MASTER

EVALUATION, DESIGN, DEVELOPMENT

AND DELIVERY OF A 1200 KV

PROTOTYPE TERMINATION

Second Technical Progress Report

Covering the Period From

March 1, 1979 to April 30, 1979

May 1979

Westinghouse Electric Corporation
Power Circuit Breaker Division
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Evaluation, Design, Development and Delivery
of a 1200 kV Prototype Termination

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Second Technical Progress Report

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1.0 ABSTRACT

The conceptual design and material study, TASK 1, of a 1200kV Termination is complete. Detailed analytic and model studies have commenced. Optimal materials, configuratious, and fabrication plans are expected to be determined upon completion of these studies.

2.0 INTRODUCTION

This is the Second 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, design, production and testing of a full scale prototype and finally delivery of a prototype termination to an appropriate field site.

3.0 TASK 1 - CONCEPTUAL DESIGN AND MATERIAL STUDY

3.1 SF₆ - Film Condenser Concept

As reported in the First Technical Progress Report, the SF₆-Film condenser concept was studied as a possible configuration for improving the dimensional efficiency of a 1200 kV termination. The standard equal capacitance technique for sizing and locating the condenser foils was explored during the first period. Other techniques were investigated in the current period.

The following assumptions were used as guidelines for each different variation:

1. Maximum radial stress (perpendicular to film) = 100 kV/cm
2. Maximum longitudinal stress (average) = 8 kV/cm
3. Inner conductor diameter = 28 cm
4. Maximum stress ratings apply for 1200 kV rms 1 minute test
5. Foil termination can be achieved without dimension change
6. Minimum capacitive layer thickness = .23 cm
7. 30 capacitive layers are adequate to achieve uniform longitudinal voltage gradient
8. CGIT Conical insulator can provide adequate support for bottom end of bushing (if necessary)
9. Dielectric constant for SF₆ - impregnated film = 2.2
10. The design calculations may ignore the effects of all external capacitance of the condenser structure to the outer bus wall.

3.1.1 Standard equal capacitance technique

This method, as previously reported, employs equal capacitance in each condenser layer and constant axial steps between the foil ends. The voltage on each layer is equal and the axial voltage gradient outside the condenser, on either end, is quite uniform. The radial voltage stresses were shown to vary by a ratio of two or three to one from maximum to minimum. Also, the ground sleeve, and consequently, overall length must be made quite large in order to reasonably reduce overall diameter.

3.1.2 Equal field intensity techniques

The electric field intensity E_n on the n th layer of a concentric cylindrical capacitor may be given by the expression

$$E_n = \frac{Q}{2 \pi \epsilon R_n L_n} \quad \text{Eq 3-1}$$

Where: Q is the total charge on the layer

R_n is the mean radius of the section

L_n is the effective length of the section

and ϵ is the dielectric constant of the material between the electrodes (in this case, their foils)

A bushing condenser is made up of concentric capacitive layers in series, so the total current, in each layer, and likewise the total charge on each electrode are equal. Since the dielectric constant ϵ should be constant for all layers, also, then E_n will remain constant if the product $R_n L_n$ is kept

constant. This method, however, does not provide uniform axial voltage grading. The axial stress is highest near the bushing flange, the principal location at which we are trying to decrease the voltage gradient using a condenser.

In order to limit the axial voltage stress on the bottom end of the condenser to 8 kV/cm, it's length cannot be less than $1200 \text{ kV} \div 8 \text{ kV/cm} = 150 \text{ cm}$. The top end of the condenser must be at least 510 cm. The conductor diameter is 28 cm. The minimum dimensions of the condenser can now be computed.

$$R_n L_n = \text{constant} = R_o L_o = R_i L_i ,$$

where $L_i = 510 + L_o + 150 = L_o + 660 \text{ cm}$, so $R_o L_o = 14 (L_o + 660)$

$$\text{or } L_o = \frac{9240}{R_o - 14} \quad \text{Eq. 3-2}$$

With a constant axial gradient of 100 kV/cm, the minimum R_o is $14 + 1200 \text{ kV} \div 100 \text{ kV/cm} = 26 \text{ cm}$.

For this case, then $L_o = 770$ cm (~ 25 ft.) and overall length $L_i = 1430$ cm (~ 47 ft.). This is unacceptably long. In order to minimize the length, as can be seen in Eq. 3-2, R_o must be increased.

If R_o is assumed to be just smaller than the radius of 1200 kV bus then it may be set at ~ 35 cm (13.8 in.). For this case, then $L_o = 440$ cm (14.4 ft.) and the overall length $L_i = 1100$ (36 ft.). This is an improvement but as shown in Figure 3-1, the axial stress is too high at the bottom end of the weathercase end of the condenser for this case. Thus the $R_n L_n = \text{constant}$ concept is useful only for optimizing radial but not axial stress.

3.1.3 Equal radial and axial steps technique

Just for comparison purposes the dielectric stresses in a condenser with equal radial and axial steps between each foil layer were calculated. As shown in Figure 3-2, a condenser with fairly uniform radial voltage gradient can be designed using this technique. Here again, as shown in Figure 3-3, the axial voltage gradient varies significantly. Figure 3-4 shows the improvement in this design which can be made by increasing the overall length of the condenser. The radial voltage stress for this particular case is the same as that for the 200 cm gnd in Figure 3-2.

AVERAGE AXIAL VOLTAGE GRADIENT OUTSIDE TOP END
OF SF_6 - FILM CONDENSER WITH $R_n L_n = \text{CONST.}$ FOIL
LOCATIONS FOR TWO CASES.

Figure 3-1

AVERAGE RADIAL VOLTAGE GRADIENTS INSIDE SF_6 - FILM
 CONDENSER WITH EQUAL RADIAL STEPS AND EQUAL
 FOIL LENGTH STEPS AS LENGTH OF
 OUTSIDE (GROUND) FOIL LENGTH IS VARIED

Figure 3-2

AVERAGE AXIAL VOLTAGE GRADIENT OUTSIDE TOP END OF
 SF₆ - FILM CONDENSER WITH EQUAL RADIAL STEPS AND
 EQUAL FOIL LENGTH STEPS AS LENGTH OF OUTSIDE
 (GROUND) FOIL IS VARIED

Figure 3-3

AVERAGE AXIAL VOLTAGE GRADIENT OUTSIDE
TOP END OF SF_6 -FILM CONDENSER WITH EQUAL
RADIAL STEPS AND EQUAL FOIL LENGTH STEPS.

$R_0 = 36.6$ cm, $L_0 = 240$ cm, $R_1 = 14$ cm, $L_1 = 900$ cm

Figure 3-4

3.1.4 Constant radial voltage gradient techniques

Although the $R_n L_n = \text{constant}$ foil dimensioning method gave rather uniform radial gradients, a more accurate technique is available. This method is more useful because it sets the capacitance, and, therefore the voltage also, equal for each capacitive layer. Since the average voltage gradient on the nth layer is $V_n / \Delta r_n$,

$$\text{and } V_n \sim T / C_n$$

$$\text{and } C_n \sim \frac{L_n}{\ln \left(\frac{V_n}{r_{n-1}} \right)}$$

Where V_n is the voltage on the nth layer,

r_n = is the radius of the nth layer

T is the total series capacitance of the condenser

C_n is the capacitance of the nth layer

and L_n is the length of the nth layer

$$\text{Then } \frac{V_n}{\Delta r_n} \sim \frac{T \ln \left(\frac{r_n}{r_{n-1}} \right)}{L_n \Delta r_n} \quad \text{Eq. 3-3}$$

If the radial steps are equal, then by setting the radius of the conductor and the length of the conductor, or the outer (ground) foil, all the other dimensions may be calculated. The ratio for the length L_o of the outer layer to the overall length L_i of the condenser is

$$\frac{L_o}{L_i} = \frac{\ln \left(\frac{r_o}{r_o \Delta r} \right)}{\ln \left(\frac{r_i}{r_i \Delta r} \right)} \quad \text{Eq. 3-4}$$

Where r_o is the radius of the outer foil and
 r_i is the radius of the conductor

As r_o gets larger, the ratio of $\frac{r_o}{r_o - \Delta r}$ gets smaller. So in order to have a reasonably small L_o/L_i ratio, the outer foil diameter should be large.

For $r_i = 14$, $r_o = 35$, and $L_i = L_o + 660$ cm then the ground foil length $L_o = 434$ cm = 14 ft. and the overall condenser length $L_i = 1094$ cm = 36 ft. Again, this is too long.

3.1.5 Modified designs

Two variations present themselves as alternative condenser designs utilizing the foil dimensioning techniques presented above, but allowing for better utilization of space.

The first method employs the "split-foil" concept used on many Westinghouse EHV bushings. Usually one of the equal capacitance techniques described above is chosen to grade the voltage radially. Then the foils are split in the middle and moved to the most desirable locations at the ends of the condenser. This allows very uniform axial voltage gradients to be maintained while using favorable L_o/L_i ratios. The disadvantages of this design are that high localized stresses often occur on the "split" or inner ends of the foils, and it is very difficult to calculate the actual distribution of voltage on the foils.

