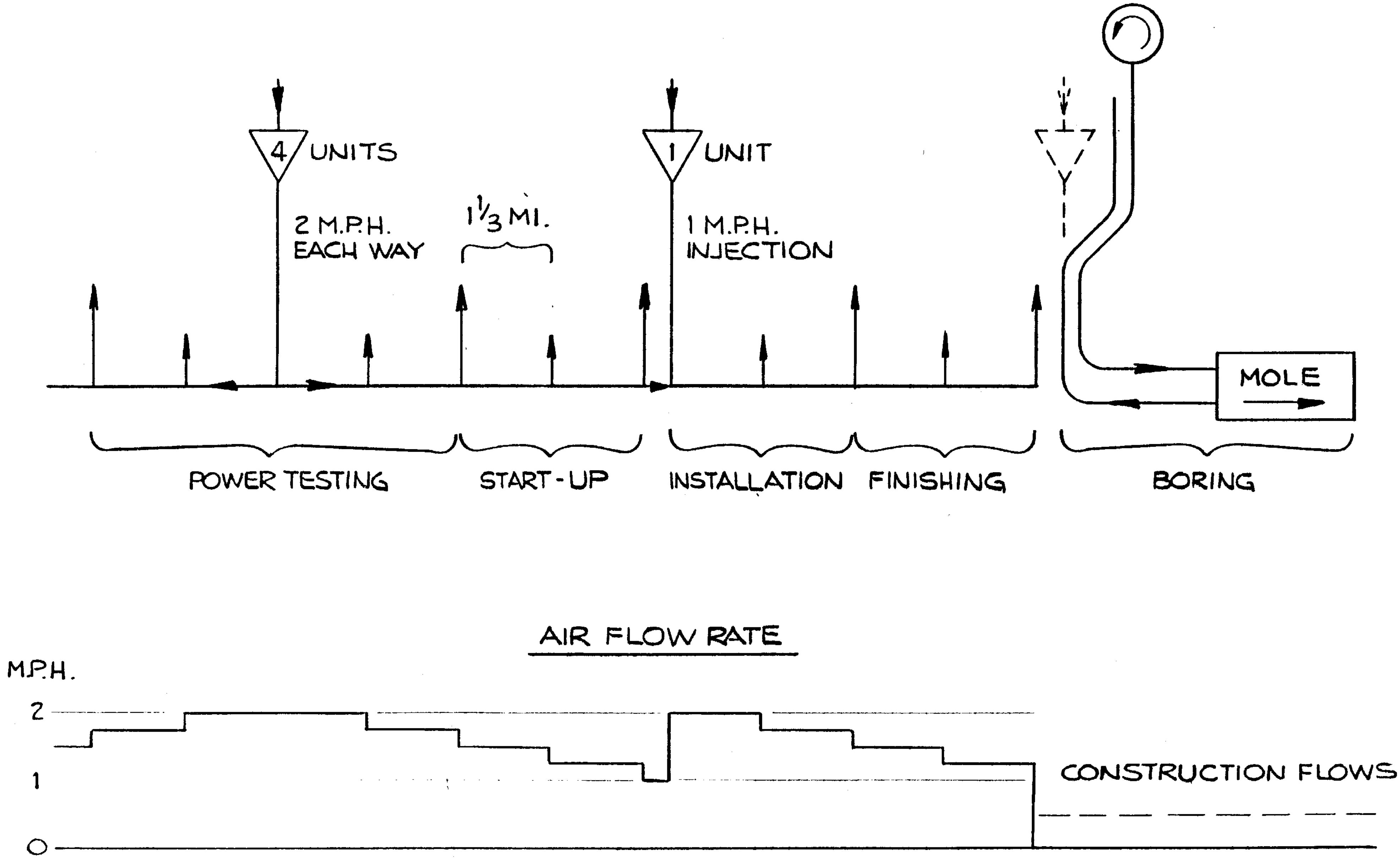


FIGURE 2
CONSTRUCTION AIR FLOW – 1/4 RING



APPENDIX 1

Calculations Regarding Injection of Outside Air into the Tunnel

1 mile/hr of air x 5280 ft/mile x 1 hr/60 min x 50 ft^2
= 4400 ft^3/min of air flow x 0.076 lb_m/ft^3 at 65^oF
= 334 lb_m/min air. Also 4400 ft^3/min x 1 m^3/35.31 ft^3
= 124.6 m^3/min x 60 min/hr = 7477 m^3/hr of air flow.

