MASTER

PERFORMANCE OF A TECHNICAL AND
ECONOMICAL FEASIBILITY STUDY OF AN
HVDC COMPRESSED GAS INSULATED
TRANSMISSION LINE

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PREPARED FOR THE DEPARTMENT OF ENERGY
UNDER CONTRACT DE-AC01-79ET 29355

FOURTH PROGRESS REPORT
FOR PERIOD 1980 JULY 01
1980 NOVEMBER 30

1980 DECEMBER 15

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Executive Summary

A. Progress Made During This Report Period

1. A new test setup is completed. This includes
 - Final test bushing with own free-standing base.
 - Straight-section of model cable with asymmetrical corrugation.
 - Additional bulge (i.e. with bulges at both ends of the straight section).
 - Additional trap (i.e. trap in each bulge).
 - Particle feeder to feed controlled particles into model cable under pressure.
2. An assembly jig is designed and fabricated. Model cable up to 20-ft length can be assembled complete outside the test tank.
3. Components to extend the test tank to accommodate a 20-ft model cable have been obtained.
4. The report has been drafted on the effect of material selection as well as processing into insulators on the long-term dielectric performance of the insulator. It is being reviewed.
5. The vertical leaf expansion joint design was improved by replacing the Alcuplate copper-to-aluminum transition piece with nickel plating on the aluminum parts.
6. The joint was fatigue tested at an amplitude equal to the expansion resulting from the full design temperature excursion (-40°C. to +120°C.) for 34000 cycles. This represents almost 2½ cycles each day for the 40 year design life of the line.
7. Electrical tests of the joint are in progress.

B. Work Planned for the Next Quarter

1. Start test to study HVDC commissioning procedure for the protection of barrier insulator.
2. Obtain fully data on the dielectric strength of gas with "as-cast" conductor with an enclosure (having asymmetrical corrugation).
3. Complete testing of the conductor expansion joint.
4. Establish the design and specifications for the conductor and enclosure.
5. Complete the design of the enclosure joint.

Task 1

Analysis, the details of which were given in the last quarterly report, led to the following conclusions:

- a) Each arrester should be made of two columns in parallel. Also, 15% of each column should be shunted by a gap which sparks over when the arrester current becomes excessive.
- b) Arresters should be installed at both ends of the cable and also at the first tower of the DC overhead line.
- c) The first mile of the overhead line should be well shielded and the footing resistance kept low so that shielding failures and backflashovers are prevented for this mile of line.
- d) Under the above conditions, the following protective levels are feasible.

BIL 1300 kV (safety margin 18%)

BSIL 1050 kV (" " 19%)

Further reduction of the protective levels is feasible with projected improvement of arrester characteristics and with more elaborate protective scheme. No such reduction is sought at the present stage of the program.

Task 2

Introduction

Effort was concentrated in acquiring and in installing the final test bushing. In anticipation of a later longer model cable, the weight of which could not be man-handled, an assembly system was designed, fabricated and partially installed.

New Features of the Test Setup

Fig. 2-1 shows the external view of the final test bushing. The grading arrangement may need improvement. The bushing stands on its own base. The base is at one end of the test tank.

In the test tank, a rail is installed (Fig. 2-2). The model cable is assembled on a mobile platform, sitting on an extension of the rail outside the test tank (Fig. 2-3). The assembled model cable is pushed into the test tank (Fig. 2-4) and is then connected to the bushing (Fig. 2-5).

The tank can be joined to another tank through a joint-unit (Fig. 2-6), more than doubling its length.

A new corrugated straight section is used. This is made of aluminum and spun in shape (Fig. 2-7). A bulge is joined to each end of the straight section. One houses the insulators and the simulated expansion joint (Fig. 2-8), the other has no insulator to offer a better view into the straight section (Fig. 2-9). Both bulges contain a trap (#3).

It is desirable to feed controlled particles into the model cable during tests. The controlled particles are placed above a ball valve, the bottom of which is connected to a pipe leading into the model cable. This pipe can be seen in Figs. 2, 4 and 9. The top of the ball valve, after the controlled particles have been in place, is evacuated and the pressurized with SF₆ at a pressure just higher than the pressure inside the test tank. The particles are then dropped by opening the valves. The technique is workable but not completely reliable. Improvement was made by adding an SF₆ reservoir to the top of the ball valve. Additional revisions will be required to prevent an occasional blockage of the pipe.