The second alternative, which is uniquely suited to a gas bus termination would have a concave rather than convex lower end. The main limitation to

this concept is that the outer diameter of the condenser must be at least as large as the diameter of the gas bus enclosure so that the radial voltage stress on the gas at the interface with the condenser is not greater than the usual maximum voltage gradient in the bus.

3.1.6 Recommended Action on SF₆ - Film Condenser Study

The four configurations described above are summarized in Figure 3-5.

The most promising configuration appears to be the last, although no procedure has been devised for its manufacture. As is shown in the next section, the SF₆ - film concept did not rate well in comparison with other voltage grading schemes, so the study has been discontinued.

FIGURE 3-5

Summary of Condenser Configurations

Configuration	Description & Comments
<p>Outer Foil </p>	<p>Full length foils, equal capacitances, equal end steps, varying radial stress, constant axial end stress, can be smaller than bus on OD.</p>
<p>Outer Foil </p>	<p>Full length foils, constant radial stress, varying end steps, varying axial end stress, must be very long. Can be smaller than bus on OD.</p>
<p>Outer Foil </p>	<p>Split foils, constant radial stress, constant axial end stress. Can be smaller than bus OD. High stress on foil ends inside condenser.</p>
<p>Outer Foil </p>	<p>Full foils, constant radial stress, constant axial end stress on top end. Must be larger than bus on OD. May be difficult to build?</p>

3.2 Concepts, Materials and Fabrication Techniques Analysis

As described in the First Technical Progress Report, 29 characteristics of 35 concepts related to the termination design were compared. Since some inconsistencies were apparent in the First Report, some of the input data was modified. It is very difficult, when comparing the individual merits of a concept, to ignore all preconcieved notions relating to the proposed concept. When the data in Table 3 was processed, the results were as shown in Table 4. In Table 5, the highest rated concepts have been rearranged according to rating and functional category.

Table 1

CONCEPT

1-Piece flanged porcelain
Multi-piece flanged porcelain
Unflanged porcelain
Rigid epoxy weathercase
Flexible epoxy weathercase
Reinforced epoxy weathercase
Polysil weathercase
Metal banded weathercase
Present shed configuration
Nonlinear resistive coatings
Conducting fibers
Flanges
Tie rods
Springs
Fiberglass liner
Fiberglass cone
Conical insulator
Frustum (lower end)
Oil-paper condenser
Film-SF₆ condenser
Epoxy condenser
Floating shields in plug
Floating internal shields
Dielectric shields
Throat shields
Large conductor
Small conductor
Heat pipe
Bottom external toroids
Intermediate external toroids
Top external toroids
Top sphere
Segmented sphere
Horizontal cylinder
Vertical cylinder

Table 2

RELATIVE WEIGHINGS OF EACH CHARACTERISTIC

<u>Characteristic</u>	<u>Weight</u>
1. Cost/Piece	11
2. New Facilities	3
3. Weight	4
4. Interface	10
5. Difficulty of Manufacture or Ass'y.	8
6. Lead Time	2
7. Storage	1
8. Int. Diel. Str. at Throat	27
9. Int. Diel. Str. Elsewhere	23
10. Ext. Diel. Str. Bottom End	28
11. Ext. Diel. Str. Intermediate	20
12. Ext. Diel. Str. Top End	29
13. R I Limit	13
14. I^2R Heating	14
15. Dielectric Loss Heating (Int. only)	12
16. Flange Heating	9
17. Other Heating (Weathercases)	17
18. Heat Transport	22
19. Material Temperature Limit	24
20. Clamping Forces	26
21. Shipping Forces	6
22. Steady State Gas Pressure	18
23. Short Circuit Forces	5
24. Earthquake Forces	15
25. Wind Load	21
26. Catastrophic Failure - Probability	25
27. Gas Energy Available	19
28. Projectile Size/Danger	16
29. Life (Established)	7

TABLE 3

RUN #2	INPUT																												
	CHARACTERISTIC #																												
CONCEPT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
ONE-PC FL. PORC	-3	1	0	0	3	-2	1	0	0	0	0	0	0	0	0	-1	3	2	4	0	0	0	0	0	0	0	0	0	4
MULTI-PC FL. PORC	-1	3	-2	0	1	-1	2	0	0	0	-2	0	0	0	0	-1	3	2	4	0	-1	0	-1	-1	0	-1	0	0	4
UNFLANGED PORC	2	4	2	0	1	0	2	0	0	0	0	0	0	0	0	3	3	2	4	2	0	-1	-2	-2	0	0	0	0	3
RIGID EPOXY W.C.	3	-2	2	0	1	3	3	0	0	0	0	0	0	0	0	3	3	2	2	0	1	0	0	0	0	0	0	0	1
FLEX. EPOXY W.C.	3	-2	2	0	1	3	3	0	0	0	0	0	0	0	0	3	3	2	0	0	-1	-2	-2	-2	0	2	0	2	1
REINF. EPOXY W.C.	3	-3	2	0	0	2	3	0	0	0	0	0	0	0	0	3	3	2	1	0	1	1	0	1	0	2	0	2	0
POLYSIL W.C.	0	-3	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	-1	-1	0	-1	0	0	0	0	0
METAL BANDED W.C.	-2	-1	-1	0	1	0	0	0	0	-3	-3	0	-3	0	0	0	0	2	2	0	0	-1	-1	0	-1	0	0	0	0
PRES. SHED CONF.	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	4
NONL. RES. COAT.	-2	-1	0	0	-2	0	-1	0	0	2	2	0	0	0	0	0	3	-2	2	1	0	0	0	0	0	0	0	0	1
COND. FIBERS	-1	-2	0	0	-1	0	-1	0	0	2	2	0	-2	0	0	3	-3	3	2	0	1	1	0	1	0	2	0	2	1
FLANGES	1	4	-1	3	3	1	3	0	0	0	-2	0	-2	0	0	-2	0	4	4	2	0	-1	0	0	0	0	0	0	0
TIE RODS	1	4	2	2	1	0	2	0	0	0	0	0	-2	0	0	2	0	3	3	2	1	0	1	-1	0	0	0	0	0
SPRINGS	2	4	1	1	1	2	3	0	0	0	0	0	0	0	0	4	-1	0	2	-2	2	1	-1	-1	-2	0	0	0	0
FIBERGL. LINER	-3	2	1	2	-1	0	-1	0	0	0	0	0	-1	0	3	3	0	-1	2	2	-1	0	0	0	0	2	0	3	0
FIBERGL. CONE	-1	2	2	2	1	0	1	0	0	0	0	0	-3	0	3	3	0	-1	2	2	0	3	1	1	0	3	3	3	0
CONICAL INS.	2	4	4	3	2	2	2	0	0	0	0	0	-1	0	4	0	0	3	2	1	0	3	1	1	0	3	3	3	0
FRUSTUM	4	3	4	-1	1	3	2	0	0	0	0	0	-1	0	4	0	0	2	2	1	0	3	1	1	0	3	3	3	0
OIL-PAPER COND.	-3	3	-3	-3	2	3	1	2	0	4	4	0	0	0	-2	0	0	-1	-1	0	-2	0	1	-2	0	3	3	3	2
FILM-SF6 COND	-3	-1	-2	-3	0	3	1	2	0	4	4	0	0	0	-2	0	0	-3	-1	0	-1	0	1	-1	0	3	3	3	1
EPOXY COND.	-3	-4	-2	-1	-1	2	2	2	0	4	4	0	0	0	-2	0	0	-2	-1	0	-2	0	1	-2	0	3	3	3	1
FL. SDS. IN PLUG	-1	-1	3	2	-1	2	1	2	0	2	2	0	-2	0	-2	0	0	-2	-1	0	0	0	0	0	0	0	0	0	3
FL. INT. SHIELDS	-1	2	-1	-1	2	3	2	2	0	2	2	0	0	0	0	0	0	-1	-2	0	0	0	0	0	0	0	0	0	4
DIEL. SHIELDS	-1	-2	2	3	2	3	3	1	1	2	2	0	0	0	2	0	0	-1	2	0	0	0	0	0	0	0	0	0	3
THROAT SHIELDS	2	4	4	3	4	3	3	0	0	2	0	0	0	0	4	0	0	2	2	0	0	0	0	0	0	0	0	0	4
LARGE CONDUCTOR	2	4	2	4	4	3	1	3	3	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SMALL CONDUCTOR	3	4	4	3	4	3	1	2	3	3	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HEAT PIPE	-1	-1	2	4	1	2	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	2
BOTTOM EXT. TOR.	-2	2	-2	0	2	3	2	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0
INTM. EXT. TOR.	0	2	2	0	3	3	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0
TOP EXT. TOR	-1	2	-2	0	2	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	-1	0	0	0
TOP SPHERE	-3	2	-2	0	2	2	1	0	0	0	0	0	4	4	0	0	0	0	0	0	0	0	0	0	-2	-2	0	0	0
SEG. SPHERE	-2	2	-3	0	1	3	1	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0
HORIZ. CYL.	-1	3	0	0	3	3	2	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	-2	-1	0	0	0
VERT. CYL.	2	3	2	0	3	3	2	0	0	0	0	0	4	4	0	0	0	0	0	0	-1	0	0	-1	-1	0	0	0	0

INPUT DATA: RELATIVE EVALUATION OF EACH CHARACTERISTIC AS IT APPLIES TO EACH CONCEPT.