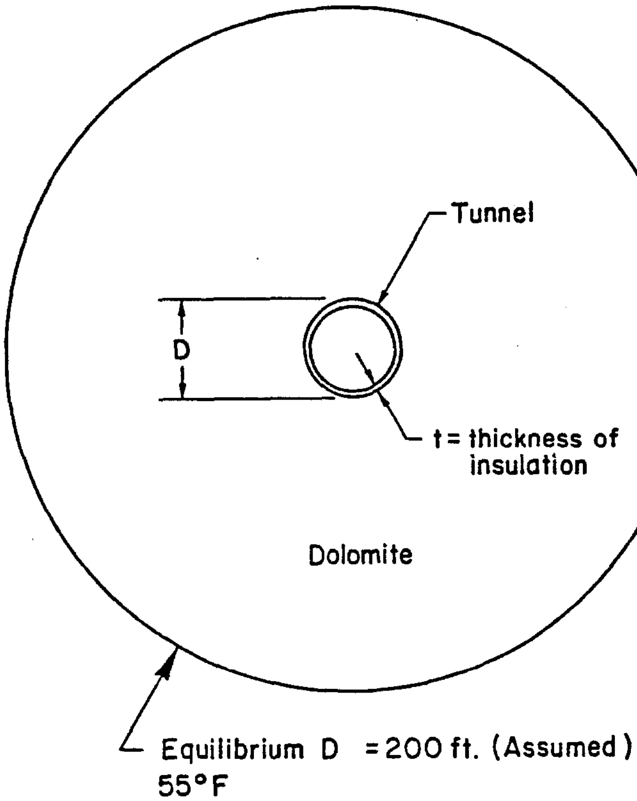
Suppose we start with 95^oF air, 100% humidity. From the Psychrometric chart this is a specific humidity of 0.0371 lb_m water per lb_m dry air. To remove water such that at 65^oF one has 65% relative humidity means reaching a specific humidity of 0.0086 lb_m water per lb_m dry air. Therefore we must remove 0.0285 lb_m water per lb_m dry air. Suppose the above air flow calculations refer to dry air, then (0.0285 lb_m water per lb_m dry air) x (334 lb_m/min dry air) = 9.53 lb_m/min water. Convert to gallons per hour: 9.53 lb_m/min x 1 gallon/8.29 lb_m x 60 min/hr = 69 gallons per hour for one mile per hour of tunnel flow on a humid summer day.

The rate of removal of latent heat of vaporization from that water is 9.53 lb_m/min x 1073 Btu/lb_m x 60 min/hr x 1 watt/3.413 Btu/hr = 180 KW. For a large dehumidifier operating with inlet air at 80^oF (a Desert Aire model # EHCC-500) the ratio of electric power consumed to latent heat removed is 0.5; for 65^oF air this ratio is 0.9. Using the 0.5 ratio to estimate power consumed by the 1 MPH unit conditioning outside air, power consumed is 90 KW.

For heating the air in winter suppose the outside air is $-25^{o}F$. Even if this $-25^{o}F$ air is at 100% relative humidity it will be much less than 20% RH at $65^{o}F$, so water will not be considered, just power to heat dry air to $65^{o}F$. 334 lb_m/min x 60 min/hr x 0.24 Btu/lb_m ^{o}F x $90^{o}F$ x 1 W/3.413 Btu/hr = 127 KW.

APPENDIX 2

Tunnel Heat Loss Analysis



Reynolds number

$$R_e = \rho \frac{VD}{\mu} \tag{1}$$

Nusselt number

$$\bar{N}_u = \frac{\bar{h}D}{k_f} = 0.023\ R_e^{\ 0.8}\ P_r^{\ .33} \tag{2}$$

Radial heat transfer

$$Q_r = \frac{T_i - T_\infty}{\dfrac{1}{\pi D_1 h} + \dfrac{\ln (D_2/D_1)}{2\pi k_1} + \dfrac{\ln (D_3/D_2)}{2\pi k_2}} \tag{3}$$

$$= \dot{m} Cp\ (T_i - T_0) \tag{4}$$

$$= \rho A V C_p\ (T_i - T_0) \tag{5}$$

FIX UNITS

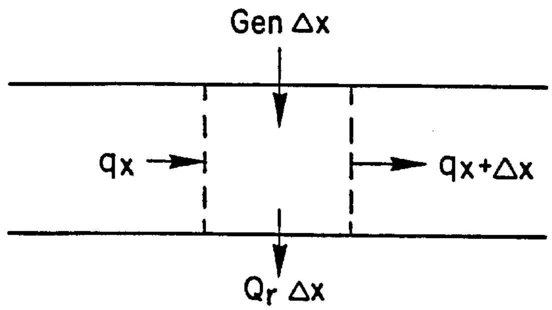
Air Properties

ρ	[=]	lbm/ft^3	0.0756
μ	[=]	lbm/ft-sec	1.2232×10^{-5}
K_f	[=]	BTU/hr ft F	0.0147
C_p	[=]	BTU/lbm-F	0.24
P_r	[=]	Prandl number	0.72

Other

T	[=]	^oF	
V	[=]	mph	Air flow
D	[=]	ft	Tunnel diameter (to dolomite)
X	[=]	ft	Axial distance
Q	[=]	KW	Heat transfer
h	[=]	$BTU/hrft^2F$	Heat transfer coefficient
D_i	[=]	ft = D- t/6	Tunnel diameter (to insulation)
t	[=]	inches	Insulation thickness
K_i	[=]	BTU/hrftF	Thermal conductivity of insulation
K_D	[=]	BTU/hrftF	Thermal conductivity of dolomite
Gen	[=]	W/ft	Internal heat generation

$$Q_r = \frac{T - T_\infty}{\dfrac{1}{\pi D_i h} + \dfrac{\ln (D/D_i)}{2\pi\ k_i} + \dfrac{\ln (D_\infty/D)}{2\pi\ k_D}}$$