Electrical Tests

The automatic control system was extended. The sequence of events is now as follows. The voltage can be raised at a preset rate to a preset value and is then held for a preset duration before it is

lowered to zero. The high-speed movie camera can be started at a preset time relative to the start of the voltage rise. After a preset interval, an intense flashlight is fired and simultaneously a marker is made on the time-record of the voltage and the current. In this way, the frames of the movie can be related to the voltage and to the current.

Electrical tests will soon be resumed, now that the new setup and the new control system have been completed.

Fig. 2-1 Test Bushing

Fig. 2-2 Rail inside Test Tank

Fig. 2-3 Model Cable being Assembled
on Mobile Platform

Fig. 2-4 Model Cable inside Test Tank

Fig. 2-5 Model Cable inside Test Tank

Fig. 2-6 Joint-Unit for Extension
of Test Tank

Fig. 2-7 Corrugated Straight Section

Fig. 2-8 Bulge Housing Insulators
Showing the Trap

Fig. 2-9 Bulge Without Insulator
Showing the Trap

Task 4.1 Enclosure

The following pages contain the confirmation of a preliminary cost estimate for making asymmetric corrugated enclosure sections. Only new tooling would be required at a cost of \$80,000. No additional premium over the cost of regular corrugation would be charged.

Task 4.2 Conductor

No additional conductor work was required during this reporting period.

PROPOSAL

PACIFIC ROLLER DIE CO., INC.
POST OFFICE BOX 3398
HAYWARD, CALIFORNIA 94540

PLANT: 415/782-7242
TWX 910-383-0191
1321 WEST WINTON AVENUE
HAYWARD, CALIFORNIA

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1980 JUL 14

July 8, 1980

METAL WORKING DIV.

Aluminum Company of America
Alcoa Technical Center
Alcoa Center, Pennsylvania 15069

Attention: Mr. R. P. Evert, Engineer
Metal Working Division

Dear Mr. Evert:

In response to your June 30 letter to Mr. R. F. Miller and in accordance with our July 8 telephone conversation, we are pleased to confirm our budget price of \$80,000.00 to furnish one twenty foot (20') length of 20" O.D. welded seam spiral corrugated pipe with corrugation configuration as illustrated in your 6/17/80 C. H. Schillinger Co. drawing (copy attached).

Price of additional footage: to be negotiated

Material: 16 gauge mild steel
post galvanized, if required

Weld: butt weld on outside crest of corrugation

Diameter tolerance: $\pm 1\%$

Shipment: approximately four (4) months after receipt of firm purchase order and down payment

Terms: 25% down with purchase order
50% sixty (60) days after date of purchase order
20% at time of shipment
5% forty-five (45) days after date of shipment

In explanation of the above quoted price, we wish to point out the principal cost is in engineering, design and fabrication of tooling for the non-standard corrugation section for a complete spiral corrugated pipe mill.

8010593

PROPOSAL

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Aluminum Company of America

- 2 -

July 8, 1980

Hopefully, this gives you the desired information for consideration at this time.

We look forward to your further comments and/or questions.

Very truly yours,

PACIFIC ROLLER DIE COMPANY, INC.

A handwritten signature in cursive script, reading 'Norris H. Wiggins', written in dark ink.

Norris H. Wiggins

NHW:k

Enclosure

0000108

-15-

MATERIAL: $\frac{1}{8}$ ALUM.
16 GAUGE STEEL

SCALE:	APPROVED BY:	DRAWN BY
DATE: 6-17-80		REVISED
C.H. SCHILLINGER CO.		
		DRAWING NUMBER

0000108

4.3 EXPANSION JOINT

4.3.1 General

A vertical leaf expansion joint was designed and fabricated for testing (see Fig. 4.3.1). Although designed for an 18 meter (60 ft.) conductor length (6.86 centimeters or 2.7 in. total movement) it could be used with conductor lengths down to 12 meters (40 ft.) (4.57 centimeters or 1.8 in. total movement). These ratings apply to the temperature range of -40°C . to 120°C .