TABLE 4

RUN	#2	OUTPUT																												3/21/79	
		CHARACTERISTIC #																													
CONCEPT		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	TOTAL
ONE-PC FL. PORC	-33	3	0	0	24	-4	1	0	0	0	0	0	0	0	0	0	-9	51	44	96	0	0	0	0	0	0	0	0	0	28	201
MULTI-PC FL. PORC	-11	9	-8	0	8	-2	2	0	0	0	0	-40	0	0	0	0	-9	51	44	96	0	-6	0	-5	-15	0	-25	0	0	28	117
UNFLANGED PORC	22	12	8	0	8	0	2	0	0	0	0	0	0	0	0	0	27	51	44	96	52	0	-18	-10	-30	0	0	0	0	21	285
RIGID EPOXY W.C.	33	-6	8	0	8	6	3	0	0	0	0	0	0	0	0	0	27	51	44	48	0	6	0	0	0	0	0	0	0	7	235
FLEX. EPOXY W.C.	33	-6	8	0	8	6	3	0	0	0	0	0	0	0	0	0	27	51	44	0	0	-6	-36	-10	-30	0	50	0	32	7	181
REINE. EPOXY W.C.	33	-9	8	0	0	4	3	0	0	0	0	0	0	0	0	0	27	51	44	24	0	6	18	0	15	0	50	0	32	0	306
POLYSIL W.C.	0	-9	-4	0	0	0	0	0	0	0	0	0	0	0	0	0	-9	34	44	48	0	-6	-18	0	-15	0	0	0	0	0	65
METAL BANDED W.C.	-22	-3	-4	0	8	0	0	0	0	0	-84	-60	0	-39	0	0	0	0	0	0	96	0	0	0	0	0	0	0	48	7	-53
PRES. SHED CONF.	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	66	0	0	0	0	0	0	0	0	0	28	118
NONL. RES. COAT.	-22	-3	0	0	-16	0	-1	0	0	0	56	40	0	0	0	0	27	-34	44	24	0	0	0	0	0	0	0	0	0	7	122
COND. FIBERS	-11	-6	0	0	-8	0	-1	0	0	0	56	40	0	-26	0	0	27	-51	66	48	0	6	18	0	15	0	50	0	32	7	262
FLANGES	11	12	-4	30	24	2	3	0	0	0	0	-40	0	-26	0	0	-18	0	88	96	52	0	-18	0	0	0	0	0	0	0	212
TIE RODS	11	12	8	20	8	0	2	0	0	0	0	0	0	-26	0	0	18	0	66	72	52	6	0	5	-15	0	0	0	0	0	239
SPRINGS	22	12	4	10	8	4	3	0	0	0	0	0	0	0	0	48	-9	0	44	-48	52	6	-18	-5	-30	0	0	0	0	0	103
FIBERGL. LINER	-33	6	4	20	-8	0	-1	0	0	0	0	0	0	-13	0	36	27	0	-22	48	52	-6	0	0	0	0	50	0	48	0	208
FIBERGL. CONE	-11	6	8	20	8	0	1	0	0	0	0	0	0	-39	0	36	27	0	-22	48	52	0	54	5	15	0	75	57	48	0	388
CONICAL INS.	22	12	16	30	16	4	2	0	0	0	0	0	0	-13	0	48	0	0	66	48	26	0	54	5	15	0	75	57	48	0	531
FRUSTUM	44	9	16	-10	8	6	2	0	0	0	0	0	0	-13	0	48	0	0	44	48	26	0	54	5	15	0	75	57	48	0	482
OIL-PAPER COND.	-33	9	-12	-30	16	6	1	54	0	112	80	0	0	0	-24	0	0	-22	-24	0	-12	0	5	-30	0	75	57	48	14	290	
FILM-SF6 COND	-33	-3	-8	-30	0	6	1	54	0	112	80	0	0	0	-24	0	0	-66	-24	0	-6	0	5	-15	0	75	57	48	7	236	
EPOXY COND.	-33	-12	-8	-10	-8	4	2	54	0	112	80	0	0	0	-24	0	0	-44	-24	0	-12	0	5	-30	0	75	57	48	7	239	
FL. SDS. IN PLUG	-11	-3	12	20	-8	4	1	54	0	56	40	0	-26	0	-24	0	0	-44	-24	0	0	0	0	0	0	0	0	0	0	21	68
FL. INT. SHIELDS	-11	6	-4	-10	16	6	2	54	0	56	40	0	0	0	0	0	0	-22	-48	0	0	0	0	0	0	0	0	0	0	28	113
DIEL. SHIELDS	-11	-6	8	30	16	6	3	27	23	56	40	0	0	0	24	0	0	22	48	0	0	0	0	0	0	0	0	0	0	21	307
THROAT SHIELDS	22	12	16	30	32	6	3	0	0	56	0	0	0	0	0	48	0	0	44	48	0	0	0	0	0	0	0	0	0	28	345
LARGE CONDUCTOR	22	12	8	40	32	6	1	81	69	56	0	0	0	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	355
SMALL CONDUCTOR	33	12	16	30	32	6	1	54	69	84	0	0	0	0	-14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	323
HEAT PIPE	-11	-3	8	40	8	4	1	0	0	0	0	0	0	0	0	0	0	0	66	0	0	0	0	0	0	0	0	0	0	14	127
BOTTOM EXT. TOR.	-22	6	-8	0	16	6	2	0	0	0	0	20	0	13	0	0	0	0	0	0	0	0	0	0	0	-21	0	0	0	0	12
INTM. EXT. TOR.	0	6	8	0	24	6	3	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	-15	-21	0	0	0	0	24
TOP EXT. TOR	-11	6	-8	0	16	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-30	-21	0	0	0	0	-41
TOP SPHERE	-33	6	-8	0	16	4	1	0	0	0	0	0	116	52	0	0	0	0	0	0	0	0	0	0	-30	-42	0	0	0	0	82
SEG. SPHERE	-22	6	-12	0	8	6	1	0	0	0	0	0	87	39	0	0	0	0	0	0	0	0	0	0	-15	-21	0	0	0	0	77
HORIZ. CYL.	-11	9	0	0	24	6	2	0	0	0	0	0	87	39	0	0	0	0	0	0	0	0	0	0	-30	-21	0	0	0	0	105
VERT. CYL.	22	9	8	0	24	6	2	0	0	0	0	0	116	52	0	0	0	0	0	0	0	-6	0	0	-15	-21	0	0	0	0	197
SUM		-55	123	84	230	392	120	52	432	161	728	320	406	-13	14	192	180	255	682	840	364	-30	90	5	-270	-168	625	342	480	280	

OUTPUT DATA: RELATIVE VALUE OF EACH CHARACTERISTIC AS IT APPLIES TO EACH CONCEPT AND TOTAL VALUE OF EACH CONCEPT.

TABLE 5

Function	Rating	Concept	Relation Score
Weathercasing	1	Reinforced Epoxy	306
	2	Unflanged Porcelain	285
	3	Rigid Epoxy	235
	4	One-piece Flanged Porcelain	201
Clamping-Fastening Mechanism	1	Fiberglass Cone	388
	2	Tie Rods	239
	3	Flanges	212
	4	Fiberglass Liner	208
Internal Control of Voltage on Weathercasing	1	Throat Shields	345
	2	Small Conductor	323
	3	Dielectric Shields	307
	4	Oil-Paper Condenser	290
External Control of Voltage on Weathercasing	1	Vertical Cylinder Top Shield	197
	2	Horizontal Cylinder Top Shield	105
Conductor Bottom End Support	1	Conical Insulator (CGIT)	531
	2	Frustum	482
Current Path	1	Large Diameter Conductor	355
	2	Heat Pipe	127

Functional Rating of Termination Concepts

The analysis of concept comparison data indicates that the original plans for investigating promising concepts were appropriate in most cases. The relative ratings, at this time, of some of the concepts are, however, enlightening. Despite the uncertainty of the use of epoxy rather than porcelain weathercasings, the epoxy design is claimed to provide considerable cost and design flexibility benefits. But isolating of porcelain weathercase from the large volume of high pressure gas by means of a fiberglass cone or liner still appears to be a viable alternative. The electric field distortions created by the intermediate flanges of a multi-piece flanged porcelain (as used in DOE Project EX-76-C-01-2061) counted heavily against this concept. Polysil has not been proven to exhibit adequate long term physical properties for serious consideration in this project. The metal bands proposed to limit the destructive potential of porcelain would likely create unbearable external corona and dielectric degradation problems.