Energy Balance

$$q_x = q_{x+\Delta x} + (Q_r - \text{Gen})\ \Delta x \quad \text{Steady State}$$

$$\dot{m}C_p T_x = \dot{m}C_p\ T_{x+dx} + (Q_r - \text{Gen})\ \Delta x$$

$$\dot{m}C_p\ (T_x - T_{x+\Delta x}) = \frac{T - T_\infty}{\Sigma R}\ \Delta x - \text{Gen}\ \Delta x$$

$$\frac{T_x - T_{x+\Delta x}}{\Delta x} = \frac{T - T_\infty}{\dot{m}Cp\Sigma R} - \frac{\text{Gen}}{\dot{m}\ Cp}$$

$$\frac{dT}{dx} = \frac{T - T_\infty - \Sigma R\text{Gen}}{\dot{m}Cp\Sigma R}$$

$$\int_{T_I}^{T_x} \frac{dT}{T - T_\infty - \Sigma R\text{Gen}} = \int_0^x \frac{dx}{\dot{m}Cp\Sigma R}$$

$$\ln \left[\frac{T_I - T_\infty - \Sigma R\text{Gen}}{T_x - T_\infty - \Sigma R\text{Gen}}\right] = \frac{x}{\dot{m}Cp\Sigma R}$$

$$\frac{T_I - T_\infty - \text{Gen}\Sigma R}{T_x - T_\infty - \text{Gen}\Sigma R} = e^{\left(\frac{x}{\dot{m}Cp\Sigma R}\right)}$$

Solve for Tx using prescribed units

$$\boxed{T_x = T_\infty + 3.413 \ \text{Gen}\Sigma R + (T_I - T_\infty - 3.413 \ \text{Gen}\Sigma R) \ e^{\left(\frac{-x}{A}\right)}} \qquad (^{o}F)$$

