EVALUATION, DESIGN, DEVELOPMENT AND
DELIVERY OF A 1200 kV PROTOTYPE TERMINATION

Sixth Technical Progress Report

Covering the Period From

March 1, 1980 to May 31, 1980

September 16, 1980

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Sixth Technical Progress Report

September 16, 1980

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Evaluation, Design, Development and Delivery
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1.0 ABSTRACT

Computer field calculations were made of the electrostatic shield effectiveness model and plans were made for intermediate scale testing of the resistive grading coating. A detailed thermal analysis of the SF₆ impregnated film condenser shows natural reflux cooling of the configuration keeps temperatures within acceptable limits. Favorable results are reported on the final set of puncture tests of shatter-resistant weathercases.

2.0 INTRODUCTION

This is the Sixth Technical Progress Report on the Evaluation, Design, Development and Delivery of a 1200 kV Prototype Termination. The SF₆ gas bushing termination will be integrated into a gas insulated substation. The produced design will be economically attractive and will exhibit improved electrostatic performance, acceptable temperature gradients, and better mechanical integrity when compared with the gas/air termination of typical ratings built with conventional technology.

The project is divided into nine tasks which include the evaluation of innovative and novel concepts and materials uses, thorough paper and model studies of the electrical, thermal and mechanical characteristics of the most promising configurations, designs, production and testing of a full scale prototype and finally delivery of the prototype termination to an appropriate field site.

3.0 TASK 2 - ELECTROSTATIC STUDIES

3.1 SHIELD EFFECTIVENESS STUDIES

As described in Section 3.1 of the Fifth Technical Progress Report, a gas bushing model was tested with three different conductor diameters (see also Figure 3-1). The results proved that electrode shaping in the throat area of the bushing can have significant effect on the dielectric strength of the air outside the bushing. As a check on the test results, the electrostatic field was calculated for each of the three conductor diameters. Figure 3-2 compares the equipotential lines at 10 percent intervals for the three configurations. The lines obviously become more bunched near the throat shield as they exit the weathercase for the larger diameter conductors. Note, for example the separation of the 30 and 40 percent lines just outside the weathercase. Thus, the most uniform weathercase surface gradient was obtained for the 7.5 cm (smallest) conductor. The maximum surface gradients for the 15.2 and 20.3 cm conductors were calculated to be 21 and 34 percent higher respectively than the 7.5 cm conductor. This agrees well with the 60 Hz withstand performance tabulated in Table 3-8 of the Fifth Technical Progress Report repeated here as Table 3-1.

Unfortunately the grid size for the calculations was not small enough to obtain an accurate absolute value for the maximum voltage gradient. If time permits a magnification of the critical area may be calculated during the next period.

FIGURE 3-1 SHIELD EFFECTIVENESS MODEL

FIGURE 3-2 Electrostatic Field Plots

SHIELD EFFECTIVENESS MODEL

60 Hz PERFORMANCE

<u>7.5 cm Conductor</u>	<u>Test Voltage</u> kV rms	<u>Time</u>	<u>Result</u>
1. Standard Top Shield	529	60 Sec.	O.K.
	552	60 Sec.	O.K.
	575	1 Sec.	F.O. Ext.
2. Extension on Top Shield	529	60 Sec.	O.K.
	552	60 Sec.	O.K.
	575	60 Sec.	O.K.
	598	1 Sec.	F.O. Ext.
3. Extension on Top Shield + 3.3 x.3.3 m Ground Plane at Bottom of Bushing	506	60 Sec.	O.K.
	483	60 Sec.	O.K.
	506	60 Sec.	O.K.
	529	1 Sec.	F.O. Ext.
<u>15.2 cm Conductor</u>			
1. Extension on Top Shield	437	60 Sec.	O.K.
	460	60 Sec	O.K.
	483	60 Sec	O.K.
	506	-	F.O. Ext.

Table 3-1

3.2 RESISTIVE GRADING

3.2.1 Small Model Tests

No work was performed on the small semiconducting coated models during this period. The present plan is to submit the models to simulated wet switching surge tests in a fog chamber. The mist rate will be adjusted to form a continuous flow of water down the surface of the model.

3.2.2 Intermediate Scale Model

Since it is extremely dangerous to scale up from 20 cm to 5 meters, tests at intermediate sizes are very desirable. The largest epoxy weathercase presently in production at the Trafford facility is a 152.4 cm (60 in) long shell normally used on 242 kV oil/paper condenser bushings. This weathercase shell can be easily mated with production gas bushing parts and the test tank used for the shield effectiveness tests. An experimental model bushing was designed, therefore, as shown in Figure 3-3 using the production flange and bottom end parts to fit the tank. The bushing will be mounted as in Figure 3-4.

Two models will be made -- one with a coating of silicon carbide paint on the inside of the weathercase, and the other without a coating. Comparison tests will determine 60 Hz corona threshold voltage and wet switching surge flashover levels for both models. These should be good tests of the voltage grading ability of paint since the model's weathercase are otherwise very poorly graded.

FIGURE 3-3 Resistive Grading Bushing Model

FIGURE 3-4 Resistive Grading Bushing and Test Fixture

4.0 TASK 3 - THERMAL STUDIES

4.1 CONFIGURATION

The geometry of the bushing is shown in Figure 4-1. The conductor is a 25.4 cm (10 in) I.D. aluminum cylinder with a 1.3 cm (0.5 in) wall thickness. The height of the bushing is 864 cm (340 in). The conductor is insulated by a tapered insulation layer having a thickness of 1.3 cm (0.5 in) at each end and a maximum thickness of 19.7 cm (7.75 in) near the middle. A radial gap of 2.54 cm (1 in) is assumed between the insulation and the porcelain weathershed. This gap and the inside of the conductor are filled with SF₆ gas at a gauge pressure of 345 kPa (50 psig).