The various forms of resistive grading rated better than the present unmodified weathercasing configuration with no other voltage grading means, but were not rated anywhere near as well as the capacitive voltage control techniques. Uncertainty as to cost, manufacturing problems, effectiveness and resistive losses contributed to this conclusion. If equal in voltage grading capability, conductive fiber filled weathercases would probably exhibit better mechanical properties than would the non-linear resistor coated weathercases. All of the condenser schemes for voltage gradient control would add considerable cost (mostly labor), weight, and thermal problems to the termination in comparison to the other methods. The oil-paper concept was rated the best of these methods since it is easiest to cool and has

considerable field experience although oil presents an undesirable flammable liquid problem. The throat shield and small conductor in a hollow gas bushing concept was rated the highest for voltage stress grading due primarily to its inherent simplicity. Floating internal shields such as those used on the bus project DOE No. EX-76-C-01-2061 have proved to be expensive and difficult to assemble. The external shielding (top end sphere and toroids around the base of the weathercasing used on that project) is also quite expensive and adds significantly to the weight of the bushing. A cylindrical top end shield (especially a vertical cylinder) is expected to provide considerably improved voltage performance while costing and weighing much less.

Bottom end lateral support for the central conductor and isolation of the termination gas volume from connected gas compartments would most easily be provided by a standard CGIT conical insulator. If the insulator must transmit considerable axial forces from the conductor to the sheath, then a special frustum would likely be required. This later configuration is more difficult to interface with the connected bus, however.

Weathercases, due to their circumferentially ribbed shape, are stronger radially than axially. Brittle materials are stronger in compression rather than tension. Thus spring loaded caps on the ends of weathercases rated higher than flanged configurations for meeting the mechanical requirements. Spring loading, however, requires a tensile member to transfer the top end load to the termination mounting flange. A fiberglass cone inside the weathercase or separate fiberglass tie rods were judged best to serve this purpose. Although the conductor should be capable of carrying the required tensile

load, it is difficult to transfer the load from the bottom end of the conductor back to the sheath. A fiberglass liner just inside the porcelain was rated about the same as flanged weathercases for carrying the axial load.

Due to the great length of the termination and high voltage, a large diameter conductor was rated better than a small diameter conductor with heat-pipe cooling. Heat pipes become ineffective if their vertical length is too great.

3.3 Conclusions from Concepts, Materials and Fabrication Analysis

The concepts rated highest by the formal comparison program are in most cases the same concepts being studied in detail during this project. Thus the choices made for study were apparently well made. The formal comparison quantizes the relative value of studying specific areas also. The model studies and tests will verify the estimates so that when finished the studies and tests can be analyzed and input to the comparison program. A final discernment of the best configuration can then be found, with good data to support that decision.

4.0 TASK 2 - ELECTROSTATIC STUDIES

4.1 Shield Effectiveness Study

To minimize the size of the 1200kV termination and maximize its reliability it is essential that the electrical gradients in air both at the bottom and top of the termination be minimized.

4.1.1 Model Design Considerations

The simplest form of a gas termination is shown on Figure 4-1. In this design, four main areas must be considered from a dielectric withstand capability.

1. The gradient in the SF₆ gas.
2. The gradient in air at the bottom of the weathercasing.
3. The gradient in air at the top of the weathercasing.
4. The height of the throat shield L₂.

For the simple gas termination, Figure 4-1, the distribution along the weathercasing is non-uniform. The regions of highest electrical stress, which are the cause of external flashover, are generally at the bottom of the weathercasing and at the top end shield.

The highest gradient in the gas occurs on the conductor in the grounded cylinder region. The stress on the conductor can be calculated by the equation

$$\text{kV/radial length} = \frac{E}{R_1 \ln R_2/R_1} \quad \text{Eq 4-1}$$

Where: E is the applied voltage in kV
 R₁ the radius of the conductor
 R₂ the radius of the grounded cylinder.

The stress on the conductor must be kept below the breakdown strength of the SF₆ gas at any of the test levels.

FIGURE 4-1 CONVENTIONAL GAS TERMINATION

The minimum stress for a given diameter of outer cylinder occurs when the conductor diameter is equal to the cylinder diameter divided by 2.73. For this configuration the maximum gas gradient becomes $\frac{E}{R_1}$ as $\ln \frac{R_2}{R_1} = \ln 2.73 = 1$. The stress at the outer cylinder is equal to the stress at the conductor multiplied by $\frac{R_1}{R_2}$. The stress at the outer cylinder is not equal to, but is indicative of, the stress experienced in air adjacent to the throat shield. A reduction in stress at the outer cylinder is therefore a reduction in stress in air at the bottom of the bushing.

Figure 4-2 shows the relative stresses at the conductor and at the throat shield for varying R_2/R_1 ratios. It will be noted that if the ratio of R_2/R_1 is increased to values greater than 2.73, the stress on the conductor increases while the stress on the outer cylinder (throat shield) decreases at a greater rate. For example if the ratio of R_2/R_1 is increased from 2.73 to 4.75 the stress on the conductor is increased to 1.1 of its minimum level while the stress on the outer cylinder is decreased to .65 of its value when $R_2/R_1 = 2.73$. This represents a significant reduction in air stresses at the bottom of the weathercasing. This method of reducing the bottom end air stress appears to be extremely useful.

The reduction in air stresses caused by reducing the size of the conductor can be investigated by the use of computer techniques. However, to obtain actual design levels experimental results are required. Fig. 4-3 shows the test device that has been designed to investigate the effect of conductor diameter on air stresses.

NORMALIZED STRESS ON CONCENTRIC
CYLINDER CONFIGURATION

Figure 4-2

Past computer analyses have indicated that the height of throat shield has little effect in reducing the gradients in air, however, experience gained during testing of bushings has shown that proper throat shield sizing can be beneficial. Little data is available, however, on the relative values of varying throat shield heights. The test device has been designed so that the effect of throat shield height can also be investigated.

For terminations rated 500kV and below, very little attention is paid to the voltage gradients in air at the top of the weathercasing since approximately the same strike distance is required for withstanding both the lightning impulse and switching impulse test levels. At the 1200 kV level, however, this is not the case. For rod to plane configurations, less than 4 meters of strike distance is required to withstand the specified 2175 kV lightning impulse test level; on the other hand over 9 meters would be required to withstand the 1800 kV switching impulse test. The gradients in air at the top of the weathercasing must be reduced to well below corona inception so as to minimize the required strike distance. Cylindrical shields appear to offer a distinct advantage in both size and cost and this top test device has been designed to permit the investigation of cylindrical shielding.

4.1.2 Model Drawings

Drawings of the shield effectiveness model have been made and are being reviewed. The design is built around a 242 kV flanged porcelain weather-casing purchased by Westinghouse for another project. It uses a tank from a Westinghouse gas circuit breaker for its bottom end. Figure 4-3 was made from the assembly drawing.

SHIELD EFFECTIVENESS MODEL
FIGURE 4-3

4.2 Resistive Grading Study

Improvement in the axial grading can be achieved by coating the surface of the insulator with an electrically non-linear resistive layer whose electrical conductivity increases with increasing field. The current flow in this layer will alter the field distribution in such a way as to always reduce the maximum field.

4.2.1 Resistive Grading Design Criteria

A resistive coating suitable for use on a 1200 kV termination should have the following characteristics:

1. At the continuous operating voltage of 690 kV rms which results in an average gradient of 1.4 kV per cm, the resistive losses should be as low as possible with an upper limit of .015 watts per cm^2 .
2. At the low frequency one minute withstand level (1200 kV rms) the losses should be low enough so as not to cause thermal run-away or damage to the substrate. It is estimated that the losses should be limited to .15 watts per cm^2 .
3. At the lightning impulse test level (2175 Kv , 1.2/50 μs) the resistance should be low enough to produce satisfactory grading and must be capable of withstanding an average gradient of 4.35 kV/cm.
4. At the switching impulse test level (1800 kV , 250/2500 μs) the resistance should be low enough to produce satisfactory grading and must be capable of withstanding an average gradient of 3.6 kV per cm.

