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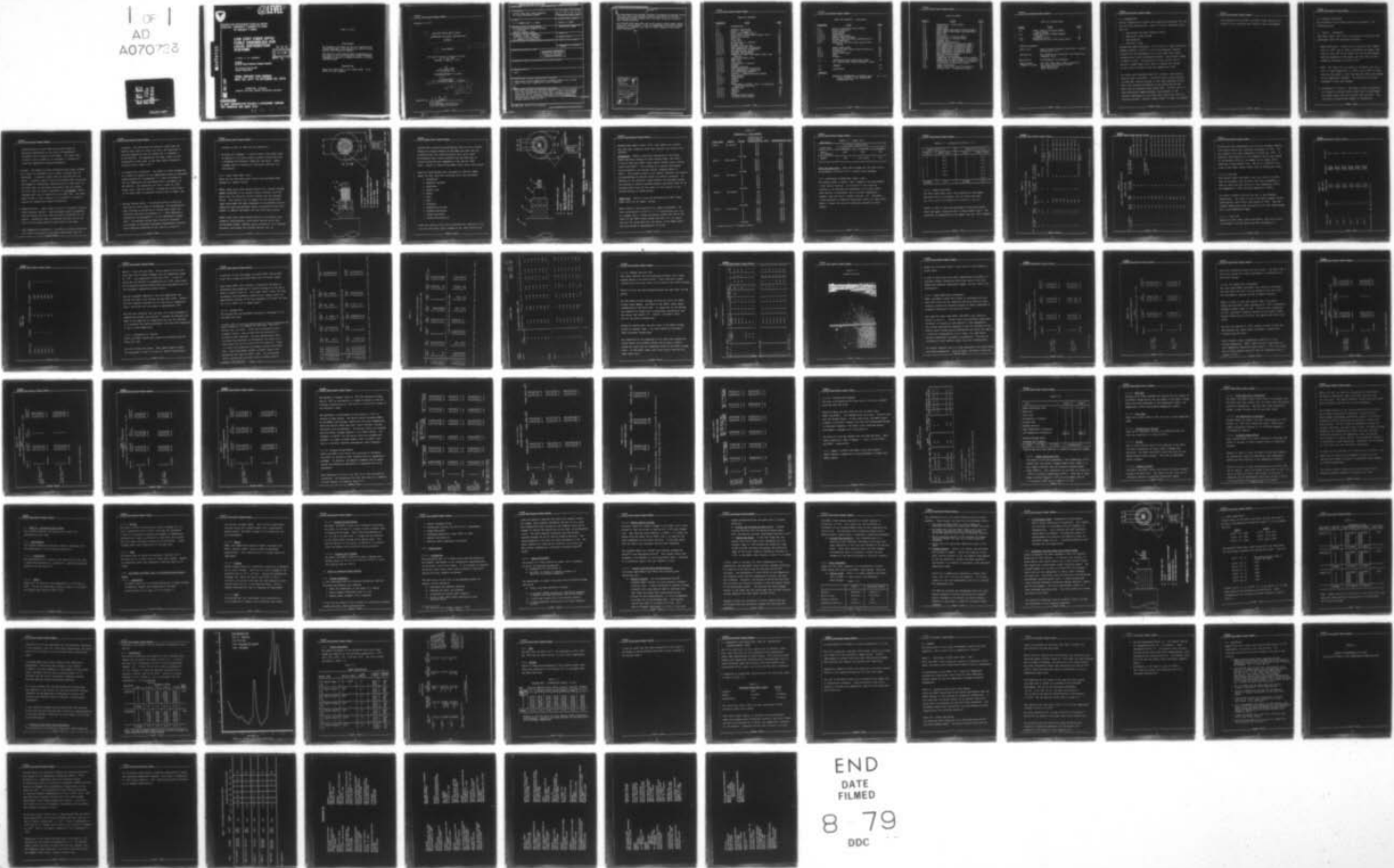
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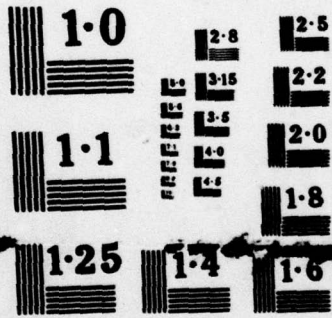
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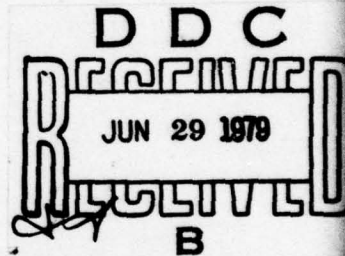
RESEARCH AND DEVELOPMENT TECHNICAL REPORT  
CORADCOM- CONTRACT # DAAB07-77-C-2681  
ITT PROJECT # 36015

