SINGLE MODE FIBER BENDING LOSS AND ITS ENVIRONMENTAL DEPENDENCE

HUGHES AIRCRAFT CO CANOGA PARK CA MISSILE SYSTEMS GROUP

H P HSU 31 AUG 86 ARD-22707.1-MS

UNCLASSIFIED DAAL03-86-C-0012
INTERIM TECHNICAL REPORT
ON
SINGLE MODE FIBER BENDING LOSS
AND
ITS ENVIRONMENTAL DEPENDENCE

CONTRACT NO. DAAL03-86-C-0012
CLIN: 0002AD

SPONSORED BY
U.S. ARMY LABORATORY COMMAND ARMY RESEARCH OFFICE
AND
U.S. ARMY COMMUNICATIONS AND ELECTRONICS COMMAND

PREPARED BY
H.P. HSU
PRINCIPAL INVESTIGATOR

HUGHES AIRCRAFT COMPANY
MISSILE SYSTEMS GROUP
OCTOBER 1986
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<tr>
<td><strong>4. TITLE (and Subtitle)</strong></td>
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<td>Interim Technical Report 1 May 1986 - 31 August 1986</td>
</tr>
<tr>
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<td>H. P. Hsu</td>
</tr>
<tr>
<td><strong>7. PERFORMING ORGANIZATION NAME AND ADDRESS</strong></td>
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<tr>
<td><strong>8. CONTRACT OR GRANT NUMBER(S)</strong></td>
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<td><strong>10. PROGRAM ELEMENT, PROJECT, TASK AREA &amp; WORK UNIT NUMBERS</strong></td>
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**DD FORM 1473 EDITION OF 1 NOV 65 OBSOLETE**
INTRODUCTION

The objective of this study contract is to develop a practical single mode bending loss model for special fibers critical to several future Army Weapon Systems. The model will facilitate the selection of fiber and aid the design of high speed missile payout canisters used in major Army fiber optics systems such as FOG-M and AAWS-M. The initial effort will be directed to study various bending induced loss mechanisms in fiber. A theoretical bending loss model, expressed in appropriate computer algorithms is being formulated. Practical fiber characterization schemes will be devised to yield relevant input data to the loss model. The model will then be modified to improve its adequacy for bending loss analysis. Environmental effects on fiber bending loss will be investigated. Reduction of temperature induced fiber loss of missile payout bobbins and field deployable fiber cables is the ultimate goal.

PROGRESS

In the first phase of the Basic Program we have laid the foundation for the real thrust of the project. The schedule is shown in Figure 1. An oral progress report was given to ARO and CECOM personnel at CECOM on September 26, 1986 and represents the detailed portion of this interim report. Progress is summarized and documented in this report. A copy of the oral presentation is shown as Appendix A. A literature survey was conducted and completed on the subject of single mode fiber theory and
bending loss phenomena. The survey has produced a reference list of 76 titles, presented as Appendix B. It shows extensive work to date in pursuit of fundamental understanding of fiber bending loss. Numerous articles have been published on both the macrobend and microbend fiber loss study. However, many experimental data still cannot be fully explained by the existing theory. There is no unified theoretical equation or a single model that adequately predict actual fiber bending loss. In addition, there are problems generated by the different analytical approaches employed during fiber bending loss research. Our immediate effort is to review these existing theories and to formulate a comprehensive single mode fiber loss model that combines the output of past re-

Figure 1. Basic Program Schedule
search efforts with new work. The fiber parameters and measured bend loss are the inputs and the output of the mode.

The basic mechanism of bend induced loss on a single mode fiber is a mode coupling process taking place between a guided mode \(\text{HE}_{11}\) and the radiation modes of fiber. Specifically, the radiation modes include both cladding modes and air modes. A mode coupling into the cladding modes, in which the optical power is still trapped in the fiber cladding, often creates a slow power leakage along the fiber length. A mode coupling to the air modes will cause a radiation loss as the optical power actually radiates out the fiber. The fiber bend loss mechanism can be roughly divided into two categories, depending on its physical dimensions and the abruptness of the bend. The categories are shown in Figure 2.