The joint is designed to accommodate a complete temperature excursion every day of its 40 year life, giving a 15,000 cycle life. These temperature extremes will probably not occur in an actual line, but it is evident that substantial cyclical loading will occur in an HVDC link when used for handling peak power loads.

4.3.2 Soldering

The prototype expansion joint was soldered at the Alcoa Technical Center. The soldering method was as follows:

1. All copper and aluminum parts were vapor degreased.
2. The aluminum parts were cleaned in a caustic solution.
3. The leaf and leaf spacers were assembled into bundles.
The ends of the bundles were milled so that the solder surfaces would be flat.
4. The leaf bundles were placed into a furnace and preheated to 450°F . before fluxing and tinning. Nokorode soldering paste and 50/50 tin lead solder were used for tinning the milled surfaces of the leaf bundles.
5. The Alcuplate transition pieces were tinned on both sides with 50/50 tin lead solder.
6. The joint body center piece (see Fig. 4.3.2) and the aluminum subassembly of end conductor, end plate, and joint body were preheated to 500°F . and was tinned. Alcoa #69 flux and 50/50 tin lead solder were used. After cooling the residue from the flux was washed off in water and the parts were fully dried before proceeding.
7. The leaf bundles, transition pieces, and the joint body center piece were soldered together by preheating these pieces in the furnace to 475°F . and then setting them in

a fixture and torch heating them until the solder reflowed. To insure the best fill, additional flux and solder were added to the accessible solder surfaces.

8. The aluminum subassemblies were then preheated in the furnace and soldered to the subassembly of the joint body center piece and leaf bundle. The method described in 7. was employed to solder these subassemblies together.

4.3.3 Fatigue Testing Apparatus Description

Ref: Figure 4.3.3

During the design of the vertical leaf expansion joint a fatigue testing apparatus was also designed and built. The apparatus was constructed to accommodate any expansion joint that fell within certain dimensional limits.

A rigid structure was needed so that there would be no relative movement between the expansion joint and the drive mechanism. A concrete pier with cast iron bed plates bolted to it was used for the base. A single structure was built for the motor, gear reducer, and linear bearings. A bracket was constructed to hold the center mount of the joint in place so that one half of the joint is tested at a time.

The drive mechanism consists of a 1/6 horsepower motor connected to a gear reducer with a 900 to 1 ratio. Output torque of the reducer is 1784 inch-lbs. An adjustable eccentric is at the end of the output shaft so that total displacements from 0 to 2 inches are possible. A rod with spherical rod end bearings on each end is the link between the eccentric and the push rod. The push rod moves in the linear bearings imparting sinusoidal motion to the expansion joint.

The only parts that were purchased or fabricated for this apparatus were the framework, linear bearings, spherical rod ends, eccentric and rods. The other materials were present in the laboratory and are the property of Alcoa.

Fatigue Apparatus Set-Up: The following set-up was used:

1. Loosely set joint and bracket on the bed plate.
2. Connect push rod to the end of joint.
3. Orientate spherical rod ends and eccentric to their natural positions.

4. Connect link between push rod and eccentric (at this time the joint will locate itself on the bed plate).
5. Tighten down the expansion joint.
6. Jog machine to maximum expansion and contraction position and measure the displacements, and adjust if necessary.
7. When the desired displacement is measured the joint is ready for continuous cycling.

As the joint is cycled, the displacement is checked periodically.

4.3.4 Mechanical Testing

Upon initial fatigue testing (Test 1), the solder joint failed between the aluminum side of the Alcuplate and the joint body around 500 cycles. Examination of the interface showed that very little of the aluminum was actually wet by the solder. This was compounded by the fact that rocking of the center support caused a bending moment across the joint, increasing stresses significantly. This bending would not be present in the field, where a nearly equal force would exist from the other half of the joint.

The joining problem arose because the wetting surface and adjoining mass is much larger than that for parts usually soldered. This can be solved by reducing the soldering area by design or by increasing the wetting of the surfaces by nickel plating. The latter was chosen, and is described in the following section.

The rocking action of the support was corrected by providing two support points a distance apart, instead of a single support. In the case where a slight bending moment is present (due to misalignment or unequal heating) a tearing action must be dealt with.