This analysis was performed to determine whether natural circulation of SF₆ up through the hollow conductor and down through the gap would be sufficient to limit the maximum conductor temperature rise to 60°C above a 40°C ambient. For an assumed circulation rate, the analysis obtains the gas and conductor temperatures as a function of position. The temperature difference between the gas in the hollow cylinder and the gas in the gap provides a buoyancy pressure difference to circulate the gas. The pressure drop for circulation of the assumed flow is then calculated and compared to the buoyancy pressure difference. This process is iterated until convergence is obtained.

FIGURE 4-1 - BUSHING GEOMETRY

4.2 ANALYSIS OF PRESSURE DROPS

4.2.1 Pressure Drop in the Pipe

The flow rate of the circulating SF_6 is denoted by $\dot{M}$ and the inside pipe diameter is D_p . Then the velocity is

$$U_p = \frac{\dot{M}}{\rho A_p} \quad (1)$$

where ρ = density of SF_6

$$\begin{aligned} A_p &= \text{Pipe cross sectional area} \\ &= \frac{\pi}{4} D_p^2 \end{aligned}$$

The Reynolds number is:

$$Re_p = \frac{U_p D_p}{\nu} = \frac{4\dot{M}}{D_p \mu} \quad (2)$$

Where ν = kinematic viscosity

μ = dynamic viscosity

For turbulent flow, the friction factor is:

$$f_p = \frac{0.3162}{Re_p^{0.25}} \quad (3)$$

and the pipe pressure drop is:

$$\Delta P_p = \frac{1}{2} \left(\frac{\rho U_p^2}{D_p} \right) \left(\frac{f_p L}{D_p} \right) \quad (4)$$

4.2.2 Pressure Drop in the Gap

The centerline diameter of the annulus at distance x from the bottom is:

$$D_m = D_o \left(1 + \alpha_o \frac{x}{L_1} \right) \quad (4)$$

Where D_o = Centerline gap diameter at $x = 0$.

D_i = centerline gap diameter at $x = L_1$

$$\alpha_o = \frac{D_i}{D_o} - 1$$

L_1 = length from bottom to maximum taper.

The annular gap area at x is:

$$A_g = \pi D_m b \quad (6)$$

Where b is the width of the gap.

The hydraulic diameter is $2b$ and the Reynolds number at x is:

$$Re_g = \frac{2bu_g}{\nu} = \left(\frac{2bu_o}{\nu} \right) \frac{1}{\left(1 + \alpha_o \frac{x}{L_1} \right)} \quad (7)$$

and the local friction factor is:

$$f = \frac{0.3162}{(Re_g)^{\frac{1}{4}}} \quad (8)$$

Where: $u_o = \frac{\dot{M}}{\rho A_o}$ = velocity at $x = 0$

$$A_o = \pi D_o b$$

The local pressure gradient is:

$$\begin{aligned} \frac{dp}{dx} &= \frac{\rho u_g^2}{2} \left(\frac{f}{2b} \right) \\ &= \frac{K U_o^{1.75}}{(1 + \alpha_o \frac{x}{L_1})^{1.75}} \end{aligned} \quad (9)$$

Where $K = \frac{0.3162\rho}{4b} \left(\frac{v}{2b} \right)^{\frac{1}{4}}$ (10)

Integration of equation (9) to obtain the pressure drop for the length L_1 gives:

$$\begin{aligned} \Delta P_{gi} &= \int_0^{L_1} \left(\frac{dp}{dx} \right) dx \\ &= K K_1 U_o^{1.75} L_1 \end{aligned} \quad (11)$$

where $K_1 = \frac{(1 + \alpha_o) \cdot 0.75 - 1}{0.75 \alpha_o (1 + \alpha_o) \cdot 0.75}$ (12)

Since length L_2 has a linear taper between the same mean diameters, the total pressure drop for the gap may be written

$$\Delta P_g = K K_1 U_o^{1.75} L \quad (13)$$

Where $L = L_1 + L_2$

4.2.3 Total Pressure Drop

The total pressure drop is the sum of the pipe and gap pressure drops and the pressure drop due to turning losses at each end. The turning losses are:

$$\Delta P_e = C_e \frac{\rho U_o^2}{2} \quad (14)$$

Where $C_e = 3$ is assumed.

Then the total pressure drop is:

$$\Delta P_t = \frac{C_e \rho U_o^2}{2} + \frac{\rho U_p^2 f_p L}{2 D_p} + K K_1 L U_o^{1.75} \quad (15)$$

4.2.4 Buoyancy Pressure Difference

It is useful to express the pressure drop in terms of a required mean temperature difference in the two legs necessary to produce the pressure drop. Let $\bar{T}$ be the mean gas temperature in the pipe and $\bar{T}_g$ be the mean gas temperature in the gap. Then the buoyancy pressure difference is:

$$\Delta P_b = g \rho \beta L (\bar{T} - \bar{T}_g) = g \rho \beta L \Delta \bar{T} \quad (16)$$

The mean value of $\Delta \bar{T}$ required to make ΔP_b equal to ΔP_t is:

$$\Delta \bar{T} = \frac{\Delta P_t}{g \rho \beta L} \quad (17)$$

4.3 THERMAL ANALYSIS

A typical cross section of the bushing is shown in Figure 4-2a. Temperature of the various parts are labeled in Figure 4-2b. Here, T denotes the local gas temperature in the pipe and T_w is the local pipe or conductor temperature. The temperature of the outside surface of the insulation is T_1 and T_2 is the temperature of the porcelain surface at the gap. T_g is the local gas temperature in the gap and T_3 is the mean temperature of the outside porcelain surface. The ambient temperature is T_a .

4.3.1 Thermal Resistance Network

The unsimplified thermal resistance network is shown in Figure 4.3. Resistances are evaluated for the total length of the bushing. It is assumed that mean values of insulation thickness and porcelain external area are used as well as mean heat transfer coefficients. The thermal resistance from the conductor to the gas inside it is:

$$R_H = \frac{1}{HSL} \quad (18)$$

where

H = Heat transfer coefficient from conductor to gas.

$S = \pi D_i$ = inside perimeter of the conductor.

L = Total length of the bushing.