- **MACROBENDS**: LARGE BENDING CURVATURE \((R \gg D)\) THAT COVERS A FIBER LENGTH OF \(L \gg D\)

  SPOOL; MANDREL
  CORRUGATION PLATE
  PAYOUT PEEL POINT

- **MICROBENDS**: SHARP BENDING CURVATURE \((R \sim D)\) THAT INVOLVES LOCAL AXIAL DISPLACEMENTS OF A FEW MICRONS AND SPATIAL WAVELENGTHS OF A FEW MILLIMETERS.

  FIBER DIMENSION NONUNIFORMITY (CORE SIZE)
  CABLING STRESS, PACKING PRESSURE
  BOBBIN WINDING STRESS
  ENVIRONMENTAL STRESS ON BOBBIN WOUND FIBER (LOW TEMPERATURE)

**Figure 2. Types of Fiber Bending Loss**
Macrobend generally refers to a bend curvature several orders larger than the optical wavelength. It can introduce radiation loss as the result of field deformation on the fiber guided mode. The radiation loss depends strongly on the bend curvature and the fiber index profile. In contrast, microbend refers to the microscopic random deviation of fiber axis from its natural straight condition defined by the original drawing of the fiber. It can be introduced on fiber by cabling, winding, and ambient environment change. Microbends often generate gentle mode coupling between the guided mode and the cladding modes of fiber and generally lead to a small optical power loss in fiber over a long length. The microbending loss is known to depend on fiber structure, jacketing material, cabling design, winding condition, and ambient conditions. In theory, microbending loss is a complex process that often requires statistical methodology to characterize the loss behavior. Nevertheless, the formula for both macrobending and microbending fiber loss employs many identical mathematics.

We started our computer model effort by working on the mathematical programming of the constant curvature bending loss of step-index single mode fiber. Marcuse has shown that the bending loss, \( \alpha \), can be expressed in terms of the fiber index profile and the bend radius \( R \) as: (Ref. 47 in Appendix B)
\[ a = \frac{\sqrt{\pi} \kappa^2 \exp \left[ -\frac{2}{3} \left( \frac{\gamma^2}{\lambda^2} \right) \right]}{2 \gamma^{3/2} \sqrt{\rho} (K_{-1}(\gamma^a) K_{3}(\gamma^a))} \]

where \( \kappa = (n_c^2 \kappa^2 - n_c^2)^{3/4} \), \( \gamma = (\beta^2 - n_c^2 \kappa^2)^{3/4} \), \( \nu = \kappa^a (n_c^2 - n_cl^2)^{1/4} \), \( \kappa = \frac{2\pi}{\lambda} a. \)

\( a \) is the fiber core radius. \( n_c \) and \( n_cl \) are the refractive index of fiber core and cladding respectively. \( \lambda \) is optical wavelength.

A computer program has been written using Professional FORTRAN as its source language. This program has been tested on an IBM PC AT with math processor and should run on IBM PC, XT, or compatibles with a math coprocessor. The preliminary program listing is included as Appendix C. The program calculates the bending loss curves as a function of fiber parameters and bending radius as shown in Figure 3. It shows that the bend induced loss depends critically on the fiber core-cladding refractive index difference and the bend radius \( R \). The next step will compare the calculated loss values with measured constant curvature bend loss data generated from fiber samples designed for use in high speed missile payout dispensers. Expected discrepancies between the two sets of loss data will be analyzed for improving the bending loss model as well as for bend loss measurement.
Figure 3. Sample Results for Calculated Constant Curvature Bending loss

- Page 6 -
Although this bending loss program is written specifically for a step-index single mode fiber, it is believed that it will be applicable to other single mode fibers with different refractive index profiles. This extension will be required to establish an "equivalent step-index fiber mode field size" for other fibers by matching their evanescent field tails in cladding region against an ideal step-index fiber. Theoretical analysis and fiber output spot size measurements for sample fibers will be conducted to validate this bending loss analysis concept.

One potential application for the constant curvature bending loss study is to evaluate the fiber excess loss while the fiber is subjected to a constant speed payout. The payout peel point curvature is suspected to be a major loss contributor in the fiber payout process. A mechanical model analysis on the peel point curvature in terms of fiber parameters and payout conditions is being improved on a separate project. The calculated peel point curvature will then be used in the bending loss computer program to predict the fiber loss during the payout.