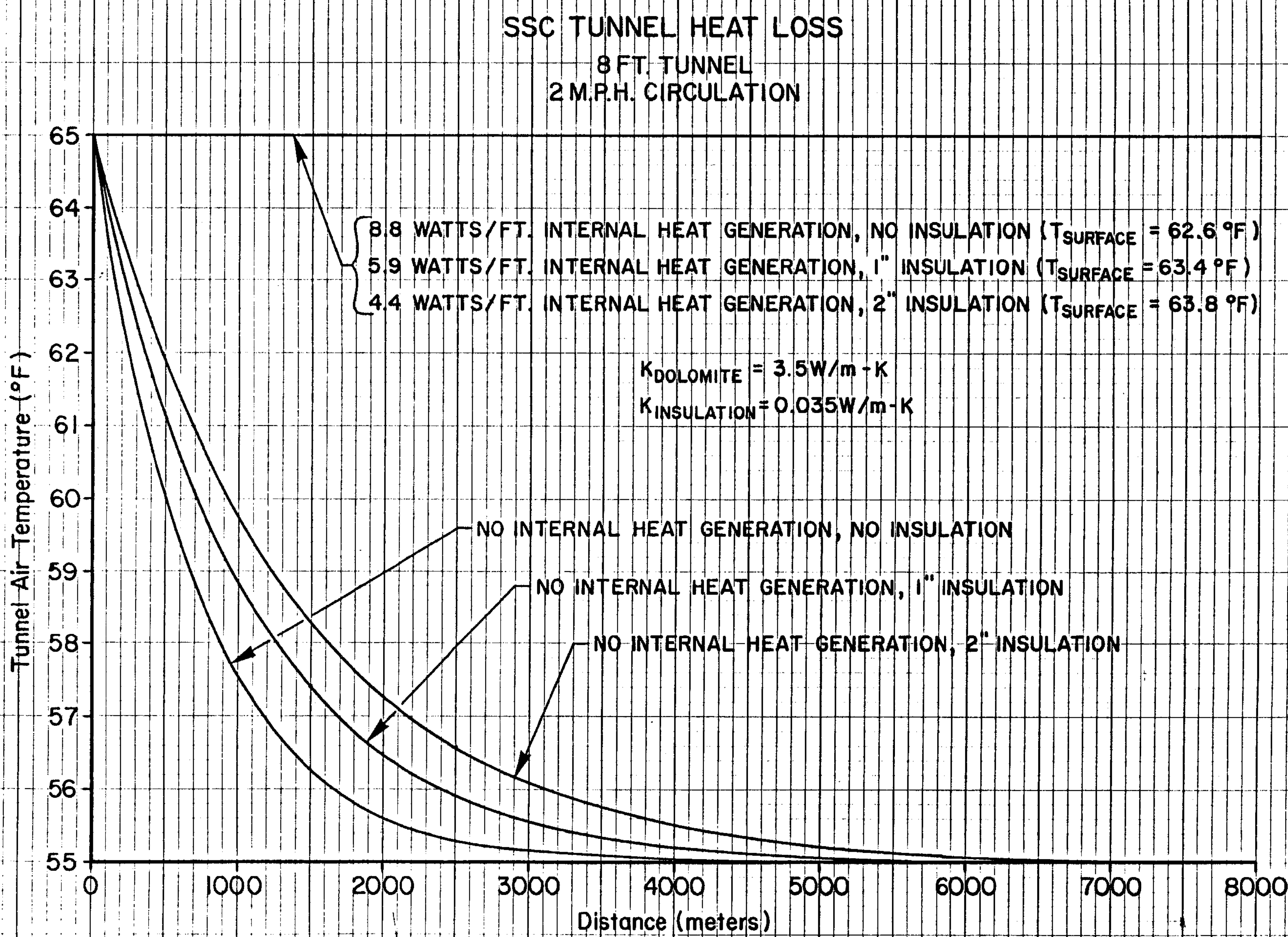
$$A = \dot{m}Cp\Sigma R \qquad (ft)$$

$$\Sigma R = \frac{1}{\pi Dih} + \frac{\ln(D/D_i)}{2\pi \ k_i} + \frac{\ln(D_\infty/D)}{2\pi \ k_D} \qquad \left(\frac{hrftF}{BTU}\right)$$

$$\dot{m}Cp = 56.43D_i^{\ 2} \ V \qquad (BTU/hrF)$$

$$\boxed{Q = \frac{\text{Gen X}}{1000} + \left[\dot{m} \ C_p \ (T_I - T_x)\right] /3413} \qquad (KW)$$

$$h = 0.4446 \ \frac{(VD_i)^{0.8}}{D_i} \qquad \left(\frac{BTU}{hrft^2F}\right)$$


SSC TUNNEL HEAT LOSS
8 FT. TUNNEL
2 M.P.H. CIRCULATION
8.8 WATTS/FT. INTERNAL HEAT GENERATION, NO INSULATION ($T_{SURFACE}$ = 62.6 °F)
5.9 WATTS/FT. INTERNAL HEAT GENERATION, 1" INSULATION ($T_{SURFACE}$ = 63.4 °F)
4.4 WATTS/FT. INTERNAL HEAT GENERATION, 2" INSULATION ($T_{SURFACE}$ = 63.8 °F)
$K_{DOLOMITE}$ = 3.5W/m-K
$K_{INSULATION}$ = 0.035W/m-K
NO INTERNAL HEAT GENERATION, NO INSULATION
NO INTERNAL HEAT GENERATION, 1" INSULATION
NO INTERNAL HEAT GENERATION, 2" INSULATION
Tunnel Air Temperature (°F)
65
64
63
62
61
60
59
58
57
56
55
0
1000
2000
3000
4000
5000
6000
7000
8000
Distance (meters)

APPENDIX 3

TUNNEL HUMIDITY PROFILE

Radial Water Vapor Mass Transfer

$$\dot{m}_r = h\pi DS\ (\rho_s - \rho)\ \Delta X$$

$$= \frac{h\pi DS}{RT}\ (P_s - P)\ \Delta X$$

where h = mass transfer coefficient

D = Tunnel dia.

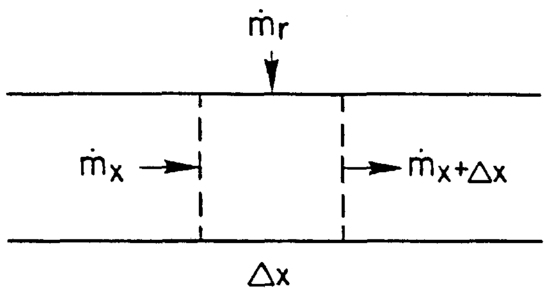
S = fraction of tunnel wall covered by water

P_2 = Water saturation vapor pressure

P = Water vapor pressure

ρ = Water vapor density

Integrate over tunnel length



Consider mass balance of water

$$\dot{m}_x + \dot{m}_r = \dot{m}x{+}\Delta x$$

$$\rho_x AV + \dot{m}_r = \rho_{x+\Delta x}\ AV$$

$$P_x \frac{\pi D^2 V}{4\ RT} + \frac{h\pi DS}{RT} (P_s - P)\ \Delta X = P_{x+\Delta x} \frac{\pi D^2 V}{4RT}$$

$$(P_x - P_{x+\Delta x}) \frac{DV}{4} = - hS\ (P_s - P)\ \Delta X$$

$$\frac{P_x - P_{x+\Delta x}}{\Delta x} = - \frac{4hs}{DV} (P_s - P)$$

Take the limit as $\Delta X \to 0$

$$\frac{dP}{dx} = \frac{4hs}{DV} (P_s - P)$$

$$\frac{dP}{P_s - P} = \frac{4hs}{DV}\ dx$$

Integrate

$$l_n \left[\frac{P_s - P_I}{P_s - P_x} \right] = \frac{4hsx}{DV}$$

$$P_x = P_s - (P_s - P_I)\ e^{\left(- \frac{4hSX}{DV} \right)}$$

In terms of relative humidity (ϕ)

