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Final Report on Preliminary Dielectric Studies

Spir-O-Line Cable for Application at Power Frequencies

December 4, 1978

Published April 1979

Prepared for

U.S. Department of Energy

Assistant Secretary for Energy Technology

Division of Electric Energy Systems

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FINAL REPORT

PRELIMINARY DIELECTRIC STUDIES

SPIR-O-LINE CABLE FOR APPLICATION AT POWER FREQUENCIES

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I. INTRODUCTION

The Spir-O-Line coaxial cable type, developed and manufactured by Prodelin, Inc. for high power RF application, has been in service for several decades. The design, as shown in Fig. 1, is unique in that the center conductor is continuously supported by high density polyethylene tubes resulting in a light, flexible low cost construction. The work covered by this report represents a preliminary investigation of the power frequency and impulse dielectric behavior of this cable type, to determine if Spir-O-Line has potential in the power transmission cable industry.

The proposed program consisted of 5 tasks as listed below:

- Task 1. A brief study of the composite dielectric tests by Prodelin to predict the most likely behavior patterns and design the experimentation ranges of pressures and voltages consistent with available equipment.
- Task 2. Study available test termination means, choose the most applicable, and establish designs suitable for the desired voltages and pressures.
- Task 3. Perform the experimental corona inception, a.c. breakdown, and impulse breakdown tests sufficient to characterize the cable's performance as a function of gas pressure and dimensions.
- Task 4. Analyze test results to establish a controlling mechanism and means for a reasonable extrapolation to larger cable dimensions.
- Task 5. Assign possible voltage levels to 3" and 6" cable sizes, perform a preliminary comparative economic analysis against conventional U.G. systems, and develop recommendations for future work.

The results of this effort are reported in that order.

II. ANALYSIS OF DIELECTRIC PERFORMANCE (TASK 1)

A necessary prelude to the examination of the viability of a new type of power transmission cable is the establishment of reliable design criteria. For the Spir-O-Line concept, the dielectric performance at power frequencies and under impulse application has little background since most experimental work has been done at radio and higher frequencies. Further, application as an RF cable is usually not at high dielectric stress, so primary attention has not been paid to dielectric breakdown behavior. Thus, before assigning voltage levels to available sizes for system and/or economic study, a better knowledge of the dielectric breakdown behavior is required.

The system is not easily assessed for its dielectric breakdown characteristics because it represents an unusual geometric mixture of gaseous and solid dielectrics.

It was anticipated that the gas dielectric behavior will control the dielectric performance of the assembly. However, it was not clear which of the "separate" geometries would limit or control breakdown strength. The dielectric can be visualized as three shapes: the six triangular spaces between adjacent tubes and the inner conductor, the areas enclosed by the tubes, and the six triangular spaces between adjacent tubes and the outer conductor. A section of the dielectric is shown in Figs. 2, 3 and 4 for each of three commercially produced Spir-O-Line sizes — 1/2", 7/8" and 1-5/8" respectively.

The initial guide to expected breakdown levels came from the manufacturer's catalog which lists RF peak breakdown values. These values, along with dimensional data, are shown in Table I:

TABLE I

Spir-O-Line Dimensions and Breakdown Data
from Manufacturer's Catalog

Size, In.	O.D., In.	I.D., In.	Air @ 1 atm., kV peak	SF ₆ @ 3 atm., kV peak	Geometric Stress, vpm/kV
1/2	0.456	0.167	5.7	32.7	11.9
7/8	0.837	0.311	10.6	60.9	6.5
1-5/8	1.622	0.606	20.6	118.3	3.35

The tabled data reduce to a peak maximum stress of 70 vpm for air at 1 atmosphere and 400 vpm for SF₆ at 3 atmospheres for each size if computed for a cylindrical geometry, ignoring the support tubes. The geometric stress for this "free space" coaxial electrode arrangement is included for convenience. This number, when multiplied by an applied voltage, gives the maximum stress at the conductor. If breakdown is assumed to be independent of frequency and a function of the peak applied voltage, then the strength of the system in SF₆ at 3 atmospheres would be 283 vpm 60 Hz RMS and 400 vpm impulse. These numbers compare closely with those suggested for GITL design in Ref. 1, namely, 250-300 vpm 60 Hz RMS and 425 vpm impulse at 3 atmospheres.

A review of the literature regarding breakdown data for coaxial electrodes as a function of gas type and pressure, to expand on the above data and provide a base level for evaluation of the Spir-O-Line system was performed, wherein it was found that pertinent data is surprisingly sparse. However, a report of some private experimental work in 1968 presented applicable data for the coaxial system in this range of pressures and sizes. Data from this report were used to develop the curves on Graph 1 which are base level breakdown values as a function of N₂ and SF₆ pressure for the three sizes under investigation. The manufacturer's breakdown levels of Table I are shown on Graph 1 as circles for N₂ and squares for SF₆. They are seen to be consistent with, but slightly lower (about 10%) than the data

of the above report. Table II summarizes the data for Graph 1.