Another analysis effort currently under way involves the collection of optical loss data on bobbin wound fibers and experimental data on different loss measurement techniques. Existing fiber loss data indicate that winding loss and low temperature excess loss of bobbin wound fibers are both bending loss in nature. Winding geometry and the material thermal-mechanical properties of
fiber buffer layer have been identified as the prime factors in 
the loss analysis. Additional modeling is needed to formulate 
thermal mechanical effects in a bobbin wound fiber pack. The 
stress profile of the fiber pack will then be translated into 
microbending parameters and used for a fiber loss prediction.

FUTURE PLAN

The immediate plan is to expand the bending loss computer 
program to include periodic bend loss analysis. The periodic bend 
loss program will then further be expanded to cover the 
microbending loss analysis that will integrate the loss contribu-
tions from an ensemble of microbend perturbations in different 
spatial frequencies. This effort, along with bend loss measure-
ment on sample fibers, will be the primary task in the remainder 
of the Basic Program. Unless the option of the proposed Optional 
Program is exercised, a final report for the Basic Program will be 
prepared to cover the finding of this study. If the option is ex-
ercised, the study effort will be continued as shown in Figure 4 
in the Optional Program. The results will be presented in the 
form of a progress report as specified by the contract.

The critical task of the Optional Program is to devise prac-
tical fiber loss characterization schemes that will yield relevant 
input data useful for the bending loss model. Preliminary loss 
measurements, including Optical Time Domain Reflectometer (OTDR)
and spectral loss tests, with fibers subjected to various bend profiles and perturbations, will be conducted with Government supplied fibers. Bending loss data generated by mandrel wrapping and bobbin winding will be compared with the calculated results from the bending loss model. The discrepancy analysis will be analyzed to provide new leads for the improvement of the bending loss model. Similar procedure will then be expanded to deal with both the periodic bend case and the microbending induced bobbin wound fiber loss case.

Figure 4. Option Program Schedule
APPENDIX A

PROGRAM STATUS REVIEW
ON
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ITS ENVIRONMENTAL DEPENDENCE
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PREPARED BY
H. P. HSU
S C I E N T I S T
HUGHES AIRCRAFT COMPANY
MISSILE SYSTEMS GROUP
SEPTEMBER 26, 1986
TECHNICAL OBJECTIVES

- Study the bending induced loss of single-mode optical fibers

- Develop fiber bending loss model and analysis algorithms

- Analyze winding loss and low temperature excess loss of robbing wound fibers

- Develop practical tests that reveal fiber bending loss susceptibility
### BASIC PROGRAM SCHEDULE

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*Will be submitted if option is not exercised.*
PROGRESS ON THE BASIC PROGRAM

- LITERATURE SURVEY COMPLETED

- COMPUTER PROGRAM FOR STEP-INDEX, SINGLE-MODE FIBER CONSTANT CURVATURE BENDING LOSS COMPLETED.

- CONSTANT CURVATURE BENDING LOSS STUDY FOR ARBITRARY INDEX PROFILE SINGLE-MODE FIBER IN PROGRESS

- STUDY ON MICROBENDING LOSS MECHANISMS FOR BOBBIN WOUND FIBERS IN PROGRESS

- START THE STUDY ON THE THERMAL-MECHANICAL MODEL OF BOBBIN WOUND FIBERS
SCOPE

- BASIC PROGRAM (MAY'86 - OCT '86)

  THEORETICAL STUDY ON FIBER BENDING LOSS

- OPTIONAL PROGRAM (NOV'86 - OCT'87)

  EXPERIMENTAL STUDY ON FIBER BENDING LOSS
BASIC PROGRAM

- SIX MONTHS - MAY '86 TO OCT '86
- BUDGET: $60K
- CONDUCT THEORETICAL STUDY ON OPTICAL FIBER BENDING LOSS
- STATEMENT OF WORK
  - TASK 1: FIBER BENDING LOSS THEORY AND COMPUTER MODEL
    - LITERATURE SURVEY
    - IDENTIFY BENDING LOSS MECHANISMS
    - GENERATE FIBER BENDING LOSS FORMULA
    - DEVELOP A TRANSPORTABLE BENDING LOSS COMPUTER PROGRAM
  - TASK 2: BOBBIN WOUND FIBER LOSS DATA ANALYSIS
    - REVIEW IF0CL FIBER LOSS DATA
    - GENERATE THERMAL - MECHANICAL MODEL OF BOBBIN WOUND FIBER
LITERATURE SEARCH