4.2.2 Study Objectives

The objective of this work is to determine whether satisfactory electrical stress grading of the 1200 kV termination can be obtained by the use of resistive (linear or non-linear) coatings, and if so, to define suitable coatings for this purpose. Both electrically linear and non-linear coatings have been used for stress grading in large motors and generators, and other electrical apparatus, for many years; the linear coatings have generally contained carbon (beech char), while the non-linear ones have employed silicon carbide powder. The characteristics of such coatings are conveniently plotted as e-L curves on log-log paper; on such a representation a straight line of slope X would imply a relation of form $i = ke^{\alpha}$, where here e is electric stress in volts/cm and i is current density in amps/cm. The surface resistance of such a coating is then, in ohms/square, $R = \frac{e}{L} = \frac{i}{k} e^{1-\alpha}$. For a linear coating, $\alpha = 1$ and R is independent of e; but for a coating for which $\alpha > 1$, the resistance will decrease as the stress increases. Non-linear coatings are usually much more effective than linear ones in stress-grading, for the reduction of R in high-field regions lowers the stress there at the expense of raising it in regions where it was initially lower, hence resulting in a more nearly uniform stress. The silicon carbide coatings take the form of a paint in which the silicon carbide powder is dispersed in an organic resin, typically an air-drying alkyd varnish.

These paint coatings typically show an α of 5 to 6; figure 4-4 shows a range of resistance vs. field characteristics which have been developed for use on generators in air or hydrogen. The different curves result from different SiC granule size. The non-linearity appears to arise from the nature of the interparticle contacts between SiC granules, and does not depend significantly on the resin. In order to maintain sufficient particle contacts for conduction, the SiC content of the paints is rather high.

An upper limit to the fields at which such paints can operate is set by thermal dissipation in the paint (which of course also depends on the substrate), and also by surface flashover along the paint. As a rough guideline, dissipation in generator applications is kept below 15.5 mw/cm^2 (0.1 watts/in.^2), and electric fields in air below about 4 kV/cm (10 kV/in.). In pressurized SF_6 much higher fields can of course be tolerated without flashover.

Because of the rapid increase of current in the paint with electric field, the power dissipation rises steeply with applied voltage, and can become a limiting consideration during overvoltage proof tests. Fortunately, the highest voltage tests are impulse tests, whose short duration tends to compensate for the higher power dissipation in determining the temperature rise. The greatest temperature rise may be during the switching surge test, which is longer than the impulse and higher in voltage than the 60 Hz tests.

STRESS-GRADING COATING CHARACTERISTICS

FIGURE 4-4

4.2.3 Work to be undertaken

The 1200 kV termination will have air outside and pressurized SF_6 inside. Even though the outside is convoluted while the inside is not, the external flashover voltage will be the limiting factor rather than the internal. Although it might thus appear that the application of a stress grading coating to the outer surface would be the most effective way to suppress external flashover, such factors as weatherability make this unattractive. It is, therefore, expected that the coating would be applied to the inside of the termination, relying on the capacitance through the wall to couple to the outer surface the stress distribution imposed by paint on the inner surface. Fortunately, stress grading is most necessary for fast transients (impulse and switching surge) when the capacitive coupling will be most effective. Further, since the stress grading layer will thus be subject to gradients below that required for air flashover, while in SF_6 , flashover on the paint itself will be very unlikely.

Once the termination dimensions and stresses have been defined, it will be necessary to verify that silicon carbide paints will perform satisfactorily in the SF_6 environment, and possibly to modify the paint composition if resistivities outside the present ranges are required. Although these paints have not been extensively used in SF_6 , there has been enough use in SF_6 to afford considerable confidence that no adverse interactions will occur. Regarding the modification of resistivity, past experience has shown that resistivity is primarily a function of granule size, increasing as the size decreases. It is, therefore, expected that the work to be done will be to verify the electrical behavior of high-resistivity SiC paint

layers in SF_6 for 60 Hz, impulse and switching surge stresses in the range of those expected in the 1200 kV termination, modifying granule size, if necessary, to achieve suitable resistances.

5.0 THERMAL STUDIES (TASK 3)

5.1 Work to be Undertaken in Next Period

As soon as information is available from the electrostatic and mechanical studies on the expected dimensions of the most promising termination dimensions, a thermal transport study will be initiated.

Thermal network analysis will be performed to determine the temperature distribution of the conductor, gas and weathercase enclosure. The model for analysis will include axial conduction in the conductor, radiation and convection from the conductor to the enclosure through the insulating gas, conduction through the weathercase enclosure, and radiation and convection from the external surface to the ambient. It is expected that an existing computer code can be utilized with only minor modifications to account for the different configurations.

6.0 MECHANICAL STUDIES (TASK 4)

6.1 Shatter-Resistant Weathercase

6.1.1 The needed characteristics of a cast insulator with a reinforcing membrane were considered. The practical materials which can be used for an insulator are all relatively brittle and weak. The addition of a strong membrane material, such as a fiber glass, during the casting process will greatly improve the strength and shatter resistance of the insulator.

Primary characteristics desired are:

- a) The membrane addition be possible on a production basis.
- b) The membrane will strengthen the insulator to allow higher impact or gas pressure before breakage.
- c) When the insulator breaks, the membrane does not break, except locally near an impact location. But will allow the pressurized gas to leak out safely with only small (less than three cm) particles of the insulator being thrown by the escaping gas.
- d) The membrane will not be a high percentage of the insulator material.
- e) The insulator material will be as flexible and insensitive to impact as possible.
- f) Insulator-membrane characteristics will not be effected significantly by temperature from -40°C to $+60^{\circ}\text{C}$.
- g) Dielectric strength of the membrane will be greater than six kV/cm.

Calculations were made to define the needed strength and to predict the performance characteristics of the membrane.

Define,

$$S_c \equiv \text{needed circumferential strength} = \frac{PD}{2}$$

$$S_L \equiv \text{needed longitudinal strength} = \frac{PD}{4}$$

Where: P = gas pressure

D = bushing diameter

The effective membrane thickness to resist the gas will be:

$$t_m = S_L / \text{membrane allowed stress} \quad \text{eq 6-1}$$

For example, if

$$P = 55.12 \text{ N/cm}^2 \quad (5.44 \text{ atmospheres gage})$$

$$D = 1 \text{ meter (100 cm)}$$

$$\sigma_m = \text{membrane stress} = 80,000 \text{ N/cm}^2 \quad (\text{working stress limit})$$

Then, membrane width $\equiv$ 0.034 cm for the circumferential direction.

Assuming the membrane is a mesh with only 0.33 cm fiber per cm of membrane length, the bundle thickness in the mesh will be 0.102 cm. This is well within the possible size mesh to use in an insulator. There are several commercially available meshes of fiber glass which approximate this size.

For the membrane to function properly, it may be necessary for the membrane fibers to slip relative to the insulator near an insulator break point. The fiber will probably be stiffer than the insulator and slippage will be necessary to assure that the fiber remain unbroken after the insulator breaks.

Define, S_f = fiber strain at yield point

S_I = insulator strain at break point

R = fiber radius, cm

L = length, cm

f = load on fiber, newtons

σ_t = fiber tensile stress, Newtons/cm²

σ_s = shear stress at fiber-insulator interface at slip load, newtons/cm²

E_f = elastic modulus of the fiber, newtons/cm²

E_I = elastic modulus of the insulator, newtons/cm²

σ_I = insulator tensile strength, newtons/cm²

fiber crossection area = πR^2 (cm²)

fiber shear area = $2\pi RL$ (cm²)

$$\sigma_t = \frac{f \text{ break}}{\pi R^2} \longrightarrow f \text{ break} = \pi R^2 \sigma_t$$

$$\sigma_s = \frac{f \text{ slip}}{2\pi RL} \longrightarrow f \text{ slip} = 2\pi RL \sigma_s$$

assume that $f \text{ break} > f \text{ slip}$

$$\text{then, } L < \frac{R \sigma_t}{2 \sigma_s}$$

Eq 6-2

This means that the fiber can slip for a length less than $\frac{R\sigma_t}{2\sigma_s}$ before it breaks.

Also, the insulator will break before the fiber if

$$S_f > S_I$$

$$\text{or, } \frac{\sigma_t}{E_f} > \frac{\sigma_I}{E_I} \longrightarrow \frac{\sigma_t E_I}{\sigma_I E_f} > 1 \quad \text{Eq 6-3}$$

If this relation is true, the insulator will break before the fiber. Separation at the break can be approximated based on these calculations and the pressure load in the insulator. Assuming the membrane is able to restrain the pressure load without breaking, ($t_m > PD/2\sigma_t$)

if, σ_1 is the stress on the fiber due to pressure, and

S_1 is fiber strain, Δ is actual fiber strength,

$$\sigma_1 = \frac{PD}{2t_m} = S_1 E_f = \frac{\Delta E_f}{L}$$

also,

$$\frac{f}{\pi R^2} = \frac{PD}{2t_m} \longrightarrow f = \frac{\pi R^2 PD}{2t_m}$$

$$\text{and } f = 2\pi R L \sigma_s$$

Put these together and we get

$$L \text{ slip} = \frac{RPD}{4t_m \sigma_s}$$

$$\text{and } \Delta = \frac{P^2 D^2 R}{8t_m^2 E_f \sigma_s} \quad (\text{crack width in cm})$$

Assuming that a filled epoxy is used and a glass fiber weave is used as the membrane, the possible results can be calculated. For example:

$$\sigma_I = 2500 \text{ N/cm}^2$$

$$E_I = 0.34 \times 10^6 \text{ to } 1.38 \times 10^6 \text{ N/cm}^2$$

$$E_f = 4.13 \times 10^6 \text{ to } 6.55 \times 10^6 \text{ N/cm}^2$$

$$\sigma_s = 2070 \text{ N/cm}^2 \quad (\text{approximate})$$

$$P = 55.12 \text{ N/cm}^2$$

$$D = 100 \text{ cm}$$

$$\sigma_t = 80,000 \text{ N/cm}^2$$

$$t_m = 0.034 \text{ cm}$$

$$R = 0.00065 \text{ cm}$$

This data gives:

$$\frac{\sigma_t E_I}{\sigma_I E_f} = 2.63 \quad \text{so epoxy will break and fiber will not.}$$

$$\Delta = 2.5 \times 10^{-4} \text{ cm} \quad \text{crack.}$$

$$\text{if } \sigma_s = 350 \text{ N/cm}^2,$$

$$\Delta = 1.5 \times 10^{-3} \text{ cm} \quad \text{crack.}$$

Thus with a straight mesh, the crack will be small.