The resistance of the insulation is:

$$R_I = \frac{1}{2\pi K_i L} \ln \left(\frac{d_o}{d_i} \right) \quad (19)$$

a

b

FIGURE 4-2 - TYPICAL CROSS SECTION AND
LOCATION OF TEMPERATURES

INITIAL NETWORK

Figure 4-3

where:

d_o = Mean outside diameter of insulation
 d_i = Inside diameter of insulation
 K_i = Thermal conductivity of insulation

The thermal resistance of the porcelain is:

$$R_p = \frac{1}{2\pi K_p L} \ln \frac{d_3}{d_2} \quad (20)$$

where:

d_3 = Effective outside diameter of porcelain
 d_2 = Mean porcelain inside diameter
 K_p = Thermal conductivity of porcelain

The thermal resistance from the outside porcelain surface to ambient is:

$$R_m = \frac{1}{A_r H_r + A_c H_c} \quad (21)$$

where:

A_r = External radiation surface area = $\pi d_3 L$
 A_c = External surface area = $\pi d_3 L L_s / P_s$
 H_c = External convection coefficient
 H_r = External radiation coefficient
 L_s = Creepage length per water shed
 P_s = Axial spacing of water sheds

The thermal resistance from the insulation surface to the gas in the gap is

$$R_A = \frac{1}{H_g A_g} \quad (22)$$

and the thermal resistance from gas in the gap to the porcelain surface is

$$R_B = \frac{1}{H_g A_g} \quad (23)$$

where:

$A_g = \pi \bar{D}_g L$ = mean gap surface area

H_g = heat transfer coefficient.

The thermal resistance for radiation heat transfer across the gap is

$$R_C = \frac{1}{H_{rg} A_g} \quad (24)$$

where:

H_{rg} = radiation heat transfer coefficient across the gap.

4.3.2 Heat Transfer Coefficients

The heat transfer coefficient, H , from the conductor to gas inside the hollow conductor is taken as the larger of the natural convection coefficient, H_{pn} , and the forced convection coefficient, H_{pf} . The natural convection coefficient is obtained from

$$H_{pn} = (c K_g)^{3/4} (aq)^{1/4} \quad (25)$$

where:

K_g = Gas thermal conductivity

$$a = \frac{g\beta Pr}{2u}$$

q = Surface heat flux

c = 0.129 = turbulent convection constant

The forced convection coefficient is

$$H_{pf} = 0.023 \frac{K_g}{D_p} Re_p^{.8} Pr^{.4} \quad (26)$$

The radiation coefficient across the gap is approximated by

$$H_{rg} = 4\sigma\epsilon T_g^3 \quad (27)$$

where:

ϵ = Emissivity factor

σ = Stefan Boltz mann constant

T_g = Mean gap temperature.

The radiation coefficient from the outside porcelain surface to ambient is

$$H_r = 4\sigma T_a^3 \quad (28)$$

The convection coefficient from the outside porcelain surface to ambient for laminar convection is

$$H_c = (C_1 K_a)^{4/5} \left(\frac{q_a A_a}{L_s} \right)^{1/5} \quad (29)$$

where:

K_a = Thermal conductivity of air
 q_a = Convection heat flux to ambient

$$A_a = \frac{g\beta Pr_a}{v_a^2}$$

L_s = Creepage length per watershed on the porcelain
 $C_1 = 0.59$ = laminar convection constant

The forced convection coefficient from the gap surface to gas in the gap is calculated for turbulent flow using

$$H_g = \frac{0.023}{2b} K_g (Re_g)^{.8} Pr^{.4} \quad (30)$$

and for laminar flow using

$$H_g = 4.12 K_g / b \quad (31)$$

At low flows, free natural convection may dominate, in which case turbulent natural convection gives

$$H_g = (c K_g)^{3/4} (a q_g)^{1/4} \quad (32)$$

where:

$$q_g = \frac{2}{3} \frac{Q}{A_g} \quad (33)$$

$C = .129$ = turbulent convection constant.

The larger of the three coefficients calculated by equations (31), (32) or (33) should be used.

4.3.3 Transformation of Resistance Network

The unsimplified network Figure 4-4a requires one to use T , T_w , T_1 , T_2 , T_g as unknowns. By appropriate Y- Δ and Δ -Y transformations, the network can be transformed to that shown in Figure 4-4b and then to the one shown in Figure 4-4c which only involves T , T_w and T_g as unknowns when all coefficients are specified. The values for R_1 , R_2 and R_3 are:

$$\begin{aligned} R_1 &= \frac{R_B R_C}{\Sigma} \\ R_2 &= \frac{R_A R_C}{\Sigma} \\ R_3 &= \frac{R_A R_B}{\Sigma} \end{aligned} \quad (34)$$

where:

$$\Sigma = R_A + R_B + R_C$$

Then letting

$$\begin{aligned} R_1' &= R_1 + R_p + R_m \\ R_2' &= R_2 + R_I \\ R_3' &= R_3 \end{aligned} \quad (35)$$

one obtains

$$\begin{aligned} R_a &= \frac{R_S}{R_1'} \\ R_b &= \frac{R_S}{R_2'} \\ R_c &= \frac{R_S}{R_3'} \end{aligned} \quad (36)$$

(a) INITIAL NETWORK

(b) NETWORK AFTER Δ -Y TRANSFORM

(c) SIMPLIFIED NETWORK AFTER Y- Δ TRANSFORM

FIGURE 4-4 - THERMAL RESISTANCE NETWORKS

where:

$$R_s = R_1' R_2' + R_1' R_3' + R_2' R_3' \quad (37)$$

The above values of R_H , R_a , R_b and R_c describe the simplified network of Figure (3c) in terms of the original network parameters.

4.3.4 Energy Balance Equations

In the following thermal analysis, the tapered geometry is replaced by an effective geometry having uniform diameters along the length of the bushing. In this effective geometry, the mean values of insulation thickness and porcelain diameter are used to evaluate the heat transfer from the conductor to ambient. These mean values correspond to the values used in calculating the thermal resistance in previous sections.