SEARCH PERIOD: 1974 - 1986

TOTAL TITLES: 76

SUBJECTS:
- SINGLE MODE FIBER THEORY (22)
- SINGLE MODE FIBER MICROBENDING LOSS (21)
- SINGLE MODE FIBER MACROBENDING LOSS (14)
- EFFECT OF FIBER JACKET AND TEMPERATURE ON FIBER LOSS (14)
- BOBBIN WOUND FIBER LOSS (5)
COMPUTER PROGRAM FOR FIBER BENDING LOSS

- IBM - PC/XT/AT WITH MATH CO-PROCESSOR
- SOURCE LANGUAGE IS PROFESSIONAL FORTRAN
- STEP-INDEX, SINGLE-MODE FIBER
  - EIGENVALUE SEARCH FOR THE FIBER \textit{HE}_{11} MODE PROPAGATION CONSTANT (\(\gamma\))
  - CONSTANT CURVATURE BENDING LOSS CALCULATION

COMPATIBLE WITH CECOM EFOCL COMPUTER
FIBER BENDING LOSS MECHANISMS

MODE CONVERSION LOSS - COUPLING FROM A GUIDED MODE TO

- OTHER GUIDED MODES (MULTIMODE FIBER ONLY)
- QUASI-GUIDED MODES OR CLADDING MODES
- RADIATION MODES

\[ n_{ca} = \text{core refractive index} \]
\[ n_{cl} = \text{cladding refractive index} \]
\[ k = \text{wave number in free space (c/2\nu)} \]
CONSTANT CURVATURE FIBER BENDING LOSS

STEP INDEX FIBER (D. Marcuse)

\[ \alpha = \left( \frac{\kappa'}{r_{1/4}^\lambda \kappa_{1/2}^\lambda} \right) \exp \left[ -\frac{2}{3} \left( \frac{L}{R} \right) \right] \frac{1}{k_{1/2}^\lambda \sqrt{R} \left[ k_{1/2}^\lambda \left( \frac{L}{R} \right) \right]} \]

where

\[ \kappa' = n_c^2 k^2 - \beta^2 \]
\[ \beta^2 = \frac{1}{\lambda} \left( n_c^2 - n_{c1}^2 \right) \]
\[ V = \frac{2\pi}{\lambda} a (n_c^2 - n_{c1}^2)^{1/2} \]

FOR SINGLE-INDEX SINGLE-MODE FIBER = \( V \leq 2.405 \)
WHY CALCULATE CONSTANT CURVATURE FIBER BENDING LOSS

- GENERATE AND TEST THE EIGENVALUE SEARCH PROGRAM FOR STEP-INDEX FIBER

- ARBITRARY INDEX - PROFILE FIBER CAN BE STUDIED BY DEFINING A EQUIVALENT STEP-INDEX PROFILE FIBER
  - MATCH THE EVANESCENT FIELD IN THE CLADDING REGION FOR BENDING LOSS STUDY
  - MATCH THE PROPAGATION CONSTANT FOR TRANSMISSION CHARACTERISTICS
  - MATCH THE FIBER SPOT-SIZE FOR FIELD CONFINEMENT ANALYSIS
SAMPLE RESULTS FOR CALCULATED CONSTANT CURVATURE BENDING LOSS

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**BetaA**

| 17.47373487535026750 |

**KapaA**

| 1.662412662647931370 |

**GamaA**

| 1.8289.3219.9546.58650 |

**R (Spool Radius):**

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NEAR TERM MAJOR EVENTS

- STATUS REVIEW AT CECOM ON SEPTEMBER 26

- EVALUATE FURUKAWA VAD FIBER SUPPLIED BY CECOM

- TEST THE BENDING LOSS COMPUTER PROGRAM

- DISCUSS THE FUNDING FOR OPTION PHASE PROGRAM
TEST PLAN FOR FURUKAWA FIBER SAMPLE

- OTDR
- SPECTRAL LOSS W/NO CORRUGATED PLATE PAIR
- 90° BEND AND MANDREL WINDING
- SPOOL WINDING W/O ADHESIVE
- SPOOL WINDING W/ ADHESIVE
OPTICAL LOSS OF BOBBIN WOUND FIBERS

- Analyze the optical loss data generated from IFOCL and EFOCL program.