6.1.2 Work to be Done

Several different fiberglass meshes will be cast into several epoxy formulations in bar form and broken as in Figure 6-3. Epoxy samples with no reinforcement will be tested as a comparison. From this work, the most suitable mesh design and epoxy formulation will be determined. Several epoxy insulators with and without reinforcing mesh will be manufactured, pressurized and failed by shooting with a rifle bullet. Projectile scatter will be determined in all tests and results will be compared to the computer predicted results.

Figures 6.2 and 6.3 deleted to protect Westinghouse and
Department of Energy patent rights on subject material.

Figure 6-3

6.2 Reinforcing-Liner

6.2.1 Design Criteria and Calculations

The reinforcing liner approaches for a safer termination involve the limiting of gas energy (or volume) available to an insulator when failed. The liner acts as a gas flow barrier. The liner may also be used as a structural member in the termination. The use of such tubes in electrical equipment is not new but is not standard practice in presently manufactured bushings.

A computer program was created to calculate the characteristics of a termination with such a liner. The text of the program is in the appendix as /JMBUSH/. It predicts the average projectile velocity and ground impact distance for a failed weathercasing with and without a liner for a given size and gas pressure.

The program and calculations are based on the configuration shown in Figure 6-4.

Figure 6-4

Gas volumes are:

$$V_g \equiv \text{gap volume} = V_B - \frac{\pi L}{12} \left[d_1^2 \left(1 + \frac{d_2}{d_1} + \left(\frac{d_2}{d_1} \right)^2 \right) \right]$$

$$V_p \equiv P_1 \text{ volume} = \frac{\pi L}{12} (d_1 - 2T)^2 \left[1 + \frac{d_2 - 2t}{d_1 - 2t} + \left(\frac{d_2 - 2t}{d_1 - 2t} \right)^2 \right]$$

$$V_B \equiv \text{Total weathercase volume} = \frac{\pi d_4^2}{12} \left[1 + \frac{d_3}{d_4} + \left(\frac{d_3}{d_4} \right)^2 \right]$$

Define,

K = ratio of specific heats, 1.12 assumed

A = gas flow area through liner

C = orifice coefficient

t = time in seconds

ν_o = initial gas density inside liner

ν_g = initial gas density in liner-insulator gap

E_B = gas energy without liner

$E_t(t)$ = gas energy with liner available to insulator as it fails

C_v = specific heat at constant volume.

T_1, T_2 = initial and final gas temperature, resp.

P_1, P_2 = gas pressure and atmospheric pressure, resp.

Assuming adiabatic expansion,

$$E_B = \nu_o \nu_B C_v (T_1 - T_2) \quad \text{where} \quad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\left(\frac{K-1}{K} \right)}$$

$$E_T = C_v \nu_g \nu_g (T_1 - T_2) \frac{\nu_o \nu_p}{\nu_g \nu_g} \left[\left(1 - e^{-\left[\frac{P_1 A_1 t}{\nu_o \nu_p} \right]} \right) + 1 \right]$$

$$P(T) = P_o e^{-\left[\frac{P_1 A_1}{\nu_o \nu_p} t \right]}$$

$$A_1 = CA \left[\frac{K}{RT_1} \left(\frac{2}{K+1} \right)^{K_1} \right]^{1/2}$$

$$K_1 = (K+1)/(K-1)$$

The analysis for projectile motion was covered in the previous reporting period and is used without modification.

The effectiveness of the liner in reducing energy available to the insulator can be shown by:

- 1) Energy ratio, $\frac{E_T}{E_B}$
- 2) Initial velocity and throw distance of projectiles of various sizes and initial heights.

The results of this analysis, shown graphically in Figures 6-5 through 6-9 indicate the liner effectiveness and the value of using lower gas pressure in the weathercasing and/or liner gap. The curves show results for a straight cylindrical insulator for simplicity of comparison.

Figure 6-5 shows the effect of varying the gas pressure (SF_6) in an unlined porcelain weathercasing.

Figures 6-6 and 6-7 show the characteristics of a lined weathercasing with gas flow area through the liner to the insulator liner gap. Figure 6-7 also compares the results if no flow area is provided and shows that the energy available to the insulator is reduced.

UNLINED PORCELAIN WEATHERCASE

(5 cm PROJECTILE)

Figure 6-5

LINED PORCELAIN WEATHERCASE

WITH FLOW HOLE IN LINER

Figure 6-6

LINED PORCELAIN WEATHERCASE

Figure 6-7

Figure 6-8

Figure 6-9

Figures 6-8 and 6-9 show the results of no flow area in the liner and varying the gap pressure and width. Available energy is greatly reduced by lowering the liner gap pressure and the gap width is not a large factor in determining this energy in the size range of a 500 kV or larger termination.

The Figures are for porcelain insulators only. Epoxy insulators would have similar results but have higher velocities and throw distances due to the lower density of epoxy relative to porcelain density. This information only shows typical effects for chosen sizes and pressures for possible weathercasings.

The program was used to predict the failure characteristics of two Westinghouse 69 kV SF₆ pressurized epoxy insulators which were purposely failed for another project. Results were as follows:

insulator - { 4.62/3.12 inch I.D.
7.50/6.0 inch O.D.

75°F temperature

75 psig SF₆ gas

1.4 cubic feet of SF₆ available in connected vessel

1.44 inches average insulator thickness

Test Number	Maximum Actual Throw Distance (feet)	Predicted Average Throw Distance (feet)	How Failure Was Caused
1	30 (2 to 4 in. proj- ectiles)	40 to 52	Hit by crane hook. 48" to 77" height above ground.

<u>Test Number</u>	<u>Maximum Actual Throw Distance (feet)</u>	<u>Predicted Average Throw Distance (feet)</u>	<u>How Failure Was Caused</u>
2	90 ft.	65 to 81 (1 inch projectile)	Hit by 30-30 bullet. 12 feet to 14.5 feet height above ground

The data shows that the body impact such as a crane hook impact allows much gas to escape and not accelerate the weathercase projectiles. A Bullet impact, however, allows a more uniform failure and more energy is given to the projectiles. The probabilistic scatter in this case was small, however, and the maximum average scatter predicted was close to the actual measured.

6.2.2 Model Sketches

Figures 6-10 through 6-15 show several possible configurations in which the liner is the main structural support member and the gap is a separate gas volume and can be at a lower pressure than the gas inside the liner. This lower pressure will greatly reduce the damage potential of the insulator should it fail. It is also very possible that the liner remain essentially intact during an insulator failure and the system voltage could remain on the bushing for some time after the failure (i.e., minutes to a few hours).

The figures show various techniques of sealing and supporting the insulator at the top of the weathercasing. Sliding seals, static bolted connection and spring loaded designs are shown. Analysis of desirable and undesirable features was included in the comparison described in Section 3.0.

Figure 6-10 SIMPLE TOP STRUCTURE

Figure 6-11 SIMPLE TOP STRUCTURE

Figure 6-12 ALTERNATE TOP STRUCTURE

Figure 6-13 ALTERNATE TOP STRUCTURE

Figure 6-14 SPRING LOADED INSULATOR

Figure 6-15 SPRING LOADED INSULATOR

6.2.3 Work to be Done

Sketching and calculations will continue on the termination design with and without a liner. This will lead to test models of a medium voltage size (69 kV to 242 kV) which will be failed and the results compared with the computer prediction. Also, standard unlined weathercasings will be failed as a comparison performance test. Actual test dates are dependent upon procurement of models.

7.0 MODEL STUDIES (TASK 5)

7.1 Work to be Undertaken in Next Period

Parts and materials for the model studies will be ordered as soon as the drawings and specification are available. A detailed schedule for the procurement, assembly, and tests of models is shown in Figure 7-1.

