Progress Report

on

Mechanical Behavior of
Underground Laminar Pipe
Type Power Cable Systems

MASTER

submitted to

Division of Electric Energy Systems
U.S. Department of Energy

by

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Summary

This report updates our earlier progress report of December 1, 1978 and its addendum dated December 22, 1978. The December report was devoted to developing a theory describing the mechanical interaction between the conductor and the insulation; raw test data was included to indicate the progress made with various tests.

In the present report we show for the first time how this theory is to be combined with some rather sophisticated experimental procedures to describe the detailed internal mechanical response to applied load. It is shown, for example, how compressive and torsional forces give rise to changing tape tensions in the insulation making the gross moduli function of the composite properties of the insulation and the conductor. More importantly, as the Pirelli group has pointed out, overly large tape tensions obviate intratape slip and lead directly to cable failure. This implies that our results showing significant increase in tape tensions under TME can have an important impact in cable design.

We see this contract entering its final phase in which the "pieces" of experimental data and theory now available are to be combined and refined yielding a comprehensive model of the mechanical behavior of underground laminar pipe type power cable systems.

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Part 1
Introductory Material

PROGRESS REPORT

Introduction

During the period of time since the last progress report (December 1, 1978) the work of this project has gone from the developmental stage to a stage in which experimental procedures and theories have been tested and formalized. With the exception of the superposition of axial load and bending in the fatigue test, all development has been completed and we are now in the final (production) phase of this contract.

This report is presented in four parts, an introduction followed by three major sections, which are summarized below. Two of the major sections are recent RPI master's theses and are included here as such as a matter of convenience for the present. They will, of course, not persist in this form in the final report.

Briefly, this contract is concerned with modifications and extensions of the original Pirelli work in an attempt to model mathematically the TMB phenomenon. While the Pirelli people were originally concerned with cable manufacturing, we are concerned with modeling the in situ behavior. Because of the manner in which pipe type cable is constructed, compression and torsion -- and to a lesser extent flexure -- all give rise to changing tape tensions in the TMB environment. It is a primary goal of the work performed under the contract to establish the theory under which these effects occur and then to relate them to the formation of soft spots and TMB failure. Major portions of this theory and its experimental verification are included in this report.

Most of the experimental results included here come from tests on the experimental 550 kv Pirelli cable. This is largely due to the fact that during most of the duration of this contract it was the only cable available to us. However, we now have four types of cable in house (see below) and will include an analysis of each of these in our final report.

Synopsis of the Technical Material Included in This Report

PART 2

Part 2 is the master's thesis of Mr. Bruce Bunin. Mr. Bunin worked on this contract since it came into effect in November of 1977. He has worked on all phases of this project but only reports on some of his efforts in this thesis.

By title, his thesis is concerned with the effects of compressive forces in pipe type cable. After some introductory material, he describes the experimental procedures used in the compression test and then develops the analytical model used to explain these results. (This analytical model was in fact presented in our last progress report.) Bunin shows forces in the external metal tapes ranging up to 14 # in compression tests in which axial loads range up to 10,000#. Within the expected range of 0-3000# of axial load he shows one case of a tape force of about 10#. Quite in general, his work shows that the presence of axial load can have a major effect on tape tensions creating additional tensions well within the range of the tensions used when the cable is manufactured.

As Bunin points out, the theory at the moment predicts a much lower force level in the external tapes than that which was observed. This is due, we believe, to the fact that we have had some difficulty measuring the Pirelli coefficients required by this theory. We in fact underestimated the difficulties involved in obtaining these coefficients and are now in the process of using more sophisticated means to measure them. (We had presumed that these coefficients would be available from the manufactures of the cables. They were not available and we have had to attempt to measure them on our own.)

In an appendix Bunin presents some of his work on the flexure test. He describes modifications of test procedures which have been made over a period of some months and then compares a typical flexural modulus obtained to a computed flexural modulus using the work of Costello. Again, there are some differences to be resolved but we are largely pleased with these results and the present state of this work.

PART 3

Part 3 is the master's thesis of Miss Jeanne Beesley. She has been concerned with the response of pipe type cable to torsional loads, probably the most difficult case for us to deal with experimentally.

After some introductory material Miss Beesley describes the experimental procedures used in the torsion test. (It was, in fact, necessary to reinstrument an old torsion machine in order a) to be able to accommodate the cables themselves and b) to be able to reverse the load.) Using

the theory described in our earlier progress report, she presents an analysis of this torsional behavior. Again, the analysis describes the behavior of a cable under load such that additional tape tensions are required to maintain torsional equilibrium. And again, tape forces comparable to those used in the manufacture of cable are measured under test conditions.

As Beesley points out, she was unable to complete her analysis due to the fact that when she wrote her thesis no values at all of the Pirelli coefficients were available. But this does not present any particular problem for us since she has carried the analysis to the point at which it becomes identical with the case of compression which has been discussed by Bumin.

As far as we have pursued the work of Beesley, it represents conditions as we expected to find them. The tape forces generated are comparable to those which occur when the cable is manufactured and they exhibit the expected lack of symmetry (due to winding and unwinding of the conductor). We feel that these results are excellent and only need to be extended somewhat.