- Identify bending-related losses in terms of:
  - Fiber parameters
  - Winding condition
  - Winding sclm, winding tension, adhesive
  - Environmental dependence
  - Temperature, pressure

- Analyze bobbin wound fiber by the bending loss model.
### SPOOL-WOUND FIBER

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FIBER BENDING LOSS CHARACTERIZATION

- TRANSMISSION LOSS MEASUREMENTS WITH FIBER SUBJECTED TO
  - CORRUGATED PLATE PAIR
  - MANDREL WINDING
  - SAND PAPER SANDWICH
- OTDR
  - LONG LENGTH BOBBIN
- SPECTRAL LOSS MEASUREMENTS
**OTDR LOSS MEASUREMENT**

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<table>
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<th>LOSS RESOLUTION</th>
<th>POWER RATIO (PIN/POUT)</th>
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<tr>
<td>1 dB</td>
<td>.794</td>
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<tr>
<td>0.1 dB</td>
<td>.977</td>
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<tr>
<td>0.01 dB</td>
<td>.9977</td>
</tr>
<tr>
<td>0.001 dB</td>
<td>.99977</td>
</tr>
<tr>
<td>0.0001 dB</td>
<td>.999977</td>
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</table>
The figure depicts the functional block diagram of a long range optical time domain reflectometer (OTDR). The optical source is an 1.55 µm Nd:YAG laser. In GaAs photodiode detects, the return signal, EG&G boxcar averager provides the signal noise ratio enhancement.
COMPOSED OTDR LOSS TRACES OF 3.3 Km SMF BOBBIN
AT DIFFERENT TEMPERATURES

FIBER LOSS TRACES OF A 3.3 KM SINGLE MODE FIBER CANNISTER MEASURED BY AN OPTICAL TIME DOMAIN REFLECTOMETER (OTDR). THE FIBER IS PRECISION WOUND ON A 6-INCH DIAMETER PAYOUT SPOOL. THE LOSS TRACES ARE MEASURED AT DIFFERENT AMBIENT °C TEMPERATURES. THE SLOPE CHANGE OF EACH TRACE INDICATES THE FIBER LOSS DEPENDS ON THE LOCATION OR LAYER IN THE CANNISTER.

VERTICAL SCALE IS 0.25 dB/cm
HORIZONTAL SCALE IS 100 m/cm
Fiber Loss Temperature Dependence of 3.3 km SMF wound on a 5" bobbin (total 15 layers)

This figure depicts the optical loss, in dB/Km, of individual winding layers at different temperatures for a 3.3 km single mode fiber wound on a 6-inch diameter spool. The canister has 15 layers of wound fiber. The loss calculation for the outer traces exhibits a stronger temperature dependence for inner winding layers.
A spectral loss measurement is designed to monitor the effect of bending on the loss of single mode fiber in spectral domain. Monochromator is used to disperse the white light fiber output. The fiber insertion loss with and without the test fiber subjected to the corrugation plates are compared to assess the bending loss susceptibility of fiber.
SPECTRAL INSERTION LOSS DATA OF
A CORRUGATED CORNING SINGLE-MODE FIBER

Fiber length 2.930 km
Launch NA=0.20

Coating ORGANIC
UNPER.
HER 7.2/7.7 [0.29 dB]

MULTI-LAYER LARDGE DRUM
CORNING FIBER

SPECTRAL INSERTION LOSS OF A CORRUGATED CORNING SINGLE MODE FIBER. THE LOSS INCREASE AT LONG WAVELENGTH END (>1300 nm)
CONFIRMS THAT FIBER Suffers A LARGER BENDING LOSS AT LARGER
WAVELENGTHS DUE TO A LOOSER POWER CONFINEMENT IN FIBER.
The LOSS INCREASE AT SHORT WAVELENGTH (<1000 nm) REFLECTS THE
BENDING LOSS DUE TO THE RADIATION OF THE SECOND ORDER MODE.
<table>
<thead>
<tr>
<th>Fiber</th>
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<th>Winding</th>
<th>Environment</th>
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<tbody>
<tr>
<td>n(r)</td>
<td>Material</td>
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<td>Temperature</td>
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<td>Pressure</td>
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<tr>
<td>Core size</td>
<td>Thickness</td>
<td>Adhesive</td>
<td>Spool Geometry</td>
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<td>Tension</td>
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<td>Fiber OD</td>
<td>Thermal Exp.</td>
<td>Cross-Over/</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Core.</td>
<td>Transition</td>
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<tr>
<td>Dim. Uniformity</td>
<td>Glass Trans.</td>
<td>Conditioning</td>
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</tr>
<tr>
<td></td>
<td>Temp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Young's Module</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fiber Bending Loss Due to Thermal-Mechanical Effects

- Loss mechanisms caused by differential thermal expansions:
  - Between fiber winding and metal (aluminum) spool.
  - Between fused Si and plastic buffer jacket.