$$\phi_x = 1 - (1 - \phi_I)\ e^{\left(\frac{-4hSX}{DV} \right)}$$

Find mass transfer coefficient

$$j_d = 0.023\ R_e^{-0.17} S_c^{0.11}$$

$$= \frac{Sh}{R_e S_c^{1/3}}$$

$$Sh = 0.023\ Re^{0.83} S_c^{0.44}$$

$$= \frac{h_D D}{D_v} \quad \frac{Pam}{Pt}$$

$$h_D = 0.023\ R_e^{0.83}\ S_c^{0.44}\ \frac{D_v}{D}\ \frac{Pt}{Pam}$$

$$\frac{Pam}{P_t} \equiv 0.98$$

$D_v = 0.243\ cm^2/sec$ Ashrae Handbook of Fundamentals (1978) 5.1 table 4

$\rho = 1.211 \times 10^{-3}$ g/cc

$\mu = 1.8203 \times 10^{-4}$ g/cm-sec

$V = 2$ mph

$= 90$ cm/sec

$$R_e = \frac{1.211 \times 10^{-3} g}{cc} \left| \frac{2\ mi}{hr} \right| \frac{8ft}{} \left| \frac{cm\ sec}{1.803 \times 10^{-4} g} \right\| \frac{5280 \times 12 \times 2.54\ cm\ hr}{mi} \left| \frac{2.54 \times 12\ cm}{ft} \right.$$

$= 145000$

$R_e = 9065\ VD$ where $V\ [=]\ mph$, $D\ [=]\ ft$

$$S_c = \frac{\mu}{\rho \Delta v} = \frac{1.8203 \times 10^{-4} g}{cm\ sec} \left| \frac{cc}{1.211 \times 10^{-3} g} \right| \frac{sec}{0.243\ cm^2}$$

$S_c = 0.6186$

$$h_D = 0.023\,(9065\ VD)^{0.83}\,(0.6186)^{.44}\ \frac{1}{0.98}\ \frac{0.243\ cm^2}{sec}\ \frac{ft}{Dft\ 30.48\ cm}$$

$$= 0.2917\ V^{0.83}\ D^{-0.17}$$

where V [=] mph
D [=] ft

For V = 2 mph D = 8' h_D = 0.3641 cm/sec

$$\frac{4h_D SX}{DV} = 4\ \frac{0.2917V^{0.83}D^{-0.17}\ cm}{sec}\ \Big|\ S\ \Big|\ Xft\ \Big|\ \frac{1}{Dft}\ \Big|\ \frac{hr}{V\ mi}\ \Big|\ \frac{mi\ \ 3600}{5280 \times 12 \times 2.54\ cm}\ \Big|\ \frac{sec}{hr}$$

$$= 0.02610V^{-0.17}D^{-1.17}SX$$

$$\phi_x = 1 - (1-\phi_I)\ e^{(-0.02610V^{-0.17}D^{-1.17}SX)}$$

where V [=] mph

D [=] ft

X [=] ft

S [=] unit less

$$\dot{m}_{dehydration} = (\rho_{wo} - \rho_{wI}) \; AV$$

$$= (p_{wo} - p_{wI}) \; \frac{AV}{RT}$$

$$= p_{sat}(\phi_o - \phi_I) \; \frac{AV}{RT}$$

$$P_{sat} \text{ (atm)} = 218.16710 \quad \frac{-\beta}{T} \left(\frac{a+b+\beta+c\beta^3}{1+d\beta} \right)$$

see ASHRAE Handbook of Fundamentals

$T \; [=] \; {}^{o}K$

$$\dot{m} = \Delta\phi \; \frac{P_{sat} \text{ atm}}{} \; \frac{\pi D^2 \text{ft}^2}{4} \; \frac{\text{lbm R}}{85.76 \text{ ft lbf}} \; \frac{}{T \; {}^{o}K} \; \frac{K}{1.8R} \; \frac{14.7 \text{ lbf}}{\text{atm in}^2} \; \frac{V_{mi} \; 5280 \times 12\text{in}}{\text{hr mi}} \; \frac{12\text{in}}{\text{ft}}$$