The energy balance for the gas flowing up through the hollow conductor is:

$$m \frac{dT}{dZ} = h(T_w - T) \quad (38)$$

where:

$$m = \dot{M} c_p$$

$$h = \frac{1}{R_H}$$

$$Z = \frac{x}{L}$$

T = Gas temperature rise at Z

T_w = Conductor temperature rise at Z

L = Total length of the bushing.

The energy balance on the conductor including the effect of axial conduction is

$$K \frac{d^2 T_w}{dz^2} + h(T - T_w) + u(T_g - T_w) - w T_w + Q = 0 \quad (39)$$

where:

$$K = \frac{K_w A_w}{L}$$

$$u = \frac{1}{R_a}$$

$$w = \frac{1}{R_c}$$

T_g = Temperature rise of gas in the gap at z

Q = Total heat dissipation in the conductor

K_w = Thermal conductivity of conductor

A_w = Cross section area of conductor

The energy balance on the gas in the gap is

$$m \frac{dT_g}{dz} = (u+v)T_g - u T_w \quad (40)$$

where:

$$v = \frac{1}{R_b}$$

The boundary conditions for the energy balance equations are:

$$\frac{dT_w(0)}{dz} = -\frac{q_o}{k} \quad (41)$$

$$\frac{dT_w(1)}{dz} = \frac{q_L}{k} \quad (42)$$

$$T(0) = T_g(0) \quad (43)$$

$$T(1) = T_g(1) \quad (44)$$

where:

q_o = Heat flow into the bottom of the bushing.

q_L = Heat flow into the top of the bushing.

4.3.5 Solution of Energy Balance Equations

By differentiation and substitution, equations (38), (39) and (40) can be combined into one fourth order differential equation for the gas temperature inside the conductor. This equation is:

$$a_4 \frac{d^4 T}{dz^4} + a_3 \frac{d^3 T}{dz^3} + a_2 \frac{d^2 T}{dz^2} + a_1 \frac{dT}{dz} + a_o T = a_5 \quad (45)$$

where:

$$a_o = (uv + vw + uw)/u \quad (46)$$

$$a_1 = m(a_o/h + v/u - w/u) \quad (47)$$

$$a_2 = -(\frac{m^2}{u}(1 + \frac{u}{h} + \frac{w}{h}) + k(1 + v/u)) \quad (48)$$

$$a_3 = \frac{mk}{u}(1 - \frac{u}{h} - \frac{v}{h}) \quad (49)$$

$$a_4 = \frac{m^2 k}{uh} \quad (50)$$

$$a_5 = (1 + \frac{v}{u})Q \quad (51)$$

The solution of equation (45) can be written as:

$$T = \sum_{i=1}^5 C_i e^{\lambda_i z} \quad (52)$$

where:

$$C_5 = a_5/a_0 \quad (53)$$

$$\lambda_5 = 0 \quad (54)$$

and where $\lambda_1, \lambda_2, \lambda_3$ and λ_4 are the four real roots of

$$a_4 \lambda^4 + a_3 \lambda^3 + a_2 \lambda^2 + a_1 \lambda + a_0 = 0 \quad (55)$$

and where C_1, C_2, C_3 and C_4 are constants to be obtained from the boundary conditions given in equations (41) to (44).

From equation (38) and (52), T_w can be written as:

$$\begin{aligned} T_w &= T + \frac{m}{h} \frac{dT}{dz} \\ &= \sum_{i=1}^5 b_i C_i e^{\lambda_i z} \end{aligned} \quad (56)$$

where:

$$b_i = 1 + \frac{m}{h} \lambda_i \quad (57)$$

From equation (39) one obtains

$$T_g = T_w \left(1 + \frac{w}{u} + \frac{h}{u}\right) - \frac{k}{u} \frac{d^2 T_w}{dz^2} - \frac{h}{u} T - \frac{Q}{u} \quad (58)$$

which becomes

$$T_g = -\frac{Q}{u} + \sum_{i=1}^5 d_i C_i e^{\lambda_i z} \quad (59)$$

where:

$$d_i = (1 + \frac{w}{u} + \frac{h}{u}) b_i - \frac{k}{u} b_i \lambda_i^2 - \frac{h}{u} \quad (60)$$

Equations (52), (56) and (59) give the temperature distribution in the two gas streams and in the conductor. The unknown coefficients C_1 to C_4 can now be obtained from the boundary conditions as follows.

Boundary condition (41) gives

$$\frac{dT_w(0)}{dz} = \sum \lambda_i b_i C_i = -q_o/k$$

or

$$\lambda_1 b_1 C_1 + \lambda_2 b_2 C_2 + \lambda_3 b_3 C_3 + \lambda_4 b_4 C_4 = -q_o/k \quad (61)$$

Boundary condition (42) gives

$$\frac{dT_w(1)}{dz} = \sum \lambda_i b_i e^{\lambda_i} C_i = q_L/k$$

or

$$\lambda_1 b_1 e^{\lambda_1} C_1 + \lambda_2 b_2 e^{\lambda_2} C_2 + \lambda_3 b_3 e^{\lambda_3} C_3 + \lambda_4 b_4 e^{\lambda_4} C_4 = q_L/k \quad (62)$$

Boundary condition (43) gives

$$T(0) - T_g(0) = \sum (C_i - d_i C_i) + \frac{Q}{u} = 0$$

or

$$(1-d_1)C_1 + (1-d_2)C_2 + (1-d_3)C_3 + (1-d_4)C_4 = \frac{w}{u} C_o - Q/u \quad (63)$$

Boundary condition (44) gives

$$T(1) - T_g(1) = \Sigma (C_i - d_i C_i) e^{\lambda_i} + Q/u = 0$$

or

$$\begin{aligned} & (1-d_1)e^{\lambda_1}C_1 + (1-d_2)e^{\lambda_2}C_2 + (1-d_3)e^{\lambda_3}C_3 + (1-d_4)e^{\lambda_4}C_4 \\ & = \frac{w}{u} C_o - Q/u \end{aligned} \quad (64)$$

Equations (61) through (64) are four linear simultaneous equations for the four unknown C_i ($i = 1,2,3,4$) which complete the solution for the temperature distribution.