- Loss mechanisms caused by winding geometry:
  - Cross-over bending.
  - Post-cure adhesive characteristics.
  - Bending due to spool radius of curvature.

- Loss mechanisms caused by reduction of fiber tension (in spool):
  - Visco-elastic relaxation and creep of buffer jacket material.
  - Fiber tension loss due to thermal cycling (conditioning).

- Loss mechanism associated with fiber pay-out:
  - Peel-point curvature.
# Option Program Schedule

<table>
<thead>
<tr>
<th>MILESTONES</th>
<th>1986</th>
<th>1987</th>
</tr>
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<tbody>
<tr>
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<td>DCC</td>
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<tr>
<td>Fiber Sample Procurement</td>
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<tr>
<td>Thermal-Mechanical Model of Doubly Wound Fibers</td>
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<td>Fiber Cable Mechanical Property Characterization</td>
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<td>Environmental Chamber Fiber Loss Characterization</td>
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<tr>
<td>Fiber Loss Characterization Test Development</td>
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<td>Fiber Bending Loss Analysis</td>
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<td>Fiber Micromolding Loss Model Updated</td>
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<tr>
<td>Final Report</td>
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</table>
SUMMARY

- LITERATURE SURVEY INDICATES THAT MOST OF RESEARCH HAS BEEN DIRECTED TO STUDY THE FIBER BENDING LOSS UNDER CABLELING CONDITION.

- LOSS ANALYSIS OF BOBBIN WOUND FIBER REQUIRES A THERMAL MECHANICAL MODEL FOR THE FIBER PACK AND MICROBENDING LOSS MODEL.

- BOBBIN WOUND FIBER LOSS DATA EXHIBITED STRONG LOW TEMPERATURE EXCESS LOSS COATING AND ADHESIVE MATERIAL PHYSICAL PARAMETERS ARE CRITICAL.

- LOSS MEASUREMENT SHOULD CONCENTRATE ON LONG-LENGTH SAMPLE EVALUATION TO OBTAIN RELEVANT DATA FOR THE BENDING LOSS MODEL.

HPHsu.9/24/86
APPENDIX B

REFERENCES
REFERENCES ON SINGLE MODE FIBER BENDING LOSS STUDY

This reference list complies the published literatures on the following subjects:

- References 1 to 22: Single mode fiber theory
- References 23 to 43: Single mode fiber microbending loss
- References 44 to 57: Single mode fiber macrobending loss
- References 58 to 71: Effect of fiber jacket and temperature on fiber loss
- References 72 to 76: Bobbin wound fiber loss


APPENDIX C

PROGRAM LISTING
This program calculates the normalize frequency, $V$, with given values: lambda (wavelength), delta, $A$, and $N$ (index of refraction). Furthermore, it calculates BetaA, KapaA, and GamaA of the transcendental problem of the Bessel and the Modified-Bessel functions. All the values are calculated in double-precision.

All the variables are implicitly declared real except I and M.

Fifty(50) elements are reserved for the arrays.

```
IMPLICIT REAL*8(A-H,J-L,N-Z)
DIMENSION RoA(50), R(50), Alpha(50), Argumt(50), Expnt(50),
DeAlpha(50), NuAlphaA(50), AlphaA(50), AlphaL(50)
```

There is an input file called "IP" that this program reads its data directly from.

```
OPEN (UNIT=8, FILE='IP', STATUS='OLD')
READ(8,10) lambda, delta, A, N, aInc
DO 5 I=1,19
   READ(8,20) RoA(I)
5 CONTINUE
CLOSE (UNIT=8)
```

This is where the NORMALIZE FREQUENCY, $V$, is calculated.

```
V=((2.*Pi)/lambda)*A*N*(DSQRT(2.*delta))
```