TABLE II
Coaxial Electrode Breakdown Voltage

	Pressure, Atm.				
	1	2	3	4	5
Stress - N_2 , vpm	86	124	159	193	225
Stress - SF_6 , vpm	188	282	433	596	712
Breakdown - kV-peak					
1/2" - N_2	7.2	10.4	13.4	16.2	18.9
1/2" - SF_6	15.8	23.7	36.4	50.1	59.8
7/8" - N_2	13.2	19.0	24.5	29.7	34.6
7/8" - SF_6	28.9	43.4	66.6	91.7	109.5
1-5/8" - N_2	25.7	37.0	47.5	57.6	67.2
1-5/8" - SF_6	56.1	84.2	129.3	177.9	212.5

There is a possibility that breakdown levels could be higher than the above mentioned "free space" levels if the composite dielectric behaves better than free space. Some rough early experimental work by the manufacturer at 60 Hz found that breakdown levels tended to be about 20% higher than those predicted for the free space system. The largest free dimension is the radial diameter of a support tube, which compares with free space radial electrode separations. However, the region is shielded from both electrodes, being inside the tube. As shown in Ref. 2, "covered" electrodes can increase breakdown stress by as much as 150 vpm at 3 atmospheres of SF_6 . Because of this, the triangular regions will most likely control breakdown, following some form of Paschen relation. An excellent summary of gaseous breakdown data which culminates in the derivation of Paschen curves for air, N_2 and SF_6 is contained in Ref. 3.

A qualitative analysis of the two triangular dielectric spaces within the geometry can be made allowing some rather gross and arbitrary estimates of the field patterns within these spaces. Because of defraction caused by the difference in dielectric constant (SIC) of the high density polyethylene (2.3) relative to gas (1), the field within the gas space tends to be more uniform than the free space radial distribution. By estimating the net voltage across the bulk of the space and a principal dimension, the Paschen data can be applied to determine an expected partial breakdown. If the assumptions are made that the principal dimension of both triangular spaces is one quarter of the radial separation of electrodes, and the voltage across each is 40% of the applied voltage, the Paschen curve yields values of breakdown shown in Table III and plotted on Graph 2 for N_2 and SF_6 and each size. These data imply a 28 to 77% improvement depending on pressure, with the largest improvement occurring in the 2 to 3 atmosphere range of pressure.

The above analysis presents a range of expected breakdown levels based on a simple estimate of an improvement potential of the Spir-O-Line system. If experimental breakdown data confirms improved performance, the shape of the breakdown level/pressure curves may shed some light on the controlling mechanism and allow the desired extrapolation to larger sizes, or dictate the areas for future study.

TABLE III
Estimated Paschen Breakdown Voltage

<u>Size, In.</u>	<u>Pressure, atm.</u>	<u>Pd - Atm-mm</u>	<u>Breakdown - kV-peak</u>	
			<u>N₂</u>	<u>SF₆</u>
1/2	1	.9175	11.5	21.9
	2	1.835	19.2	41.9
	3	2.753	26.3	61.9
	4	3.67	33.4	81.9
	5	4.59	39.8	102.0
7/8	1	1.67	17.9	38.6
	2	3.34	30.9	74.5
	3	5.01	42.5	111.4
	4	6.68	54.3	148.3
	5	8.34	64.8	187.5
1-5/8	1	3.23	30.0	72.0
	2	6.45	52.9	143.4
	3	9.68	73.0	215.2
	4	12.9	93.4	237.9
	5	16.13	114.3	262.0

III. STUDY OF TERMINATION TECHNIQUES AVAILABLE (TASK 2)

Testing a cable sample to breakdown inevitably requires some form of stress control at the cable ends, especially when the cable system is to be gas filled and operated under pressure. One favorable aspect of the Spir-O-Line concept is the continuous nature of the conductor support system. If the tubes improve the strength of the system, obviously they cannot be terminated in a full stress area. Therefore, some method of stress reduction must be employed to avoid end breakdowns under test. The purpose of this Task is only to provide adequate test terminals, not to project on to a commercial termination system.

The manufacturer provides a full line of accessories for RF application which double as gas containment fittings. These fittings are designed to avoid a discontinuity which might cause traveling wave reflection (i.e., abrupt changes in characteristic impedance). As such, they usually involve a straight radial cut through the tubes, butting the tubes against an insulating disc. A unique system called Spir-O-Lock is used to seal on the corrugated sheath. It was thought the easiest approach for testing purposes was to incorporate the Spir-O-Lock mechanical fitting into the U.S.I. VEIL cell type terminal using a nylon bushing over the tubes for stress control. The resulting arrangement is shown in Figs. 5 and 6. Tapered nylon tubes and lead pipes were fabricated for the 1/2" and 7/8" size. These terminals were used at first, but were found to be difficult to assemble since the fit over the tubes was tight. Therefore, a variation which used petrolatum dielectric grease applied by hand at the edge of the entrance fitting was tried and proven successful. This arrangement is shown in Fig. 7.