SUBTASK

5.1 SHIELD EFFECTIVNESS

5.2 RESISTIVE GRADING

5.3 SHATTER-RESISTANT
WEATHERCASES

5.4 REINFORCING LINER

SCHEDULE FOR TASK 5 - MODEL STUDIES

FIGURE 7-1

8.0 REPORTING (TASK 9)

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

<u>Qty.</u>	<u>Report Title</u>
3	Project Status Reports
3	Contract Management Summary Reports
3	Cost Management Reports
1	Non-60CO Contractor Subcontracting Quarterly Report

8.1 Program Status

The progress of each individual subtask is shown in the program schedule Figure 8-1. This same schedule will be incorporated in each quarterly report as a means of showing clearly the technical progress on the project.

8.2 Manpower Status

With regard to the manpower utilization in this project, the 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 (2-1-79 to 4-30-79)</u>
J. S. Billings	216 Hours
Z. Neri	209 Hours
C. F. Hofmann	0 Hours
R. W. Crookston	0 Hours

SCHEDULE FOR 1200 kV TERMINATION

TASK 1 - CONCEPTUAL DESIGN AND MATERIAL STUDY

- 1.1 PROBLEM DEFINITION
- 1.2 INNOVATIVE CONCEPTS
- 1.3 MATERIALS INVESTIGATION
- 1.4 FABRICATION TECHNIQUES

TASK 2 - ELECTROSTATIC STUDIES

- 2.1 SHIELD EFFECTIVENESS
 - 2.1.1 CONCEPT STUDY AND MODEL DESIGN
 - 2.1.2 ESTABLISH TEST OBJECTIVES
 - 2.1.3 DATA EVALUATIONS & RECOMMENDATIONS
- 2.2 RESISTIVE GRADING
 - 2.2.1 GRADING OBJECTIVES & CRITERIA
 - 2.2.2 DESIGN MODELS
 - 2.2.3 ESTABLISH TEST OBJECTIVES
 - 2.2.4 DATA EVALUATIONS & RECOMMENDATIONS
- 2.3 FIELD PLOTTING

TASK 3 - THERMAL STUDIES

- 3.1 THERMAL TRANSPORT STUDY
- 3.2 HEAT PIPE STUDY

TASK 4 - MECHANICAL STUDIES

- 4.1 SHATTER-RESISTANT WEATHERCASE
 - 4.1.1 CONCEPT STUDY, MODEL DESIGN, AND TEST CRITERIA
 - 4.1.2 DATA EVALUATIONS & RECOMMENDATIONS
- 4.2 REINFORCING LINERS
 - 4.2.1 CONCEPT STUDY, MODEL DESIGN, AND TEST CRITERIA
 - 4.2.2 DATA EVALUATIONS & RECOMMENDATIONS
- 4.3 CLAMPING AND FASTENING

TASK 5 - MODEL STUDIES

- 5.1 SHIELD EFFECTIVENESS
- 5.2 RESISTIVE GRADING
- 5.3 SHATTER RESISTANT WEATHERCASE
- 5.4 REINFORCING LINER

TASK 6 - DESIGN OF A PROTOTYPE

- 6.1 FINALIZE DESIGN PARAMETERS
- 6.2 MAKE ENGINEERING DRAWINGS
- 6.3 REVIEW AND EVALUATE

TASK 7 - PRODUCTION AND THE TESTING OF A PROTOTYPE

- 7.1 QUALITY ASSURANCE & PREPARATIONS FOR TEST
- 7.2 PROCUREMENT OF SPECIAL TOOLING AND COMPONENT PARTS
- 7.3 FABRICATING THE WEATHERCASE AND ASSEMBLING THE PROTOTYPE
- 7.4 ELECTRICAL DESIGN TESTS
- 7.5 OTHER DESIGN TESTS
- 7.6 REVISE & FINALIZE DRAWINGS
- 7.7 DISASSEMBLY PROTOTYPE
- 7.8 MODIFY PROTOTYPE
- 7.9 REASSEMBLE PROTOTYPE
- 7.10 COMPLETE TESTS

TASK 8 - DELIVERY OF THE PROTOTYPE AND MONITORING PERFORMANCE

TASK 9 - REPORTS & RECOMMENDATIONS

FIGURE 8-1

Total Manhours Worked During The Reporting Period (Including Key Personnel)

Task 1	226 Manhours
Task 2	146 Manhours
Task 4	107 Manhours
Task 9	110 Manhours

9.0 SUMMARY

9.1 Completed Work

The Conceptual Design and Material Study (Task 1) was completed with the conclusion that the detailed studies to follow are directed to the proper concepts. The Electrostatic Shield Effectiveness Study (Task 2.1) has progressed to completion of the model drawings. The grading objectives have been established for the Resistive Grading Study (Task 2.2).

Material requirements for the fabric to be used in the Shatter-Resistant weathercase models (Task 4-1) have been calculated. A thorough failure characteristics analysis for various configurations of weathercases has been made in support of the Reinforcing Liner Study (Task 4-2).

During the next quarter, all of the model studies (Task 5) should be under way and perhaps some of them finished. A two week shutdown of the Trafford facility from June 25 through July 6 and a possible strike may delay these tasks.

The Thermal Studies (Task 3) should be started as soon as input information is available from the other studies.

APPENDIX

Weathercase Failure Analysis Program.

-COPY /JMBUSH/ TO TEL

 *THIS PROGRAM MODELS VARIOUS ASPECTS OF A HIGH VOLTAGE GAS BUSHING
 *DURING A CATASTROPHIC FAILURE. VARIOUS DESIGNS ARE CONSIDERED:
 * 1) STANDARD DESIGN, VARIABLE PRESSURE.
 * 2) BUSHING WITH INNER LINER
 * 3) BUSHING WITH INNER LINER WITH GAP HAVING LOWER PRESSURE.
 *
 *ENERGIES, DEBRIS SCATTER & TIME CONSTANTS ARE CALCULATED AND OUTPUT

```

REAL B1,B2,T,T1,A,D3,D4,F,P1,P2,L,D1,D2,V1,V2,V3,V4,D5,D6,T9
REAL T2,K,K1,C1,E1,A4,A1,T4,E2,C,K2,R1,T3,Z,U0,V8,X0,X1,L1,T5
INTEGER N,I,M,O
STRING H

WRITE(1,100)
WRITE(1,131)
O=0
1 ACCEPT$1)PORCELAIN OR 2) EPOXY (PRINT NO.)?$,B
  IF (O.EQ.1) GO TO 15
2 ACCEPT$AMBIENT TEMPERATURE T1 (F DEG)=$,T1
  IF (O.EQ.1) GO TO 15
3 ACCEPT$LINER THICKNESS T & HOLE AREA A (INCH)=$,T,A
  ACCEPT$LINER OD TOP & BOTTOM (INCH)= $,D2,D1
  IF (O.EQ.1) GO TO 15
4 ACCEPT$INSULATOR INNER DIA, TOP & BOTTOM (INCH)=$,D3,D4
5 ACCEPT$INSULATOR AVERAGE THICKNESS (INCH)=$,F
  IF (O.EQ.1) GO TO 15
6 ACCEPT$INSULATION & LINER PRESSURES (PSIG)=$,P1,P2
  IF (O.EQ.1) GO TO 15
  IF (O.EQ.1) GO TO 15
8 ACCEPT$INSULATOR LENGTH (INCH)=$,L
9 ACCEPT$GAS VOLUME IN ATTACHED BUS (CU IN)=$,V4
10 ACCEPT$PROJECTILE SIZE (INCH)=$,Z

15 WRITE(1,131)
   WRITE(1,135)
   WRITE(1,160)
   WRITE(1,130)
   WRITE(1,180)
   WRITE(1,131)

   IF (B.EQ.1) GO TO 20
   B1=0.0019
   GO TO 25
20 B1=0.0031
25 C=.6
30 C1=113.6*32.2
   K=1.12
   K2=(K+1)/(K-1)
   K1=(K-1)/K
   G=(D4-D1)/2
   V3=0.262*L*D4*D4*(1+D3/D4+(D3/D4)^2)
   V2=0.262*L*(D1-2*T)^2*(1+(D2-2*T)/(D1-2*T)+((D2-2*T)/(D1-2*T))^2)
   V1=V3-0.262*L*D1*D1*(1+D2/D1+(D2/D1)^2)