$$= 56850 \Delta\phi P_s D^2 V / T \qquad \text{(lbm/hr)}$$

$$\text{gal/hr} = \text{lbm/hr} \; \frac{7.481}{62.4}$$

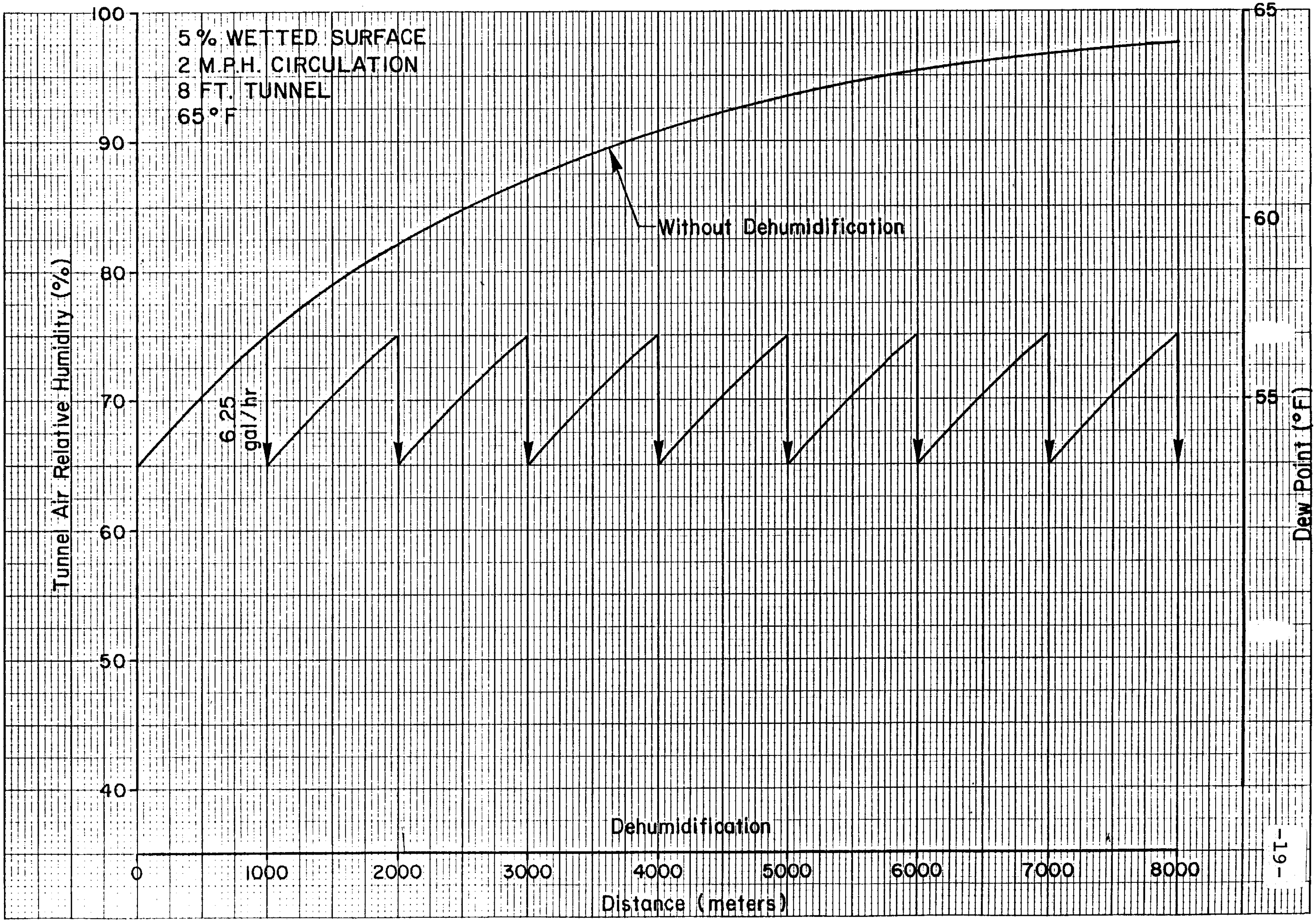
where P_s [=] atm

Δ [=] ft

V [=] mph

T [=] ${}^{o}K$

SSC TUNNEL HUMIDITY PROFILE



Fermilab

Nov. 16, 1984

EXPLANATION OF TUNNEL HEAT TABLE

The Tunnel Heat Table is the first pass at doing a heat and moisture balance on the SSC Tunnel. The basic questions we would like to answer using the information in this table are:

1. Should we think in terms of adding heat to the tunnel or removing it from the tunnel?

2. Will the tunnel be dry (is it practical to dehumidify it) or should we plan for a "wet" (100% humidity) environment with perhaps dehumidification of small enclosures where necessary?

The attached 23.9 KV cable schematic shows that there are four cases for the quantity of heat input to the tunnel from the cable between major areas. These cases are the four columns labeled sector "1" through sector "4". The only difference between these "sectors" is the heating from the 23.9 KV cable, the first row in the table. All the other rows are the same for each sector.

Within each sector two cases are considered, normal operating tunnel heat load and the cooldown tunnel heat load.

The attached electrical schematic shows the arrangement of items from the main transformer to the lights. The main transformer is assumed to be outside of the tunnel, so the heat generated is shown in parentheses and is not included in the total. The lights may be turned on or off during operation and during cooldown when personnel are not in the tunnel.

The compressors and power supply are assumed to be outside of the tunnel, so their heat generation is not included in the total. If they are at tunnel elevation and it is desirable to add heat to the tunnel one could consider distributing some of this heat.

The LCW pipes could be designed to add heat to the tunnel in amounts depending on pipe size, location, and the pipe surface (fins ?).