4.4 NUMERICAL CALCULATIONS

4.4.1 Gas Constants

Properties of SF_6 gas at 446kPa (50 psig) and 80°C (176°F) used in the calculations are:

$$C_p = 0.7482 \text{ J/g}^\circ\text{K} = 0.1787 \text{ Btu/lb}^\circ\text{R}$$

$$K_g = 0.000162 \text{ w/cm}^\circ\text{K} = 0.00936 \text{ Btu/hrft}^\circ\text{R}$$

$$\mu = 1.869 \times 10^{-5} \text{ Pa}\cdot\text{s} = 1.256 \times 10^{-5} \text{ lb/ft-sec}$$

$$\rho = 0.02335 \text{ g/cm}^3 = 1.458 \text{ lb/ft}^3$$

$$\beta = 0.00283 \text{ }^\circ\text{K}^{-1} = 0.001572 \text{ }^\circ\text{R}^{-1}$$

$$\text{Pr} = 0.8633$$

$$v = 0.008004 \text{ cm}^2/\text{s} = 0.8615 \times 10^{-5} \text{ ft}^2/\text{sec}$$

$$a = 37390 \text{ (cm}^3\text{ }^\circ\text{K)}^{-1} = 5.882 \times 10^8 \text{ (ft}^3\text{ }^\circ\text{R)}^{-1}$$

The geometry of the bushing is specified by the following list of values used in the calculations.

$$b = 2.54 \text{ cm} = 1 \text{ in.}$$

$$D_o = 31.75 \text{ cm} = 12.5 \text{ in.}$$

$$D_l = 69.85 \text{ cm} = 27.5 \text{ in.}$$

$$\bar{D}_g = 50.8 \text{ cm} = 20 \text{ in.}$$

$$D_p = 25.4 \text{ cm} = 10 \text{ in.}$$

$$d_o = 48.90 \text{ cm} = 19.25 \text{ in.}$$

$$d_i = 27.94 \text{ cm} = 11.0 \text{ in.}$$

$$d_2 = 53.34 \text{ cm} = 21.0 \text{ in.}$$

$$d_3 = 73.66 \text{ cm} = 29 \text{ in.}$$

$$L = 863.6 \text{ cm} = 340 \text{ in.}$$

$$L_s = 26.67 \text{ cm} = 10.5 \text{ in.}$$

$$P_s = 8.89 \text{ cm} = 3.5 \text{ in.}$$

Air properties used in evaluating the external heat transfer coefficient are:

$$K_a = 2.73 \times 10^{-4} \text{ w/cm-}^\circ\text{K} = 0.0158 \text{ Btu/hr-ft-}^\circ\text{R}$$

$$a_a = 75.6 \text{ 1/cm}^3\text{-}^\circ\text{K} = 1.19 \times 10^6 \text{ 1/ft}^3\text{-}^\circ\text{R}$$

Thermal conductivities for insulation, porcelain and conductor are:

$$K_i = 9.23 \times 10^{-4} \text{ w/cm-}^\circ\text{K} = .0533 \text{ Btu/hr-ft-}^\circ\text{R}$$

$$K_p = 0.0142 \text{ w/cm-}^\circ\text{K} = 0.821 \text{ Btu/hr-ft-}^\circ\text{R}$$

$$K_w = 2.087 \text{ w/cm-}^\circ\text{K} = 120.5 \text{ Btu/hr-ft-}^\circ\text{R}$$

The bushing thermal losses evaluated at 100°C is $Q = 1292 \text{ W}$.

Rather than presenting all the details of an example calculation, selected results will be presented which should permit verification of the method and application to other geometries.

For an assumed mass flow rate of $\dot{M} = 136.08 \text{ g/sec} = .31\text{lb/sec}$, one obtains

$$u_o = 23 \text{ cm/sec}$$

$$u_p = 11.5 \text{ cm/sec}$$

$$\Delta p_t = 34.71 \text{ dynes/cm}^2$$

$$\Delta \bar{T} = 0.620^\circ\text{C}$$

This means that a mean temperature difference of 0.62°C between gas in the pipe and gas in the gap is sufficient to provide bouyancy pressure difference to circulate 136.08 g/sec.

4.4.2 Heat Transfer Coefficients

Since nearly all (90%) of the heat is transferred to the circulating gas, H_{pn} was evaluated assuming all heat is transferred to the gas from the conductor. The result is:

$$H_{pn} = 1.59 \times 10^{-3} \text{ w/cm}^2\text{-}^\circ\text{K}$$

Since $H_{pf} = 6.18 \times 10^{-4}$, the value of H_p was chosen as the value of H_{pn} .

For $T_g = 50^\circ\text{C} = 323^\circ\text{K}$ and $\epsilon = 0.8$, $H_{rg} = 6.114 \times 10^{-4} \text{ w/cm}^2\text{-}^\circ\text{K}$ and $H_r = 6.95 \times 10^{-4} \text{ w/cm}^2\text{-}^\circ\text{K}$ at $T_a = 40^\circ\text{C} = 313^\circ\text{K}$.

The outside convection coefficient to air was evaluated assuming 55% of the heat transferred by convection giving

$$H_c = 2.96 \times 10^{-4} \text{ w/cm}^2\text{-}^\circ\text{K}.$$

The gap heat transfer coefficient for turbulent flow ($\bar{Re}_g = 9124$) was $H_g = 1.019 \times 10^{-3} \text{ w/cm}^2\text{-}^\circ\text{K}$ and for free convection $H_g = 1.208 \times 10^{-3} \text{ w/cm}^2\text{-}^\circ\text{K}$. To be slightly conservative, the turbulent value was used.