```

```

D5=(0.0278*(P1-5)+.53)/1728/32.2
D6=(0.0278*(P2-5)+.53)/1728/32.2
T2=(14.7/(P1+14.7))-K1*(T1+459.7)-459.7
T5=(14.7/(P2+14.7))-K1*(T1+459.7)-459.7
A1=C*A*(32.2/(10.6*(T1+459.7))*K*(2/(K+1))-K2)-0.5
T3=D5*V2/(P1*A1)*32.2
T9=T3
IF (A.EQ.0) T3=0.5
IF (T3.GT.1) T3=1
DO 50 N=1,2
IF (A.EQ.0) N=2
T4=T3*N
E4=-P1*A1*T4/(D5*V2)/32.2
E1=C1*D6 *V1*(T1-T5)*(V2/V1*D5/D6*(1-2.7183-E4)+1)
E2=D5*V3*C1*(T1-T2)
R1=E1/E2
R2=.000045/32.2
B2=(0.262*L*(D4+2*F)-2*(1+(D3+2*F)/(D4+2*F)+((D3+2*F)/(D4+2*F))-2)-V3)*B1
V0=(E2*2/B2)-0.5
V8=(E1*2/B2)-0.5
DO 40, I=0,4
L1=120+I*60
TB=(2*L1/(32.2*12))-0.5
X0=B1*Z*0.139/R2*ALOG(V0*R2*T8*7.2 / (B1*Z)+1)
X1=B1*Z*0.139/R2*ALOG(V8*R2*T8*7.2 / (Z*B1)+1)

40  WRITE(1,132) L1,V8,X1,V0,X0
    WRITE(1,140) T4
    WRITE(1,131)
50  CONTINUE
    IF (A.EQ.0) GO TO 51
    WRITE(1,120) T9
51  WRITE(1,170) R1
    WRITE(1,100)
55  ACCEPT$MODIFY ANY PARAMETER? $,H
    IF (H.EQ."YES") GO TO 60
    IF (H.EQ."NO") GO TO 200
    DISPLAY$WRONG INPUT DUMMY! TRY AGAIN, YES OR NO$
    GO TO 55
60  DISPLAY$MATERIAL-1, TEMP-2, LINER-3, INSUL SIZE-4, PRESSURE-6, PROJECTILE-10$
    ACCEPT$ PRINT NUMBER- $,M
    O=1
    IF (H.EQ.1) GO TO 1
    IF (H.EQ.2) GO TO 2
    IF (H.EQ.3) GO TO 3
    IF (H.EQ.4) GO TO 4
    IF (H.EQ.6) GO TO 6
    IF (H.EQ.10) GO TO 10
    WRITE(1,100)

100  FORMAT(72($$$$))
120  FORMAT($TIME CONSTANT OF ORIFICE=$,F6.2,$ SECONDS$)
130  FORMAT($ INIT HT $, $ INIT VEL$,7X,$SCATTER$,7X,$INIT VEL$,6X,$SCATTER$)
131  FORMAT(//)
132  FORMAT( F7.2,4X,F7.2,8X,F7.2,7X,F7.2,8X,F6.2)
135  FORMAT(17X,$WITH LINER$,17X,$WITHOUT LINER$)
140  FORMAT($TIME AFTER FAILURE=$,F5.2,3X,$SECONDS$)
150  FORMAT(12X,25($$$$),5X,25($$$$))
160  FORMAT(11X,22($$$$),6X,22($$$$))
170  FORMAT($ENERGY REDUCTION RATIO=$,F5.2)
180  FORMAT($ (INCH) $,$ (FT/SEC)$,7X,$(FT) $6X,$(FT/SEC)$,6X,$ (FT)$)

```

1)PORCELAIN OR 2) EPOXY (PRINT NO.)?1
 AMBIENT TEMPERATURE T1 (F DEG)=70
 LINER THICKNESS T & HOLE AREA A (INCH)=.5,1
 LINER OD TOP & BOTTOM (INCH)= 9,9
 INSULATOR INNER DIA, TOP & BOTTOM (INCH)=10,10
 INSULATOR AVERAGE THICKNESS (INCH)=1
 INSULATION & LINER PRESSURES (PSIG)=80,80
 INSULATOR LENGTH (INCH)=100
 GAS VOLUME IN ATTACHED BUS (CU IN)=0
 PROJECTILE SIZE (INCH)=2

INIT HT (INCH)	WITH LINER		WITHOUT LINER	
	INIT VEL (FT/SEC)	SCATTER (FT)	INIT VEL (FT/SEC)	SCATTER (FT)
120.00	92.85	69.20	155.43	111.82
180.00	92.85	83.74	155.43	134.38
240.00	92.85	95.74	155.43	152.78
300.00	92.85	106.11	155.43	168.55
360.00	92.85	115.35	155.43	182.47

TIME AFTER FAILURE= 1.00 SECONDS

120.00	107.71	79.59	155.43	111.82
180.00	107.71	96.14	155.43	134.38
240.00	107.71	109.77	155.43	152.78
300.00	107.71	121.52	155.43	168.55
360.00	107.71	131.96	155.43	182.47

TIME AFTER FAILURE= 2.00 SECONDS

TIME CONSTANT OF ORIFICE= 3.31 SECONDS
 ENERGY REDUCTION RATIO= 0.48

 MODIFY ANY PARAMETER? NO

SAMPLE WEATHERCASE WITH SMALL GAS
 FLOW HOLE IN THE LINER

1)PORCELAIN OR 2) EPOXY (PRINT NO.)?1
 AMBIENT TEMPERATURE T1 (F DEG)=70
 LINER THICKNESS T & HOLE AREA A (INCH)=.5,5
 LINER OD TOP & BOTTOM (INCH)= 9,9
 INSULATOR INNER DIA, TOP & BOTTOM (INCH)=10,10
 INSULATOR AVERAGE THICKNESS (INCH)=1
 INSULATION & LINER PRESSURES (PSIG)=80,80
 INSULATOR LENGTH (INCH)=100
 GAS VOLUME IN ATTACHED BUS (CU IN)=0
 PROJECTILE SIZE (INCH)=2

WITH LINER *****			WITHOUT LINER *****	
INIT HT (INCH)	INIT VEL (FT/SEC)	SCATTER (FT)	INIT VEL (FT/SEC)	SCATTER (FT)
120.00	119.85	87.95	155.43	111.82
180.00	119.85	106.10	155.43	134.38
240.00	119.85	121.00	155.43	152.78
300.00	119.85	133.83	155.43	168.55
360.00	119.85	145.21	155.43	182.47
TIME AFTER FAILURE= 0.66			SECONDS	

120.00	134.01	97.56	155.43	111.82
180.00	134.01	117.51	155.43	134.38
240.00	134.01	133.85	155.43	152.78
300.00	134.01	147.89	155.43	168.55
360.00	134.01	160.31	155.43	182.47
TIME AFTER FAILURE= 1.32			SECONDS	

TIME CONSTANT OF ORIFICE= 0.66 SECONDS
 ENERGY REDUCTION RATIO= 0.74

 MODIFY ANY PARAMETER? NO

SAMPLE WEATHERCASE WITH LARGE GAS
 FLOW HOLE IN THE LINER

1)PORCELAIN OR 2) EPOXY (PRINT NO.)?1
 AMBIENT TEMPERATURE T1 (F DEG)=70
 LINER THICKNESS T & HOLE AREA A (INCH)=.5,0
 LINER OD TOP & BOTTOM (INCH)= 9,9
 INSULATOR INNER DIA, TOP & BOTTOM (INCH)=10,10
 INSULATOR AVERAGE THICKNESS (INCH)=1
 INSULATION & LINER PRESSURES (PSIG)=80,80
 INSULATOR LENGTH (INCH)=100
 GAS VOLUME IN ATTACHED BUS (CU IN)=0
 PROJECTILE SIZE (INCH)=2

WITH LINER			WITHOUT LINER	
INIT HT (INCH)	INIT VEL (FT/SEC)	SCATTER (FT)	INIT VEL (FT/SEC)	SCATTER (FT)
120.00	67.75	51.25	155.43	111.82
180.00	67.75	62.20	155.43	134.38
240.00	67.75	71.29	155.43	152.78
300.00	67.75	79.18	155.43	168.55
360.00	67.75	86.24	155.43	182.47

TIME AFTER FAILURE= 1.00 SECONDS

ENERGY REDUCTION RATIO= 0.19

MODIFY ANY PARAMETER? YES

MATERIAL-1, TEMP-2, LINER-3, INSUL SIZI-4, PRESSURE-6, PROJECTILE-10

PRINT NUMBER- 6

INSULATION & LINER PRESSURES (PSIG)=80,5

WITH LINER			WITHOUT LINER	
INIT HT (INCH)	INIT VEL (FT/SEC)	SCATTER (FT)	INIT VEL (FT/SEC)	SCATTER (FT)
120.00	12.60	9.86	155.43	111.82
180.00	12.60	12.05	155.43	134.38
240.00	12.60	13.90	155.43	152.78
300.00	12.60	15.52	155.43	168.55
360.00	12.60	16.98	155.43	182.47

TIME AFTER FAILURE= 1.00 SECONDS

ENERGY REDUCTION RATIO= 0.01

MODIFY ANY PARAMETER? NO

SAMPLE WEATHERCASE WITH NO GAS FLOW HOLE
 THROUGH THE LINER; TWO LINER GAS PRESSURES