A second variation for impulse testing only used a semiconducting butyl tape to form a restrictive grading system inside the VEIL cell pothead, as shown in Fig. 8. This system suffered from stress concentration at the entrance fitting and could not be used without the grease. It was therefore abandoned since the grease alone proved adequate also for impulse testing.

IV. EXPERIMENTAL WORK (TASK 3)

The test program was designed to provide sufficient breakdown data to allow extrapolation to larger sizes for analytical purposes.

A total of 21 breakdown tests were performed, the results of which are shown in Table IV.

The test samples were prepared as shown in Fig. 9, except for Test #16 which was set up as shown in Fig. 10.

The first four tests were performed without a flushing operation. Dissection showed significant particle contamination, possibly aggravated by the sample preparation. All subsequent samples were thoroughly flushed with Heptane and blown dry with nitrogen just prior to final assembly of terminals.

All test samples except 5, 6 and 7 were evacuated for at least one hour to a pressure below 2 mm Hg, and vacuum filled with the test gas. Samples 5, 6 and 7 were blown dry with nitrogen and then left open to the atmosphere for approximately one hour before testing. No terminals were used for those tests.

Dissection of the 1/2" sizes after breakdowns showed several areas where the tubes were kinked and distorted. Also, the conductor and sheath copper were discolored in areas as if water had been present for some time. All breakdowns occurred in places where there was a separation between tubes but not necessarily in distorted or discolored areas. It was later determined that the 1/2" sample used was not the one intended for the test program but one that had been scrapped because of the tube distortion. Fig. 11 presents two photos of the first three samples after dissection, which illustrate these conditions. It was decided to move on to the 7/8" size rather than repeat the 1/2" tests because the results did not seem related to the defects.

Table IV
Results of Breakdown Tests

Test No.	Size, In.	Gas Type	Abs. Press., Atm	Voltage Application	Breakdown Level, kV peak	Remarks
1	1/2	N ₂	1	2 kV/sec.	8.5	Brkdown in fitting.
2	1/2	N ₂	2	200 V/sec.	11.0	
3	1/2	N ₂	3	500 V - 2 min.	13.7	Brkdown in fitting.
4	7/8	N ₂	3	1 kV - 1 min.	19.0	
5	1/2	Air	1	2 kV/sec.	9.3)	Flushed with Heptane, then N ₂ - no terminals used, only grease at sheath end.
6	1/2	Air	1	500 V - 1 min.	7.1 (	
7	1/2	Air	1	500 V - 1 min.	7.1)	
8	7/8	N ₂	3	500 V - 1 min.	23.3	1st spark @ 14.5 kV but holds 15.7 kV
9	7/8	N ₂	3	1 kV - 1 min.	20.6	Bad sheath leak; stress cone abandoned
10	7/8	N ₂	1-1/3	500 V - 1 min.	12.4	
11	7/8	N ₂	5	500 V - 1 min.	32.5	
12	7/8	Air	1	500 V - 1 min.	10.6	Flushed with N ₂ .
13	7/8	SF ₆	2	500 V - 1 min.	47.5	
14	7/8	SF ₆	1-1/3	1 kV - 1 min.	39.6	
15	7/8	SF ₆	3	1 kV - 1 min.	58.5	
16	7/8	N ₂	1-2/3	1 kV - 1 min.	28.3T	Oil filled interstices
17	1-5/8	N ₂	2	1 kV - 1 min.	38.2	
18	1-5/8	N ₂	1-1/3	+ impulse	28.0T	
19	7/8	N ₂	3	AC proof test	19.8T	Butyl tape ends; end failure
20	7/8	N ₂	3	+ impulse	23.0	
21	7/8	N ₂	3	+ impulse	19.5	

T = Terminal Failure

The 7/8" size was tested most extensively. Again, all breakdowns occurred between tubes in areas where the tubes were not touching. After the first two tests, the nylon stress cone was abandoned in favor of the use of about 5 inches of petrolatum grease at the termination of the sheath fitting. Removal of the corrugated copper sheath was a difficult, time consuming operation. Several methods were tried, the most successful being an unwinding operation similar to opening a coffee can.

The first 7/8" sample for impulse test (19) used a semiconducting butyl tape to form a resistive grading. This design had such low strength that the breakdown occurred on the first shot and was not detected. It was thought that a problem existed with the impulse machine. An AC proof test was finally attempted which immediately confirmed the sample failure, due to stress concentration at the interface between the shield fitting and butyl tape, as shown in the photos of Fig. 12. The last three impulse test breakdown levels coincided with the peak AC breakdown voltage levels, confirming expectations that peak stress determines breakdown. It was then decided that the planned full series of impulse tests was not necessary at this time.

Test 16 was performed with the space surrounding the tubes filled with light oil (Sun #4). Upon complete dissection of the sample, no failure could be found except for two burn marks between tubes midway up the terminal length. It appears that the breakdown occurred in the terminal area along the surface of the oil, so that data point represents a withstand level.

The rate of rise of AC voltage application was varied in the first 5 tests. At 2 kV/sec. the breakdown value was slightly higher than at 200 V/sec (adjusted for pressure). However, the step tests resulted in breakdowns after 10 to 30 seconds, so the 1-minute step test procedure was adopted.