The resistance values for the unsimplified network are:

$$\begin{aligned}R_H &= 9.127 \times 10^{-3} \text{ }^{\circ}\text{C/w} \\R_I &= 111.8 \times 10^{-3} \text{ }^{\circ}\text{C/w} \\R_P &= 4.189 \times 10^{-3} \text{ }^{\circ}\text{C/w} \\R_M &= 3.161 \times 10^{-3} \text{ }^{\circ}\text{C/w} \\R_A = R_B &= 7.122 \times 10^{-3} \text{ }^{\circ}\text{C/w} \\R_C &= 11.87 \times 10^{-3} \text{ }^{\circ}\text{C/w}\end{aligned}$$

The parameters in the energy balance equations are:

$$\begin{aligned}m &= \dot{M}c_p = 101.8 \text{ w/}^{\circ}\text{C} \\h &= 109.6 \text{ w/}^{\circ}\text{C} \\k &= 0.257 \text{ w/}^{\circ}\text{C} \\u &= 7.246 \text{ w/}^{\circ}\text{C} \\v &= 78.74 \text{ w/}^{\circ}\text{C} \\w &= 1.328 \text{ w/}^{\circ}\text{C}\end{aligned}$$

which give

$$\begin{aligned}a_0 &= 94.50 \text{ w/}^{\circ}\text{C} \\a_1 &= 1175.3 \text{ w/}^{\circ}\text{C} \\a_2 &= -1545.1 \text{ w/}^{\circ}\text{C} \\a_3 &= .7779 \text{ w/}^{\circ}\text{C} \\a_4 &= 3.354 \text{ w/}^{\circ}\text{C} \\a_5 &= 15330 \text{ w}\end{aligned}$$

The values of λ_i , b_i , d_i and C_i are given in Table 4-1.

These values were used to calculate the temperature distribution.

TABLE 4-1

<u>i</u>	<u>λ_i</u>	<u>b_i</u>	<u>d_i</u>	<u>C_i [°C]</u>
1	-21.947	-19.385	-.10459	-.02648
2	-.07333	.93188	.07223	-151.88
3	.83550	1.7760	13.7955	.59632
4	20.953	20.462	-.03106	-2.167×10^{-11}
5	0.0	1.0	1.18327	162.22

The mean temperature rise of the gas in the conductor was 16.70°C and the mean rise of the gas in the gap was 15.94°C for a $\Delta\bar{T}$ of 0.76°C .

Only 0.62°C is required to circulate the assumed flow. Thus, results are slightly conservative. Since rises are well below the allowable limit, a further iteration did not appear justified.

4.5 DISCUSSION OF CALCULATED RESULTS

The temperature distributions in the conductor and in the gas streams are given in Table 4-2. Temperatures are rise above ambient. The maximum conductor rise, 32.6°C, occurs at the top of the bushing and is well below the allowable rise of 60°C. The radial gap between insulation and porcelain was chosen to be 2.54cm (1 inch) to insure adequate circulation. It appears that this could be reduced somewhat if necessary but probably not below 2cm (.79 inch). The slots at each end of the bushing which allow SF₆ gas to circulate were assumed to have negligible pressure drop. This condition should be met if slot area is at least 390 cm² (60 in²). The analysis included a total entrance and exit loss of three dynamic heads based on the minimum cross section flow area of approximately 253 cm² (39 in²). Although slots will increase local heating, additional area is available for cooling on the outside of the conductor in the slot region. Thus, local conductor rise should not exceed values calculated.

TABLE 4-2

Calculated Temperature Rise Distribution
of Conductor and Gas Streams

<u>X/L</u>	<u>T_w [°C]</u>	<u>T [°C]</u>	<u>T_g [°C]</u>
0	22.26	10.91	10.91
.1	22.93	12.10	11.70
.2	24.00	13.26	12.56
.3	25.13	14.41	13.48
.4	26.26	15.56	14.48
.5	27.39	16.71	15.56
.6	28.53	17.86	16.73
.7	29.67	19.01	17.99
.8	30.81	20.16	19.35
.9	31.90	21.30	20.83
1.0	32.58	22.42	22.42

Notes: See Figure 4-2 for reference.

L = length of bushing

X = distance from bottom of bushing

T_w = local conductor tube, temperature at height x

T = local gas temperature inside the conductor at height x

T_g = local gas temperature in the gap between the film condenser
and the porcelain.

5.0 TASK 4 MECHANICAL STUDIES

5.1 Shatter - Resistant Weathercase

5.1.1 Test Results - The remaining three insulator models were tested with very good results.

The total test matrix is:

<u>Number</u>	<u>Epoxy Type</u>	<u>Reinforcing Mesh. Type</u>	<u>Tested In Quarter No.</u>	<u>General Results</u>
1	53841TK	NONE	5	Exploded Dangerously
2	53841TK	301CRX	5	Cracked; some fragments ejected
3	53841TK	525CR70	6	Cracked; no fragments
4	53841MC	NONE	6	Exploded dangerously
5	53841MC	301CRX	5	Cracked; no fragments
6	53841MC	525CRX	6	Cracked; no fragments

The model #3 insulator cracked full length and the SF₆ gas escaped safely with no significant fragmentation. Model #6 results were similar but the cracking did not propagate the full length of the insulator because the 53841MC epoxy is less brittle than the 53841TK epoxy. The insulator developed three cracks at the stud gun impact location which propagated about one-third of the insulator length and stopped.

The unreinforced epoxy of Model #4 exploded as expected and the fragment mass and throw distance distribution was measured as in previous tests. Table 5.1 shows the data collected. Data evaluation and use of the /JMBUSH/ Program (see previous reports) give the following results for this test:

ACTUAL-

Total insulator mass - 116 kg (256 lbs.)
Total measured mass - 60.9 kg (134 lbs.)
Maximum Throw distance - 18.3 m (60 ft.)
Maximum projectile mass - 25 kg (55 lbs.)
Average throw distance - 10.7 m (35 ft.)
Average projectile mass - 3.8 kg (8.4 lbs.)
Average projectile size (cube) - 9.9 cm (3.9 inch)

PREDICTED-

Average throw distance - 16.5 m (54 ft.)
Maximum throw distance - 18.1 m (59.3 ft.)