This is where the calculation of upper and lower bound of the transcendental problem is calculated.

```
UpBd=N*(((2*Pi)/lambda)*A
LwBd=N*(1-delta)*(((2*Pi)/lambda)*A
BetaA=UpBd
FxUpBd=UpBd
FxLwBd=LwBd
KapaA=DSQRT((FxUpBd**2)-(BetaA**2))
```

```
GamaA=DSQRT((BetaA**2)-(FxLwBd**2))
CALL Jo (KapaA, FJo)
CALL J1 (KapaA, PJ1)
CALL Ko (GamaA, FKo)
CALL K1 (GamaA, FK1)
FJ=KapaA*(PJ1/FJo)
FK=GamaA*(FK1/FKo)
Error=FJ-FK
```
c This accuracy can be altered to approximately 1.0E-12
IF (ABS(Error) .LT. 0.00000001) GOTO 200
IF (Error .GT. 0.0) mSign=1
IF (Error .LT. 0.0) mSign=2
M=M+1
IF (M .EQ. 1) GOTO 100
IF (mFlag .NE. mSign) THEN
UpBd=NUUpBd
LwBd=NULwBd
BetaA=UpBd
ENDIF
100 mFlag=mSign
CALL Bound (UpBd, LwBd, BetaA, NuUpBd, NuLwBd, delta, ainc)
IF (M .GT. 50000) GOTO I
GOTO 200
200 DO 250 I=1,19
250 CONTINUE
FORMAT(' lambda = ',F5.2,4X,'delta = ',F5.3,4X,'A = ',F5.2,4X,'N = ',F5.2,4X,'Inc = ',F5.1)
265 FORMAT( )
c Calculation of AlphaL
AlphaL(I)=(1-EXP(-Alpha(I)*L))/Alpha(I)
WRITE(9,265) lambda, delta, A, N, ainc
WRITE(9,270) Beta=BetaA/A
WRITE(9,279) KapaA, GamaA
WRITE(9,265)
270 FORMAT( ' NORMALIZE FREQUENCY V = ',F20.18)  
272 FORMAT( ' Fixed Upper Bound = ',F20.17)  
274 FORMAT( ' Fixed Lower Bound = ',F20.17)  
276 FORMAT(13X,'BetaA = ',F20.17)  
278 FORMAT( ' KapaA = ',F20.18,3X,'GamaA = ',F20.18)  
279 FORMAT(' Beta = ',F20.17)  
WRITE(9,270) V
WRITE(9,279) Beta
WRITE(9,272) FxUpBd
WRITE(9,274) FxLwBd
WRITE(9,276) BetaA
WRITE(9,279) KapaA, GamaA
WRITE(9,265)
280 FORMAT( 'R (Spool Radius):',F11.2,6X,E21. 15,SX.E21. 15)
WRITE(9,280) R(I), Alpha(I), AlphaL(I)
DO 300 I=1,19
WRITE(9,290) R(I), Alpha(I), AlphaL(I)
300 CONTINUE
1 PRINT*, 'Number of loop is',M
STOP
END
THIS SUBROUTINE CALCULATES BetaA WITH GIVEN BOUNDARY

SUBROUTINE Bound (UpBd, LwBd, BetaA, NuUpBd, NuLwBd, delta, alnc)
IMPLICIT REAL*8(A-Z)
X1=UpBd
X2=LwBd
Del=(X1-X2)/alnc
BetaA=BetaA-Del
NuLwBd=BetaA
NuUpBd=BetaA+Del
RETURN
END

Following subroutines are the Bessel functions of zeroth
and of first order.

THIS SUBROUTINE CALCULATES THE Jo(X) BESSEL FUNCTIONS

SUBROUTINE Jo (KapaA, FJo)
IMPLICIT REAL*8(A-Z)
X=KapaA
IF (X .LE. 3.0) GOTO 100
T=3.0/X
F=0.79788456*T*(-0.00000077*T*(-0.00552740*T*(-0.0009512*T
C (0.000137237*T*(-0.00072805*T*0.00014476))))
THETA=X-0.78539816*T*(-0.04166397*T*(-0.0003954*T*(-0.0026573*T
C (-0.00054125*T*(-0.00029333*T*0.00013558))))
Q=1.0/DSQRT(X)
FJo=Q*F*DCOS(THETA)
RETURN
100 T=X*X/9.0
FJo=1.0-T*(2.2499997*T*(1.2656208*T*(0.3163866*T*(0.0444479*T
C (0.0039444*T*0.002100)))))
RETURN
END