The impulse test on the 1-5/8" sample failed within the terminal fitting. Upon dissection it was noticed that the bore of the fitting was not small enough to hold the tubes completely together. The fault was at the point where two adjacent tubes were not touching and is shown in Fig. 13.

Corona inception measurements were attempted in Test 3. Results were difficult to analyze because of a high noise level in the laboratory. On Test 4 the detection scope failed, and since the results were of questionable value, corona measurements were discontinued.

V. ANALYSIS OF DATA (TASK 4)

Analysis of the applicable breakdown data is facilitated by comparison of the data points with the predicted results. For this purpose, the base level curves of Graph 1 and the estimated higher performance curves of Graph 2 were combined on one graph and the data points were then added. Graph 3 presents the curves and data for the 1/2" size with N_2 ; Graph 4 covers the 7/8" size with N_2 ; Graph 5 covers the 7/8" size with SF_6 and Graph 6 furnishes the comparison for the 1-5/8" size in N_2 .

All tests with nitrogen lie on or near the base level curve. The 7/8" size data with Nitrogen would lie on a base level curve if its outer dimension were adjusted to .756" from .837". Measurements of the minimum inside diameter of the sheath indicate a dimension of .77 to .8 depending on previous handling and the degree of bend present.

The 1-5/8" sample had the best fit regarding complete contact between adjacent tubes. However, it is expected that the breakdown of Test 17 was the result of incomplete contact. The oil-filled test dramatically improved the dielectric strength of the 7/8" sample, proving beyond doubt that the spaces between tubes control the breakdown. Unfortunately, there is insufficient data at this time to assess the effect of 100% tube contact. Suffice it to say that with no positive assurance of 100% tube contact, and in spite of major disturbances or contamination, the system, in Nitrogen, behaves consistently as an ideal coaxial electrode system.

The behavior of the 7/8" system with SF_6 also approximates the base level free space prediction, though there is a tendency toward a reduced slope vs. pressure. The slope appears to be more in line with that of the deviations from Paschen's law at higher Pd values, as cited in Ref. 3. The breakdown characteristic begins to fall away from the ideal Paschen curve at small spacings. The departure from the ideal law is thought to be

caused by the onset of secondary processes, which could be amplified by the wedge-shaped spaces of the Spir-O-Line structure. Also, with SF₆, particle contamination is known to be more of a factor. These systems, though flushed, could not be considered to be free of small particle contaminants.

To summarize the findings of these tests, it appears that the Spir-O-Line cable, as presently built, could easily perform per the free space prediction of breakdown in Nitrogen, and most likely in SF₆. Further, subtle refinement in manufacturing or design should be able to improve the performance significantly, perhaps approaching the higher levels predicted by the arbitrary approximate analysis.

VI. ASSIGN VOLTAGE LEVELS TO 3" AND 6" SIZES (TASK 5)

Based on the results of Task 4, and using the stress levels of Table I, the commercial grade of 3" Spir-O-Line should qualify for service at 69 kV with a 350 kV BIL (which is controlling) at an absolute pressure of $4\frac{1}{3}$ atmospheres SF_6 . The "commercial" grade of 6" Spir-O-Line would likewise qualify for 138 kV service with a 650 kV BIL, at 4 atmospheres pressure of SF_6 . The breakdown-pressure characteristics for these sizes are shown on Graph 7.

If a 60% improvement could be effected, as implied by the estimated analysis of Task 1, the 3" would move to the 138 kV level (650) and the 6" would move to the 230 kV level (1050, not 900 BIL). On the basis of dielectric performance, the Spir-O-Line cable concept is definitely viable.

The design philosophy of Spir-O-Line as an RF cable, as well as for the geometry of the support tubes, uses an outer to inner conductor diameter ratio of e (2.718...). This ratio also minimizes the field strength at the inner conductor. The inner conductor of the 3" model is 1.1" dia., while that of the 6" model is 2.2". There is significant flexibility in the choice of conductor design.

An RF cable carries its current in the outer skin of its conductor. Thus, existing Spir-O-Line cables use copper-clad aluminum or a hollow copper tube as the outer conductor. For power frequency application, the design philosophy would change. Because the conductor system is fully supported, it can be both heavy and flexible, to a degree, as long as a reasonably smooth surface is maintained. Thus, a stranded copper conductor within an aluminum or copper tube is a feasible option. There should be no problem in providing sufficient current carrying capacity to make the above systems an interesting alternative.

VII. PRELIMINARY COMPARATIVE ECONOMIC ANALYSIS

The preliminary comparative economic analysis shows the 3" Spir-O-Line at 69 kV to be competitive with the conventional alternatives of self-contained oil-filled, high-pressure pipe-type and extruded dielectric cable in the 100-150 mva range and above on a materials-only basis. If the dielectric improvements outlined in the report could be achieved during a comprehensive R & D program, then the 3" Spir-O-Line would become a 138 kV system. This, coupled with a relatively low cost change to a crosslinked polyethylene insulator with a resulting 90°C conductor rating, would make it the lowest material cost alternative across the board.