PART 4

At the project meeting in Washington last December, it was suggested that a modified Ames hardness tester be used in conjunction with our fatigue test to obtain a quantitative measure of changing hardness as

soft spots develop. This excellent suggestion was immediately implemented through the kindness of the loan of a hardness tester from Power Technologies, Inc. in Schenectady.

We have subsequently obtained a hardness tester of our own and propose to continue with these measurements...

These results indicate an interesting progression of softening throughout the cable with an curious movement of material from one axis to another. However, since these results are relatively new to us we prefer to withhold a detailed analysis at this time.

Additional fatigue data is also included in this section. Again, we are withholding a detailed analysis of this data until some of the items above are clarified.

Cable Specimen

We now have in hand four types of cable specimen:

1. The 550 kv Pirelli cable with which this project was started.
2. A 550 kv Phelps Dodge cable obtained from Waltz Mill after they had completed their tests.
3. A 345 kv specimen from the RTI facilities at Malta.
4. 345 kv specimen from Dequesne Light (ends from a system now being installed).

It is our intention to carry out a complete set of tests on all four of these cables and to compare their behavior in our final report.

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Personnel

With regard to contract personnel, we have followed the cost estimate included in the contract document. As indicated there, Professor Greenwood spends 10% of his time on this project and Professor Spillers 20% of his time during the academic year.

Also working under this contract is one doctoral student (R. Levy), 3 masters students (G. Spiliotis, J. Beesley, B. Bunin), and 3 undergraduates (M. Forte, J. Lashwell, G. Ravn). Two of the undergraduates (Lashwell and Ravn) were working on undergraduate projects at no cost to this contract.

Part 2

Effects of Compressive Forces in Pipe

Type Cable

Part 4

Fatigue Behavior of Pipe Type Cable

VERTICAL AXIS
HORIZONTAL AXIS

HARDNESS TEST #1

— BEFORE TESTED FOR FATIGUE

--- AFTER TESTED FOR FATIGUE

300 DISC. 1.5"

500 KV.

1-1 VERTICAL AXIS

2-2 HORIZONTAL AXIS

AA" SPECIMEN.

AA" SPECIMEN.

HARDNESS TEST #4

— BEFORE TESTED FOR FATIGUE.

--- AFTER TESTED FOR FATIGUE.

DISP. 1.5"

500 KV.

1-1 VERTICAL AXIS

2-2 HORIZONTAL AXIS

30kg

15kg

AA' SPECIMEN.

30kg

15kg

AA' SPECIMEN.

HARDNESS TEST #8

— BEFORE TESTED FOR FATIGUE

--- AFTER TESTED FOR FATIGUE

DISP. 1.5"
500 KV

1-1 VERTICAL AXIS

2-2 HORIZONTAL AXIS

30 kg

15 kg

44" SPECIMEN

30 kg

15 kg

44" SPECIMEN

100

HARDNESS TEST #9

BEFORE TESTED FOR FATIGUE

350

AFTER TESTED FOR FATIGUE

DISP 1.5

500 KV.

500

250

100

1-1 VERTICAL AXIS

150

100

50

50 kg

15 kg

44" SPECIFIED

100

350

HARDNESS TEST # II

BEFORE TESTED FOR
FATIGUE

AFTER TESTED FOR
FATIGUE

300

DISP 2"

500 KV.

250

1-1 VERTICAL
AXIS

VERTICAL AXIS

2-2 HORIZONTAL
AXIS

200

150

100

50

80kg

15kg

44" SPECIMEN

30kg

15kg

44" SPECIMEN

400

350 HARDNESS TEST #12

— BEFORE TESTED FOR FATIGUE

— AFTER TESTED FOR FATIGUE

300 DISP. 2"

500 KV. NO TAPE.

250 1-1 VERTICAL AXIS

200

150

100

50

VERTICAL AXIS

2-2 HORIZONTAL AXIS

30 kg

15 kg

30 kg

15 kg

AA" SPECIMEN

AA" SPECIMEN

400

350

300

250

200

150

100

50

HARDNESS TEST #13

BEFORE TESTED FOR
FATIGUE
AFTER TESTED FOR
FATIGUE

DISP 2"
500 K.V.

1-1 VERTICAL
AXIS

2-2 HORIZONTAL
AXIS

50 kg

15 kg

AA" SPECIMEN

50 kg

15 kg

AA" SPECIMENS

U.S. COAST AND GEODETIC SURVEY

FATIGUE TEST # 9
DISP 1.5"
500 KV FILE # 75

FATIGUE TEST # 10

DISP 1.5"

500 KV FILE # 76

FATIGUE TEST # 11

DISP 2"

500 KV

FILE # 47

FATIGUE TEST # 12

DISC 2"

500 KV. WITHOUT TAPE. FILE 78

FATIGUE TEST # 13

DISP 2"

500 KV

FILE 79

FATIGUE TEST #14

DISP 2"

500 KV. WITHOUT TAPE. FILE #80.

Prof. Spillers.

FATIGUE TEST # 15
DISP 2"
500 KV FILE 81

FATIGUE TEST

JUNE 7, 1979

TEST #17

345KV CABLE

DISP. 2IN. APPARATUS A

FILE #18