The tearing action can be remedied by either adding spacers outboard from the leaves to distribute the tearing force or by using a substantially sliffer bundle, which will also serve the function of the joint body. Although it is not clear if this tearing action needs attention if the solder joint is adequate, or if little bending is present; the above solutions are being investigated.

In order to test the fatigue resistance of the flexing members (the copper leaves) a leaf bundle was fastened mechanically and adhesively bonded to the joint body. The leaves were subjected (Test 2) to a

displacement of 2.29 centimeters (.88 in.) for 15,000 cycles without any detrimental results. Figure 4.3.4 shows the expansion joint in its fully expanded and contracted positions. It is clear that plenty of space is maintained between the adjacent leaves, so that there is no chance of contact and particle generation.

It has been assumed that exposed mechanical fasteners should not be used, because of the possibility of particle generation. The next step involved trying to improve the solder joint so that these fasteners would not be needed.

To increase the solder adhesion to the aluminum, the joint bodies were nickel plated using a stannate subplating. The nickel plating both increases the wetting ability of the joint body and eliminates the need for the Alcuplate transition pieces. A plating thickness of 0.5 to 1.0 mils was specified. Fig. 4.3.6 shows the difference in the wetting ability of an aluminum surface and a nickel-plated surface. As can be seen the wetted aluminum surface is uneven in its solder layer while the nickel-plated piece has a very smooth and thin solder layer.

The soldering procedure was the same as described in 4.3.2 except that the Alcuplate was not used. When removing the joint from the furnace following the final heating, it was noticed that the leaves had taken a set. Further mechanical testing showed that substantial annealing had taken place. See Table 4.3.1 for mechanical properties.

The solder joint had little clamping force when hot, so that the parts were not drawn together as expected. The bundle was held about 1/8" off the joint body surface, which permitted much of the solder to run out.

Despite these deficiencies, a fatigue test was run (Test 3). The result was surprisingly good, with the joint surviving 34,800 cycles, or more than double the required 15,000 cycles without any detectable loosening, cracking or other ill effects. The test was stopped after 290 hours so that other tests could begin. Given these results, we feel comfortable with the design, especially if we can obtain better clamping and less annealing, which will be dealt with in following sections.

4.3.5 Electrical Testing

The apparatus for electrical testing of the expansion joint is pictured in Figure 4.3.5. Prior to mechanical testing the joint was subjected to an ac current of 7000 amps in free air and temperatures of various parts of the joint were measured. This thermal mapping procedure was used to locate the hottest points on the joint. These points will be monitored during later heat rise tests using an SF₆ atmosphere, an enclosure and a joint shield.

Results are given in Fig. 4.3.7. For a maximum conductor temperature of 205°F., the hottest part of the joint was 244°F. at the center of the top joint body. Leaf temperatures averaged 231°F. The temperature rises are very reasonable considering the joint conductance is only 30% of the conductor conductance and the test current was 60 Hz. ac. When the SF₆ tests are run, we plan to run several current loads to establish a load-temperature plot.

DC resistance measurements across the expansion joint were also recorded. The dc resistance of the expansion joint was in excess of that of a continuous solid conductor (5.5" dia.) by an amount equivalent to 9 feet of the conductor (see Appendix 4.1). Based on the actual length of the current path and the design target of 30% conductance, most of this amount of resistance can be attributed to materials. No significant additional resistance was caused by the electrical interfaces. Thus, the joint appears to be electrically sound. The reasonable temperature rises under extreme current loading and good electrical connections within the joint enables us to adjust the design parameters per economic criteria. No compromises are needed to avoid overheating. Current cycle tests will be started after the completion of the fatigue testing.

4.3.6 Design Refinements of the Vertical Leaf Expansion Joint

The construction of the pictured vertical leaf expansion joint was extremely beneficial to the project. Difficulties encountered with material and processes have led to a number of design refinements that should improve the joint's reliability and performance, in addition to lowering its cost.

A listing of the improvement areas to be addressed in a revised design are given.

Machining

1. Tolerances of the leaves and spacers must insure that the leaf bundles would have a flat surface for soldering. In the prototype case, this led to the milling of the leaf bundle after its assembly. Production tooling might not require milling.
2. The surface of the extruded joint body (where it meets the leaf bundles) also had to be milled flat to obtain a tight fit with the thinnest possible solder layer. Again, this may not be necessary in production. It has been found in previous soldering applications that the most effective solder layer is .005 to .010 inch thick.