Since the 3" and 6" Spir-O-Lines are flexible, they could be manufactured and shipped in the same lengths as conventional cable and therefore their installation costs would be comparable to oil-filled and extruded.

One predominant factor that has been ignored in this preliminary analysis is the cost of losses. This would further shift the analysis in favor of spir-O-Line and the advantage would increase with increasing mva levels.

Appendix I shows the analysis and various assumptions made. Ampacities have been calculated using standard techniques.

Tables IX and X show the Material Costs/Ampere delivered at 138 kV and 69 kV respectively for circuit lengths of 1,000, 5,000, 10,000 and 25,000 feet.

VIII. RECOMMENDATIONS FOR FUTURE WORK

The Spir-O-Line concept, with its highly efficient utilization of materials and a low cost, low energy manufacturing process, appears to have the potential to be economically attractive in the 69 kV to 230 kV range at conventional power levels and above.

The realization of the 138 kV economics appears feasible when one examines the published literature on stresses achievable in clean systems (i.e., manufactured clean) with high creepage insulators, at high pressures (mixed gases) and with coated electrodes.

It is recommended that a full-scale test program be undertaken to perform the following:

1. Maximize the dielectric design using full-scale 3" and 6" test cells.
2. Determine the thermal capability of the system.
3. Develop a commercially applicable stress control technique for splice and terminal application.
4. Demonstrate the resulting cable systems.

FIG. 1. SPIR-O-LINE GITL PROTOTYPE

FIG. 2. DIELECTRIC CONFIGURATION - 1/2" SPIR-O-LINE

FIG. 3. DIELECTRIC CONFIGURATION - 7/8" SPIR-O-LINE

FIG. 4. DIELECTRIC CONFIGURATION - 1-5/8" SPIR-O-LINE

FIG. 5. TERMINAL ARRANGEMENT - 1/2" SPIR-O-LINE

FIG. 6. TERMINAL ARRANGEMENT - 7/8" SPIR-O-LINE

FIG. 7. ALTERNATE TERMINAL ARRANGEMENT - 7/8" SPIR-O-LINE

FIG. 8. IMPULSE TERMINAL ARRANGEMENT - 7/8" SPIR-O-LINE

FIG. 9. TEST SETUP - GAS-FILLED SPIR-O-LINE

FIG. 10. TEST SETUP - OIL FILLED SPIR-O-LINE

FIG. II. 1/2" SPIR-O-LINE DISSECTION

FIG. 12 PUNCTURE OF BUTYL TAPE - TEST 19

FIG. 13 TEST 18 IMPULSE FAILURE - 1-5/8" SPIR-O-LINE

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GRAPH 1. COAXIAL ELECTRODE BREAKDOWN VOLTAGE

GRAPH 2. ESTIMATED PASCHEN BREAKDOWN VOLTAGE

GRAPH 3. BREAKDOWN DATA - 1/2" SPIR-O-LINE - N₂

GRAPH 4. BREAKDOWN DATA - 7/8" SPIR-O-LINE - N₂

GRAPH 5. BREAKDOWN DATA - 7/8" SPIR-O-LINE - SF₆

GRAPH 6. BREAKDOWN DATA - 1-5/8" SPIR-O-LINE - N₂

GRAPH 7. POTENTIAL BREAKDOWN - 3" AND 6" SPIR-O-LINE.

TABLE X

Circuit Material \$/Amp Delivered
69 kV

Cable Type	Circuit Length			
	@1,000 Ft.	@5,000 Ft.	@10,000 Ft.	@25,000 Ft.
L.P.O.F. at 85°C Cond.	\$ <u>36.40</u> ⁽¹⁾	\$ <u>145.18</u> ⁽¹⁾	\$ <u>287.84</u> ⁽¹⁾	\$ 718.48 ⁽²⁾
H.P.O.F. at 85°C Cond.	106.09 ⁽⁴⁾	196.39 ⁽²⁾	306.12 ⁽²⁾	<u>675.08</u> ⁽¹⁾
Extruded Diel. at 90°C Cond.	45.25 ⁽²⁾	215.40 ⁽⁴⁾	426.38 ⁽⁴⁾	1093.52 ⁽⁴⁾
Spir-O-Line at 75°C Cond.	48.80 ⁽³⁾	205.84 ⁽³⁾	397.26 ⁽³⁾	973.38 ⁽³⁾
Spir-O-Line at 90°C Cond.	42.46	179.08	345.62	846.84

APPENDIX I

Comparative Economic Analysis, Based on Material Costs Only, Of 3" Spir-O-Line Vs Conventional Systems

I. COMPARATIVE SYSTEM DESCRIPTIONS

A. L.P.O.F.

138 kV - 1000 kcmil copper, .505" impregnated paper insulation, lead sheath.

69 kV - 1000 kcmil copper, .285" impregnated paper insulation, lead sheath.

B. H.P.O.F.

138 kV - 1000 kcmil copper, .505" impregnated paper insulation, 6-5/8" steel pipe.