Explanation of Tunnel Heat Table (cont)

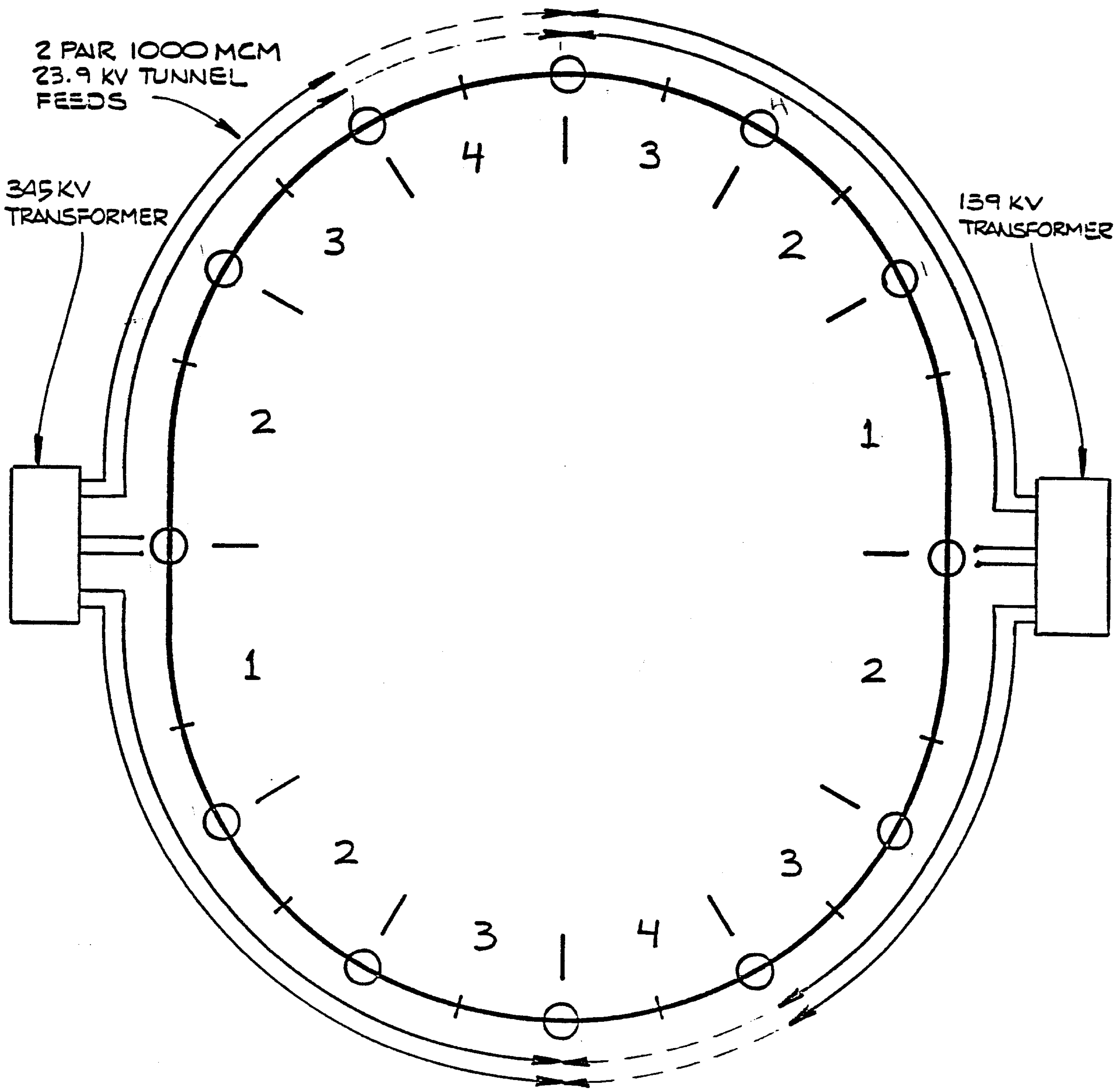
The rock conduction number, like the four rows in the table below it, is assumed to be independent of whether it it is during operation or cooldown. The calculation is based on the following assumptions: convection from 65°F air flowing through the tunnel at 2 mph to the rock surface at some intermediate temperature determined by the relative rates of conduction through the rock and convection, and conduction from the wall surface through dolomite (k = 3.5 W/m°K) radially outward to a 100 foot radius where the rock is assumed to be a constant 55°F. (See the attached Tunnel Heat Loss plot.)

The evaporation and condensation numbers are based on the 65°F, 2 mph tunnel air passing over 5% wetted surface increasing the relative humidity from 65% to 75%, and then being dehumidified from 75% relative humidity back down to 65% relative humidity. (See the attached SSC Tunnel Humidity Profile.)

The dehumidifier power comes from the fact that the dehumidifiers for Fermilabs' present main ring tunnel consume an amount of electrical power approximately equal to the heat gain from condensation under conditions of air temperature and relative humidity assumed here.

The line called "total extra cable" shows the total heat load for a sector "1" if the 23.9 kV cable through that sector is duplicated, cutting the heat generation in that sector by the 23.9 kV power in half.