TABLE 5-1

Reinforced Epoxy Model #4

Epoxy Insulator 53841 mc with no Reinforcement.
A semicircular area used for fragment data.

Distance (Meters)	Size (cm x cm)	Weight (kg)	
0.9	38 x 25	6.5	60.9 kg total picked up; 52% of the original bushing mass.
1.8 + 3.6	0	0	
4.6	24 x 5	0.9	
6.4	29 x 11	2.3	
6.4	36 x 11	3.0	
8.2	33 x 7	1.4	
9.1	41 x 8	2.0	
9.1	53 x 20	7.5	
11.0	22 x 11	1.6	
11.9	28 x 5	1.1	
12.8	30 x 15	3.2	
12.8	20 x 10	1.1	
12.8	36 x 6	1.1	
13.7	20 x 9	1.0	
13.7	94 x 51	25.0	
13.7	23 x 13	1.1	
18.3	33 x 13	2.0	

Model #4

1) PORCELAIN OR 2) EPOXY (PRINT NO.)? 2
 AMBIENT TEMPERATURE T1 (F DEG)=55
 LINER THICKNESS T & HOLE AREA A (INCH)=.5,1
 LINER OD TOP & BOTTOM (INCH)= 5,15.5
 INSULATOR INNER DIA, TOP & BOTTOM (INCH)=6.06,16.5
 INSULATOR AVERAGE THICKNESS (INCH)=1.95
 INSULATION & LINER PRESSURES (PSIG)=65,65
 INSULATOR LENGTH (INCH)=51.38
 GAS VOLUME IN ATTACHED BUS (CU IN)=0
 PROJECTILE SIZE (INCH)=3.9
 HEIGHT ABOVE GROUND, LOWER AND UPPER (INCH)=14,65,38

INIT HT (INCH)	WITH LINER *****		WITHOUT LINER *****	
	INIT VEL (FT/SEC)	SCATTER (FT)	INIT VEL (FT/SEC)	SCATTER (FT)
14.00	133.62	35.15	160.50	42.02
26.85	131.49	47.49	149.30	53.69
39.69	126.14	55.11	137.20	59.75
52.54	117.71	59.01	123.94	62.00
65.38	106.12	59.33	109.12	60.94
TIME AFTER FAILURE= 1.00 SECONDS				

14.00	133.62	35.15	160.50	42.02
26.85	131.49	47.49	149.30	53.69
39.69	126.14	55.11	137.20	59.75
52.54	117.71	59.01	123.94	62.00
65.38	106.12	59.33	109.12	60.94
TIME AFTER FAILURE= 2.00 SECONDS				

TIME CONSTANT OF ORIFICE= 2.57 SECONDS
 ENERGY REDUCTION RATIO= 0.538
 AVERAGE THROW WITHOUT LINER (FT)= 54.0
 AVERAGE THROW WITH LINER (FT)= 49.0

Table 5-2

The unreinforced epoxy unsulators models number one and four broke into fewer, larger fragments than the porcelains that were exploded in the reinforcing liner tests done previously. Model #4 results and the computer prediction was very similar to those reported for Model #1 in the 5th Technical Progress Report. The maximum throw prediction is very good (within 1%) but the predicted average throw is 54% greater than the actual measured; this due to fewer, larger fragments and greater gas dissipation into the atmosphere.

The completed test matrix shows that a 53841MC epoxy formulation with either mesh 301CRX or 525CRX will provide a suitable insulator which will not fail catastrophically. The finer mesh, 525CRX, is preferred for insulators up to approximately 60 cm diameter and the stronger mesh, 301CRX, should be used for larger diameter insulators as per previously reported calculations. This assumes a 1.3 safety factor for the needed mesh strength to hold the fractured insulator together.

5.1.2 Epoxy Formulation Characteristics

Table 5-2 in the Third Technical Progress Report, September 1979, listed some of the properties for the three epoxy formulations originally considered in this project. Since the data was incomplete, particularly at normal operating temperature extremes, tests were initiated to determine the unknown data. Properties were obtained for Westinghouse material number 53841TK, a very rigid formulation, 53841MC, a medium rigid formulation, and 53841VC, a relatively flexible formulation. All three compositions are aluminum trihydrate filled cycloaliphatic resin materials. The results are tabulated in Table 5-3; tensile creep tests are continuing and will be reported when completed.

Table 5-3

TESTS	TEMPERATURE °C	CAST EPOXY MATERIALS		
		53841MC	53841TK	53841VC
Tensile Strength (PSI)	-40	4200	5500	5000
	25	3750	6000	3340
	100	2800	2800	470
Tensile Modulus (PSI)	-40	1.55×10^6	1.42×10^6	1.56×10^6
	25	1.09×10^6	1×10^6	0.44×10^6
	100	0.54×10^6	1×10^6	0.09×10^5
Flexural Strength (PSI)	-40	10250	9950	10850
	25	7000	9300	6125
	100	4050	6900	950
Flexural Modulus (PSI)	-40	1.30×10^6	1.31×10^6	1.23×10^6
	25	0.92×10^6	1×10^6	0.37×10^6
	100	0.24×10^6	0.8×10^6	0.10×10^5
Compressive Strength (PSI)	25	15000	17690	10590
Izod Impact Ft.Lbs./Inch Width	25	0.28	0.28	0.35
Dielectric Constant 60 Hz.	25	4.1	4.1	5.0
	100	5.2	5.5	6.7
Power Factor Percent (%)	25 - 1 kV	1.36	0.87	2.80
	2.5 kV	1.38	0.96	2.92
	3.5 kV	1.56	1.66	3.76
	100 - 1 kV	5.92	6.38	8.20
	2.5 kV	6.38	6.67	8.75
	3.5 kV	6.75	6.93	9.29
Specific Gravity		1.72	1.70	1.68

5.1.3 - Work To Be Undertaken In The Next Period

Two insulators made from epoxy 53841MC will be pressurized to failure, one with mesh 525CRX and one with no reinforcement. This test will verify that the mesh does not significantly affect the overall tensile strength of the insulator. Previous tests and calculations have shown that the mesh does not improve the insulator strength before fracture and should not degrade the strength significantly either. This test will verify this needed characteristic.