69 kV - 1000 kcmil copper, .285" impregnated paper insulation, 5-9/16" steel pipe.

C. Extruded Dielectric

138 kV - 1000 kcmil copper, .925" XLP insulation, .325" jacket.

69 kV - 1000 kcmil copper, .650" XLP insulation, .325" jacket.

D. Spir-O-Line

138 kV - 1000 kcmil copper, 3" O.D. outer copper corrugated sheath, 60 mil jacket.

69 kV - 1000 kcmil copper, 3" O.D. outer copper corrugated sheath, 60 mil jacket.

Systems A, B, C - Single conductor, open circuit sheaths, 7.5" horizontal spacing, 36" depth of burial.

System D - 3-1/C in steel pipe, short circuit sheaths, 36" depth of burial.

II. AMPACITY DATA ASSUMPTIONS

Based on: Ambient Earth = 20°C

Depth of Burial = 36"

Horizontal Spacing = 7.5" for LPOF, Extruded
and Spir-O-Line.

Earth Effective Resistivity = 90°C-cm/watt

Load Factor = 75%

Single Circuit

Max. Conductor Temperatures:

- a) LPOF - 85°C, open circuited sheaths
- b) HPOF - 85°C, short circuited sheaths
- c) Extruded - 90°C, open circuited sheaths
- d) Spir-O-Line - 75°C, open circuited sheaths

Calculated Ratings

	<u>138 kV</u>	<u>69 kV</u>
a) LPOF	1003 Amps @ 85°C Cond.	1102 Amps @ 85°C
b) HPOF	841 Amps @ 85°C Cond.	855 Amps @ 85°C
c) Extruded	836 Amps @ 90°C Cond.	920 Amps @ 90°C
d) Spir-O-Line	917 Amps @ 75°C Cond.	917 Amps @ 75°C

III. ESTIMATED SYSTEM MATERIAL COSTS @ 138 KV

A. L.P.O.F.

Cable = \$30/ckt. ft.

Joints & Manhole = \$1,000 x 3 $\emptyset$ + \$3000/manhole = \$6,000 Ea.
(3 per mile).

X Bonding or Insulators = \$1,200 ea. joint

Reservoirs = \$5,000/location (assume 2 per mile).

Terminals = \$7,500 Ea. (2 per ckt.)

B. H.P.O.F. (Pipe Cable)

Cable = \$5.50/cable ft. x 3 = \$16.50/ckt. ft.

Coated Pipe = \$6.00/ckt. ft.

Oil (1 gal./ft.) = \$2.00/ckt. ft.

Cable, Oil & Pipe = \$24.50/ckt. ft.

Joints & Manhole = \$5,000 Ea. (2 per mile).

Terminations = \$10,000 Ea. (2 per ckt.)

Pumping Plant = \$60,000 Ea. (1 per ckt.)

C. Extruded Dielectric

Cable = \$12.75/cable ft. x 3 = \$38.25/ckt. ft.

Joints & Manhole = \$1,200 + \$3,000 = \$4,200 Ea. (4 per mile)

X Bonding or Insulators - \$1,000 ea. Joint

Terminals = \$5,000 Ea. (2 per ckt.)

D. Spir-O-Line

Cable = \$10.25/cable ft. x 3 = \$30.75/ckt. ft.

Joints & Manhole = \$1,200 + \$3,000 = \$4,200 Ea. (4 per mile).

X Bonding or Insulators = \$1,000 ea. Joint.

Terminals = \$6,000 Ea. (2 per ckt.)

Gas Supply Reg. = \$1,000 ea., ea. end

IV. ESTIMATED SYSTEM MATERIAL COSTS @ 69 KV

A. L.P.O.F.

Cable = \$24/ckt. ft.

Joints & Manhole = $\$500 \times 3 \emptyset + \$3,000/\text{manhole} = \$4,500$
(3 per mile).

X Bonding & Insulators = \$1,200 ea. joint.

Reservoirs = \$5,000/location (assume 2 per mile).

Terminals = \$5,500 ea. (2 per ckt.)

B. H.P.O.F. (Pipe Cable)

Cable = \$4.40/cable ft. x 3 = \$13.20/ckt. ft.

Coated Pipe = \$5.00/ckt. ft.

Oil (.65 gal./ft.) = \$1.30/ckt. ft.

Cable, Oil, Pipe = \$19.50/ckt. ft.

Joints & Manhole = \$4,000 ea. (2 per mile)

Terminations = \$7,000 ea. (2 per ckt.)

Pumping Plant = \$60,000 ea. (1 per ckt.)

C. Extruded Dielectric

Cable = \$10.20/cable ft. x 3 = \$30.60/ckt. ft.

Joints & Manhole = \$4,200 ea. (4 per mile)

X Bonding or Insulators = \$1,000 ea. Joint.

Terminals = \$4,000 Ea. (2 per ckt.)

C. Spir-O-Line

Cable = \$10.25/cable ft. x 3 = \$30.75/ckt. ft.