THIS SUBROUTINE CALCULATES THE J1(X) BESSEL FUNCTIONS

SUBROUTINE J1 (KapaA, FJ1)
IMPLICIT REAL*8(A-Z)
X=KapaA
IF (X .LE. 3.0) GOTO 100
T=3.0/X
F1=0.79788456*T*(0.000000156*T*(0.01659667*T*(0.00017105*T
C (-0.00249511*T*(0.0013653*T*0.00020033))))
THETA=X-2.35619449*T*(0.12499612*T*(-0.0005650*T*(-0.00637879*T
C (0.00074348*T*(0.00079824*T*0.00029168))))
Q=1.0/DSQRT(X)
FJ1=Q*F1*DCOS(THETA)
RETURN
100 T=X*X/9.0
FJ1=X*(0.5-T*(0.56249965*T*(0.21093573*T*(-0.03954289*T
C (0.0443319*T*(0.0031761*T*0.0001109)))))
RETURN
END

C-3
Following subroutines are the modified-Bessel function of zeroth and of first order.

**THIS SUBROUTINE CALCULATES THE \( K_0(x) \) MODIFIED-BESSEL FUNCTION**

```fortran
SUBROUTINE Ko (GamaA, FKo)
  IMPLICIT REAL*8(A-Z)
  X=GamaA
  IF (X .GT. 3.75) GOTO 100
  T=X*X/(3.75*3.75)
  F1o=1.0-T*(3.5156229-T*(3.0899424-T*(1.2067492-T*(0.2659732-T*
  c (0.0360768-T*0.0045813))))))
  GOTO 200
100 T=3.75/X
  IF (X .GT. 85.0) X=85.0
  F1o=DEXP(X)/DSQRT(X)*(0.39894228+T*(-0.01328592+T*(-0.00225319+T*
  c (-0.00015765+T*(-0.000396283+T*(-0.00000740))))))
  GOTO 200
200 IF (X .LT. 2.0) GOTO 300
  T=2.0/X
  FKo=DEXP(-X)/DSQRT(X)*(1.25331414+T*(0.23498619+T*(-0.03855620+T*
  c (0.01504288+T*(-0.00780353+T*(-0.00325814+T*(-0.00068245))))))
  RETURN
300 T=0.25*X*X
  IF (X .LT. 1.E-30) X=1.E-30
  FKo=-DLOG(0.5*X)*F1o-0.57721566*T*(0.51498869-T*(0.15084934-T*
  c (0.00301532+T*0.00324211)))))
  RETURN
END
```

**THIS SUBROUTINE CALCULATES THE \( K_1(x) \) MODIFIED-BESSEL FUNCTIONS**

```fortran
SUBROUTINE K1 (GamaA, FK1)
  IMPLICIT REAL*8(A-Z)
  X=GamaA
  IF (X .GT. 3.75) GOTO 100
  T=X*X/(3.75*3.75)
  F11=X*(0.5-T*(0.87890594-T*(0.51498869-T*(0.15084934-T*
  c (0.02658733+T*0.00301532+T*0.00032411)))))
  GOTO 200
100 T=3.75/X
  IF (X .GT. 85.0) X=85.0
  F11=DEXP(X)/DSQRT(X)*(-0.03986024+T*(-0.0362018+T*(-0.00362018+T*
  c (-0.00015680+T*(-0.02282967-T*(-0.02895312+T*
  c (0.01787654-T*0.00420059)))))))
  GOTO 200
200 IF (X .LT. 2.0) GOTO 300
  T=2.0/X
  FK1=DEXP(-X)/DSQRT(X)*(-0.23999850-T*(0.2398619-T*(-0.0365620+T*
  c (-0.00325814-T*(0.00068245))))))
  RETURN
300 T=0.25*X*X
  IF (X .LT. 1.E-30) X=1.E-30
  FK1=-DLOG(0.5*X)*F11-(0.51498869-T*(-0.67278579+T*
  c (-0.18156897-T*(-0.01919402+T*(-0.00110404-T*0.000068245))))))
  RETURN
END
```

C-4
END
2-87
D Tic