Six epoxy slabs, 3.8 cm x 10.1 cm x 30.5 cm, will be cast of 53841MC, three with mesh 301CRX and three with mesh 525CRX. Two slabs with each mesh type will be thermal cycled and all six will then be broken to determine if the mesh adhesion to the epoxy is effected. Assuming the above test results are good, the use of the fiberglass mesh in epoxy insulators will be verified as practical and desirable.

5.2 Clamping and Fastening

5.2.1 Joint Design

Work was begun to design epoxy overlap joints and to calculate the joint stresses so as to attempt an optimization. A single piece 1200 kV epoxy insulator is virtually impossible to cast and a joining technique for several pieces is needed. The most promising and least expensive method is to glue the sections together with a properly shaped overlap joint. A possible joint, using a fiberglass mesh is shown in figure 5-1. This provides a simple joint with an overlap of the fiberglass mesh to reinforce the insulator in case of fracture.

Equations were developed to predict maximum possible stress in this joint. The terms are defined as follows:

P = Internal Gage Pressure

FIGURE 5-1 - JOINT CONFIGURATION

Direct Stress in the Main Body (without sheds) -

$$\text{Longitudinal} = PR/2t$$

$$\text{Circumferential} = PR/t$$

Stress in Overlap Joint (not including end flats) -

$$\text{Tension Stress} = \frac{PR^2 \sin \phi \cos \phi}{(2R+2d+L \tan \phi) L}$$

$$\text{Shear Stress} = \frac{PR^2 \cos \phi}{(2R+2d) L}$$

The stresses in a typical joint are not high; for example:

$$P = 345 \text{ kPa} \quad (50 \text{ psig})$$

$$R = 45.7 \text{ cm} \quad (18 \text{ inch})$$

$$d = 1.3 \text{ cm} \quad (0.5 \text{ inch})$$

$$L = 5 \text{ cm} \quad (2 \text{ inch})$$

$$\text{Then Tension Stress} = \frac{55,890 \sin \phi \cos \phi}{(37 + 2 \tan \phi)}$$

$$\text{Shear Stress} = 1511 \cos \phi$$

By selecting values of ϕ we get the results shown in Table 5-4. The joint stresses are quite low. For reference, the normal tube tension stress is given also. These initial results indicate that a suitable glued joint is very possible.

5.2.2 Work To Be Done In The Next Period

The joining of epoxy tubes and possible insulator shapes will be investigated further to develop a complete insulator system in epoxy.

More detailed calculations of the overall clamping and fastening requirements will be made based on thermal, static pressure, and dynamic influences on the various components.

Example Overlap Joint Stresses

ϕ (degrees)	Tension kP	Stress (PSI)	Shear kP	Stress (PSI)
0	0	0	1,510	(219.0)
5	130	(18.9)	1,503	(218.0)
10	255	(37.0)	1,487	(215.7)
15	372	(53.9)	1,458	(211.5)
20	476	(89.0)	1,419	(205.8)
25	564	(81.8)	1,389	(198.5)
30	634	(91.9)	1,308	(189.7)

Tension Stress in straight tube without a joint is 1,551 kP (225 PSI) for a $t = 5\text{cm}$ (2 inch) insulator wall.

Table 5-4

6.0 TASK 5 - MODEL STUDIES

6.1 Electrostatic Models

An intermediate scale model of a gas bushing with a semiconductive coating on the inside of the weathercase was designed as described in section 3.2 of this report. Two models are expected to be built and tested during the next period. Tests are also continuing on the small models described in the fourth and fifth Technical Progress Reports.

6.2 Mechanical Models

Pressure tests of hollow insulators with and without fiberglass fabric reinforcing and thermocycling of reinforced slabs are being planned for the next period as described in Section 5.1.3.

No other model studies are presently underway.

7.0 TASK 9 REPORTING

Under this task the following reports were prepared and submitted to DOE during the reporting period:

<u>Quantity</u>	<u>Report Title</u>
1	Summary of Government Property
3	Project Status Reports
3	Contract Management Summary Reports.
3	Cost Management Reports
1	Conference Record

7.1 Program Status

The progress of each individual subtask is shown in the program schedule Figure 7-1. This same schedule is incorporated in each quarterly report as a means of showing clearly the technical progress on the project.

7.2 Manpower Status

With regard to the manpower utilization in the project, the following key personnel have been committed to carrying out this project in an efficient and timely manner.

<u>Key Personnel</u>	<u>Hours Worked During Reporting Period (Sixth Quarter)</u>
J. S. Billings	284 Hours
Z. Neri	84 Hours
C. F. Hofmann	38 Hours
R. W. Crookston	0 Hours

Total manhours worked during the reporting period (including Key Personnel).

TASK 1 - 105 Manhours

TASK 2 - 306 Manhours

TASK 3 - 2 Manhours

TASK 4 - 88 Manhours

TASK 5 - 323 Manhours

TASK 6 - 32 Manhours

TASK 9 - 216 Manhours

Figure 7-1 Project Schedule (Revised 9/10/80)

8.0 SUMMARY

Computer analyses of the electrostatic shield effectiveness model were made and resistor grading studies are continuing. Thermal analysis of the SF₆ impregnated film condenser shows the condenser bushing may be self-cooled. The shatter-resistant weathercase model tests were successfully completed and analyzed.

Small and intermediate scale resistive grading tests are expected to be completed during the next period. Mechanical tests on the shatter resistant epoxy weathercase materials are also expected to be completed. Each of the concepts will be evaluated to determine the best combination for the full scale 1200 kV termination. A decision is expected in the next period on which concepts will be employed in the full scale prototype. Final design will then commence.