Assembly

1. Soldering done to aluminum (or any other material) of large cross-sectional area is difficult and should be avoided if possible. Also, it is advantageous to heat the aluminum parts prior to soldering, which becomes an added expense to joint fabrication.
2. When joining the leaf bundles and joint body, pressure must be maintained to force them together when the solder reflows.
3. The assembly fixtures or design should provide for locating and maintaining the respective positions of the parts during the reflow of the solder.

Materials

1. It is difficult to "wet" large aluminum surfaces without nickel plating.
2. Work hardened OFHC copper, because of its low annealing temperature, has given us difficulty with a preferred soldering process. During our third joining procedure we did in fact partially anneal the copper.

Because fatigue and thermal testing gave good results, we can turn now to refining the design of the vertical leaf joint. An improved design is shown in Drawing B-027809-DM (Fig. 4.3.8). This drawing is a sketch of our best current approach.

Discussion of Refinements

The following discussion of the refinements will illustrate the advantages of the new design in the areas of machining, assembly, materials and processes.

Machining

1. Since the surfaces between the leaf bundles and the joint body have been omitted the tolerances on the leaves and the spacers may be increased without detrimental effects.
2. Since the joint body has been omitted one less piece has to be fabricated.

Assembly

1. Special clamps to clamp the tinned surfaces during the solder reflowing process may not be necessary.
2. All parts locate themselves at assembly and there are no subassemblies that will have to be handled.

Materials

1. By changing the copper alloy from OFHC to a silver bearing copper, the annealing temperature of the copper leaves will increase by approximately 150°F. which will leave us with an extra margin of safety when soldering.
2. The interface area between aluminum and copper is reduced, permitting higher compressive stresses and thus more metallic contact.

Selection of Materials

To further refine the design and testing procedure other parameters must be considered. Among these are the influence of cold working on conductivity, the softening tendency of the leaves with high temperature, effects of silver as an alloying element, and creep properties. Figure 4.3.8 and Table 4.3.2 show the effects of silver addition. Further information is being gathered.

FIGURE 4.3.1

FIGURE NO. 4.3.2

FIGURE NO. 4.3.3

Displacements Are For a 40' Joint

FIGURE NO. 4.3.4

EXPANSION JOINT IN HEAT CYCLE AND THERMAL MAPPING APPARATUS

FIGURE 4.3.5

Tinned Nickel Plated Surface

Tinned Aluminum Surface

FIGURE NO. 4.3.7

TEMPERATURE MAP OF VERTICAL LEAF EXPANSION JOINT

All Temperatures in °F

7000 Amps at 60 Cycles

ITEM	DESCRIPTION	MATERIAL	DETAIL
1	END CONNECTION	ALUM.	
2	END SPIDER	CU	
3	LEAF SPIDER	CU	
4	CENTER SPIDER	CU	
5	TENSION FILMERS	S. STEEL	
6	VERTICAL LEAF	CU

FIGURE 4.3.8
DWG B-027809-DM

OFHC COPPER TENSILE TESTS

As Received Material

<u>Sample No.</u>	<u>Area</u>	<u>Lbs. Breaking Force</u>	<u>Ksi Ultimate Strength</u>
1	.0295	1505	51.1
2	.0295	1515	51.3

Exposed to Preferred Soldering Process

3	.0301	1055	35.0
4	.0301	1055	35.0

TABLE 4.3.1

Effect of Silver on Electrical Conductivity of OF Copper

Copper	Cold Work %	Conductivity, % IACS		
		68 F (20 C)	265 F (130 C)	340 F (170 C)
OFHC	0	102.3	70.9	63.9
	10	101.5	70.4	63.2
	25	100.1*	71.1	64.5
	50	100.5	70.1	63.1
OF + 21 oz/ton Silver (0.072% silver)	0	102.0	71.0	63.9
	10	101.6	70.7	63.6
	25	101.1	70.3	63.2
	50	97.8	69.0	62.4

* Doubtful (Ed.)