Joints & Manhole = \$1,200 + \$3,000 = \$4,200 Ea. (4 per mile).

X Bonding or Insulators = \$1,000 ea. Joint

Terminals = \$6,000 Ea. (2 per ckt.)

Gas Supply Reg. = \$1,000 ea., ea. end.

NOTES:

1. Cable Prices on LPOF, HPOF Pipe and Extruded (XLP) from U. S. domestic cable manufacturers, 11/78.
2. 3" Spir-O-Line estimated by Prodelin, Inc., 11/78.
3. Cable Accessory Prices estimated by U.S.I., based on recent quotation history, i.e., 1978.

TABLE V

Estimated Cost, Materials Only
For 4 Circuit Lengths
138 kV

A.	<u>L.P.O.F.</u>	System Length			
		<u>1,000 Ft.</u>	<u>5,000 Ft.</u>	<u>10,000 Ft.</u>	<u>25,000 Ft.</u>
	Cable	\$ 30,000	\$ 150,000	\$ 300,000	\$ 750,000
	Joints	-	18,000	36,000	90,000
	X Bond.	-	3,600	12,000	18,000
	Reservoirs	5,000	10,000	20,000	50,000
	Termin.	<u>15,000</u>	<u>15,000</u>	<u>15,000</u>	<u>15,000</u>
	TOTAL	\$ 50,000	\$ 196,600	\$ 383,000	\$ 923,000
B.	<u>H.P.O.F. (Pipe)</u>				
	Cable, Oil, Pipe	\$ 24,500	\$ 122,500	\$ 245,000	\$ 612,500
	Joints	5,000	10,000	20,000	50,000
	Termin.	20,000	20,000	20,000	20,000
	Pumping Plant	<u>60,000</u>	<u>60,000</u>	<u>60,000</u>	<u>60,000</u>
	TOTAL	\$ 109,500	\$ 212,500	\$ 345,000	\$ 742,500
C.	<u>Extruded Dielectric</u>				
	Cable	\$ 38,250	\$ 191,250	\$ 382,500	\$ 956,250
	Joints	-	16,800	33,600	84,000
	X Bond. & Ins.	-	4,000	8,000	20,000
	Termin.	<u>10,000</u>	<u>10,000</u>	<u>10,000</u>	<u>10,000</u>
	TOTAL	\$ 48,250	\$ 222,050	\$ 434,100	\$1,070,250
D.	<u>Spir-O-Line</u>				
	Cable	\$ 30,750	\$ 153,750	\$ 307,500	\$ 768,750
	Joints	-	16,800	33,600	84,000
	X Bond.	-	4,000	8,000	20,000
	Termin.	12,000	12,000	12,000	12,000
	Gas Supply	<u>2,000</u>	<u>2,000</u>	<u>2,000</u>	<u>2,000</u>
	TOTAL	\$ 44,750	\$ 188,550	\$ 363,100	\$ 886,750

TABLE VI

Estimated Cost, Materials Only,
For 4 Circuit Lengths
69 kV

A.	<u>L.P.O.F.</u>	System Length			
		<u>1,000 Ft.</u>	<u>5,000 Ft.</u>	<u>10,000 Ft.</u>	<u>25,000 Ft.</u>
	Cable	\$ 24,000	\$ 120,000	\$ 240,000	\$ 600,000
	Joints	-	13,500	27,000	67,500
	X Bond.	-	3,600	12,000	18,000
	Reservoirs	5,000	10,000	20,000	50,000
	Termin.	<u>11,000</u>	<u>11,000</u>	<u>11,000</u>	<u>11,000</u>
	TOTAL	\$ 40,000	\$ 158,100	\$ 310,000	\$ 746,500
B.	<u>H.P.O.F. (Pipe)</u>				
	Cable, Oil, Pipe	\$ 19,500	\$ 97,500	\$ 195,000	\$ 487,500
	Joints	4,000	8,000	16,000	40,000
	Termin.	14,000	14,000	14,000	14,000
	Pumping Plant	<u>60,000</u>	<u>60,000</u>	<u>60,000</u>	<u>60,000</u>
	TOTAL	\$ 97,500	\$ 179,500	\$ 285,000	\$ 601,500
C.	<u>Extruded Dielectric</u>				
	Cable	\$ 30,600	\$ 153,000	\$ 306,000	\$ 765,000
	Joints	-	16,800	33,600	84,000
	X Bond. & Ins.	-	4,000	8,000	20,000
	Termin.	<u>8,000</u>	<u>8,000</u>	<u>8,000</u>	<u>8,000</u>
	TOTAL	\$ 38,600	\$ 181,800	\$ 355,600	\$ 877,000
D.	<u>Spir-O-Line</u>				
	Cable	\$ 30,750	\$ 153,750	\$ 307,500	\$ 768,750
	Joints	-	16,800	33,600	84,000
	X Bond.	-	4,000	8,000	20,000
	Termin.	12,000	12,000	12,000	12,000
	Gas Supply	<u>2,000</u>	<u>2,000</u>	<u>2,000</u>	<u>2,000</u>
	TOTAL	\$ 44,750	\$ 188,550	\$ 363,100	\$ 886,750