NAMING OF SECTORS 1, 2, 3, and 4 FOR TUNNEL HEAT TABLE



SECTOR POWER LAYOUT

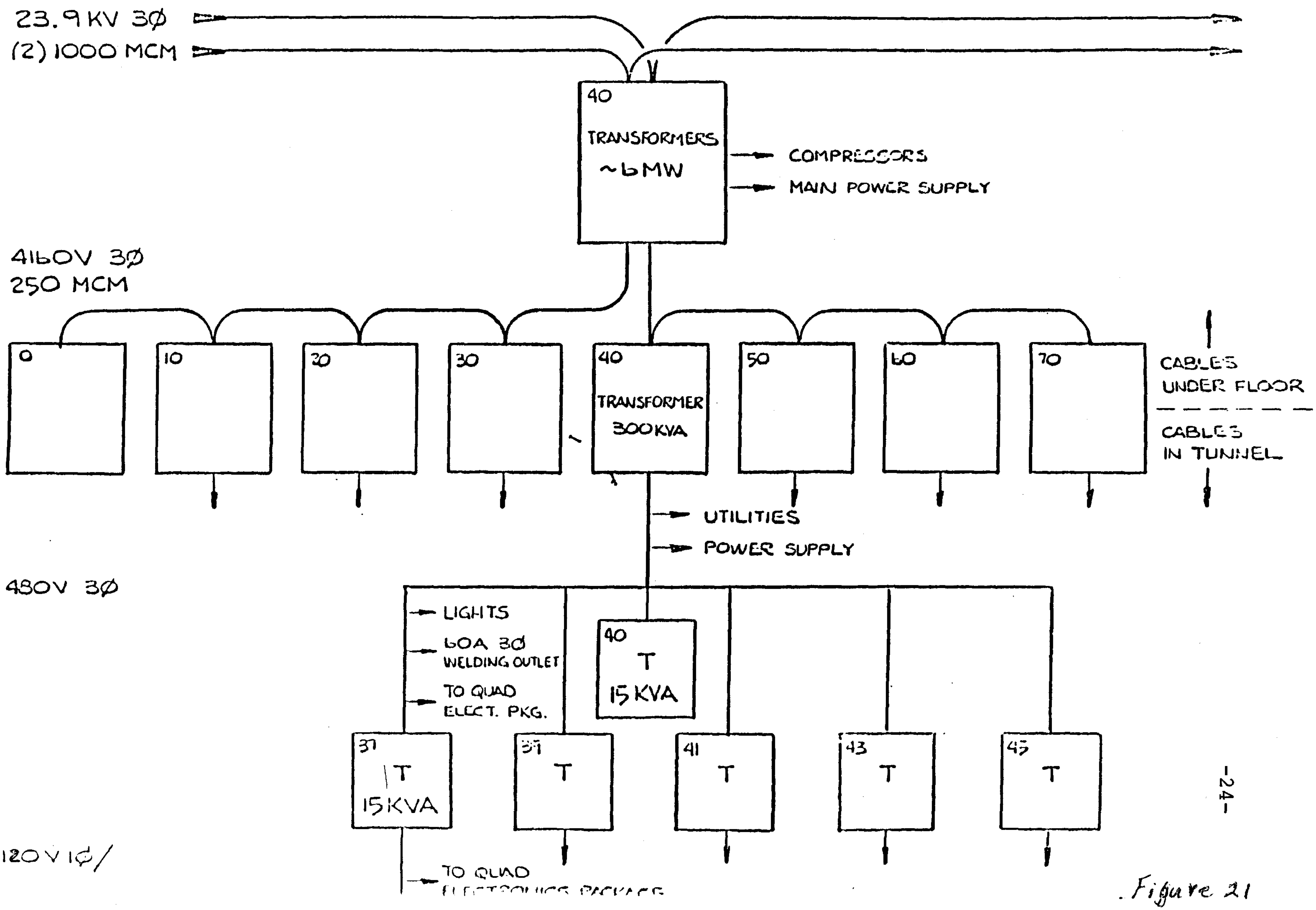


Figure 21

APPENDIX 5

ΔP in Air through SSC Sector and Required Fan Size

$\Delta P \quad = \quad 1/2 \; \rho \nu^2 \frac{L}{R_h} \; f$

$\nu \quad = \quad$ 3 miles per hour = 4.4 ft/sec

$\rho_{air} = \quad 0.076 \; lb_m/ft^3$

$R_h \quad = \quad$ hydraulic radius = R/2 = 2 ft.

$L \quad = \quad$ 8000m = 26250 ft.

$f \quad = \quad$ friction factor = f (Re)

$Re \quad = \quad \rho \nu D/\mu \quad = \quad 2.2 \times 10^5$

where D = tunnel diameter = 8 ft.

and μ = air viscosity = $1.2 \times 10^{-5} \; lb_m/ft \; sec.$

From charts for f: f = 0.004.

Thus, ΔP = 0.0083 psid = 0.23 inches of water.

Fan size: in an ILG Industries fan catalogue, 4400 ft^3 per minute through a 1/4" water static pressure is about 3/4 HP. However, the tunnel may have to be divided into shorter sections for purposes of dehumidification in the tunnel, each with a fan driving air through that section.