Time Required for 50% Softening at 300 F (150 C) and Effect of Degree of Cold Work

Cold Work %	Electrolytic Tough Pitch	OFHC	OF + 15 oz/ton Silver
90	1 day	2 days	1 year
50	1 week	2 months	10 years
30	1 month	1 year	30 years
20	3 months	8 years	100 years
10	1 year	75 years	
5	3 years		

Effect of Silver on the Creep of OF Copper

Material	Creep Stress*				Tensile Strength		Elongation %
	0.001%/hr		0.01%/hr		ksi	kgf/mm ²	
OFHC	4.8	3.4	14.4	10.1	33.1	23.3	35
OF + 0.054% Ag	6.0	4.2	16.1	11.3	33.2	23.3	36
OF + 0.070% Ag	7.2	5.1	17.2	12.1	33.1	23.3	35

* Material cold-worked 5%; creep stress based on short duration tests at 570 F (300 C)

Source: OFHC Brand Copper; A Survey of Properties and Applications

TABLE 4.3.2

APPENDIX 4.1 - RESISTANCE CALCULATIONS

Temp. Coef. of res.

a) For 53% IACS (used for NPS tubular Al conductors)

$$\alpha t_1 = \frac{1}{\frac{1}{n(.00403)} + (t_1 - 20)} = .003501$$

b) For 59% IACS (typical for 1100)

$$\alpha t_1 = .003898$$

Resistance/in of 5" NPS ASA Schedule 80 Al pipe

$$2.515 \frac{\mu\Omega}{ft} = .20958 \mu\Omega/in.$$

$$\begin{aligned} R_{70} &= R_{t_1} [1 + \alpha t_1 (t - t_1)] \\ &= .20958 [1 + .003501 (70 - 20)] \\ &= .24636 \mu\Omega/in. \end{aligned}$$

Resistance/in of 5-1/2" dia. 1100-F at 59% IACS*

$$\rho_x = \frac{100}{59} (<.7879) = 1.1505 \mu\Omega/in.$$

$$R_{20} = \frac{\rho l}{A} = \frac{1.1505}{\frac{\pi}{4} (5.5)^2} = .04843 \mu\Omega/in. \text{ at } 20^\circ$$

Temp. correction

$$\begin{aligned} R_{70} &= .04843 [1 + .003898 (70 - 20)] \\ &= .05787 \mu\Omega/in. \text{ at } 70^\circ \end{aligned}$$

$$(I^2 R)_{Bar} = (I^2 R)_{tube}$$

$$I_{Bar} = \sqrt{\frac{(3280)^2 (.2464)}{.05787}} = 6768 \text{ A}$$

Resistance of 8" section of 5.5" 1100-F conductor

$$8(.04843) = .3874 \mu\Omega$$

Lead-in bus for heat run was 1.25"x12"x48"

* 1100-F was used for the prototype - 1350 (EC) will be used in production.

ARL for 5.5" conductor

$$5(5.5)(.04843) = 1.3318 \mu\Omega$$

$$K = [1 + .003898 (33.9 - 20)] = 1.0534$$

$$\frac{1}{K} = .9493$$

Test Results: Mean of $R_1 - R_3$ and $R_2 - R_3$

$$R_T = \frac{3.47 + 3.19}{2} = 3.33 \mu\Omega$$

$$\text{Over length } 5.75 + 9" = 14.75"$$

Equivalent conductor

$$R_e = 14.75 (.04843) = .714 \mu\Omega$$

$$R_T - R_e = 3.33 - .714 = 2.62 \mu\Omega$$

Length of equivalent conductor

$$L_e = \frac{2.62}{.04843} = 54" \text{ or } 4.5' \text{ each } 1/2 \text{ joint}$$

Therefore each joint adds the equiv. of 9' of conductor

Assuming the joint bodies and leaves have 30% of conductor

Conductance

$$R_{j1} = \frac{1}{.3} R_c = 3.33 R_c$$

Due to material resistance only

$$\begin{aligned} R_m &= .04843 [(1.5 + 5.75) + 3.33 (8.5) + 3.33 (9.44)] \\ &= 3.244 \mu\Omega \end{aligned}$$

Contact resistance

$$\begin{aligned} R_{con} &= R_T - R_m \\ &= 3.33 - 3.244 = .086 \mu\Omega \end{aligned}$$

(Rough est. - based on above assumption)

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DEC 18 1950