TABLE VII

Ampacities Corrected for Charging Current
138 kV

$$I_c = \frac{2 \pi (60) (7.354) \left(\frac{138}{\sqrt{3}}\right) \times 10^{-6} \times \text{SIC}}{\text{LOG}_{10} \left(\frac{D}{d}\right)} \quad (\text{amps/1000 ft.})$$

$$I_c = \frac{.2209 \times \text{SIC}}{\text{LOG}_{10} \left(\frac{D}{d}\right)} \quad \text{Amperes per 1,000 ft. @ 138 kV}$$

Cable Type	Ins. Wall	SIC	D	d	Charging Current, Amps/1000 ft.
L.P.O.F.	.505"	3.6	2.318	1.308	3.2
H.P.O.F.	.505"	3.6	2.07	1.06	2.736
Extruded Dielectric	.925"	2.3	2.91	1.06	1.158
Spir-O-Line	N/A	1.0	3.0	1.1036	.509

So effective receiving end current = Ampacity-Charging Current.

Cable Type	Circuit Length			
	1,000 Ft.	5,000 Ft.	10,000 Ft.	25,000 Ft.
L.P.O.F.	1000	987	971	923
H.P.O.F.	838	824	811	770
Extruded Dielectric	835	832	826	809
Spir-O-Line	916	914.5	912	904

TABLE VIII

Ampacities Corrected for Charging Current
69 kV

$$I_c = \frac{2\pi (60) (7.354) \left(\frac{69}{\sqrt{3}}\right) \times 10^{-6} \times SIC}{\log_{10} \left(\frac{D}{d}\right)} \quad (\text{amps}/1000, \text{ft.})$$

$$I_c = \frac{.11045 \times SIC}{\log_{10} \left(\frac{D}{d}\right)} \quad \text{Amperes per 1,000 ft. @ 69 kV}$$

Cable Type	Ins. Wall	SIC	D	d	Charging Current, Amps/1000 Ft.
L.P.O.F.	.285	3.6	1.878	1.308	2.53
H.P.O.F.	.285	3.6	1.63	1.06	2.128
Extruded Dielectric	.650	2.3	2.36	1.06	1.144
Spir-O-Line	N/A	1.0	3.0	1.1036	.255

So effective receiving end current = Ampacity-Charging Current.

Cable Type	Circuit Length			
	1000 Ft.	5,000 Ft.	10,000 Ft.	25,000 Ft.
L.P.O.F.	1099	1089	1077	1039
H.P.O.F.	853	844	834	802
Extruded Dielectric	919	914	931	891
Spir-O-Line	917	916	914	911

TABLE IX

Circuit Material \$/Amp Delivered
138 kV

Cable Type	Circuit Length			
	@1,000 Ft.	@5,000 Ft.	@10,000 Ft.	@25,000 Ft.
L.P.O.F. at 85°C Cond.	\$ 50.00 ⁽²⁾	<u>\$199.18</u> ⁽¹⁾	<u>\$394.44</u> ⁽¹⁾	\$1000.00 ⁽³⁾
H.P.O.F. at 85°C Cond.	130.67 ⁽⁴⁾	257.89 ⁽³⁾	425.40 ⁽³⁾	<u>964.29</u> ⁽¹⁾
Extruded Diel. at 90°C Cond.	57.78 ⁽³⁾	266.89 ⁽⁴⁾	525.54 ⁽⁴⁾	1322.93 ⁽⁴⁾
Spir-O-Line at 75°C Cond.	<u>48.85</u> ⁽¹⁾	206.18 ⁽²⁾	398.14 ⁽²⁾	980.92 ⁽²⁾
Spir-O-Line at 90°C Cond.	42.50	179.37	346.38	853.40

EXECUTIVE SUMMARY

Preliminary studies were made on a unique dielectric system for both flexible and rigid power cable applications. Known as Spir-O-Line, it was developed and is manufactured by Prodelin, Inc. as a high power radio frequency transmission system, with a service record of several decades. The cable consists of a central conductor continuously supported by six high density polyethylene tubes inside a metal sheath, which operates as a GITL with either Nitrogen or SF_6 as the filling medium.

A rough analysis of the dielectric geometry concluded that its breakdown strength might be improved over that of the open coaxial conductor configuration.

A series of breakdown tests was performed on the smaller range of commercially available sizes. The results confirmed the expected behavior patterns, but did not fully explore the upper units of performance due to occasional tube separations in the samples tested.

The potential voltage ratings of the larger available sizes were estimated and found to be from 69 kV to 138 kV for a 3-inch O.D. size, and from 138 kV to 230 kV for a 6-inch O.D. size. There is considerable flexibility in the design of the conductor due to the continuous support of the dielectric tubes. In addition, the system enjoys efficient utilization of material and a low cost, low energy manufacturing process. The system economics appear competitive with conventional systems at conventional power ratings. For these reasons, a full-scale development and demonstration project is strongly recommended.

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