# LOW COST FIBER OPTIC CABLE ASSEMBLIES FOR LOCAL DISTRIBUTION SYSTEMS

J. C. SMITH & R. E. THOMPSON

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⑥ **LOW COST FIBER OPTIC CABLE  
ASSEMBLIES FOR LOCAL DISTRIBUTION  
SYSTEMS**

⑨ Final Report, 25 May 77 - 30 Oct 78

ITT Electro-Optical Products Division  
P. O. Box 7065  
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For  
U.S. Army ECOM  
Fort Monmouth, NJ

Contract # DAAB07-77-C-2681  
⑫

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⑪ 20 Nov 78

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The second phase of the contract consisted of developing an optimized optical fiber cable which would meet more stringent requirements and overcome the deficiencies found in Cables ECOM-1 and ECOM-3 during the evaluation under extreme conditions.

The optimized fiber optic cable was of the external strength member design, using 1 m.m optical fibers. It met the requirements for optical (average attenuation at .82  $\mu$ m was less than 10.5 db/km), mechanical and environmental performance.

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Related Documents:

MIL-C-13777	Cable, Special Purpose, Electrical: General Specification For
MIL-STD-202	Test Methods for Electronic and Electrical Component Parts
MIL-STD-810	Environmental Test Methods
ECOM Contract #DAA07-77-C-2681	Low Cost Fiber Optic Cable Assemblies for Local Distribution Systems Cable Design Plan Cable Test Plan

1.0 INTRODUCTION

Optical communication systems offer important advantages for Army tactical field applications. Some of the more important advantages are:

- o Light Weight and Small Diameter Cables
- o Impervious to EMI and EMP
- o Wide Bandwidth
- o Difficult to Tap

Recognizing these advantages, in 1975 the U. S. Army Electronics Command awarded a contract to ITT Electro-Optical Products Division for the development of Low Cost Fiber Optic Cable Assemblies for Local Distribution Systems. The contract number is DAAB07-75-1328. The objective of this contract was to develop a rugged fiber optic cable to replace the current 26 pair cable (CX-4566) within the Command Post Area.

Two cables were developed under that contract, they were designated ECOM-1 and ECOM-3. Since the scope of the contract included only limited testing, it was found necessary to perform a more detailed evaluation of the cables and set new goals that an optimized cable should meet. In 1977, the U. S. Army Electronics Command awarded a new contract to ITT, entitled "Optimized Low Cost Fiber Optic Cable for Local Distribution Systems", Contract Number DAAB07-77C-2681, to perform

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the evaluation of the ECOM-1 and ECOM-3 type cables and to develop a new, optimized cable based on their performance.

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## 2.0 CONTRACT OBJECTIVES

The objectives of the second contract are grouped in the following phases:

### 2.1 Phase 1 EVALUATION

ECOM cable Types 1 and 3 will be evaluated to determine their performance under the following conditions:

- o Impact Resistance - Cables will be tested at room temperature, at  $-55^{\circ}\text{C}$ , and at  $+85^{\circ}\text{C}$  to determine the impact load level at which 90% of the fibers will survive 200 impacts. With the exception of the loads, the tests shall be performed in accordance with MIL-C-13777.
  
- o Bend - The cables will be tested in accordance with MIL-C-13777 at room temperature, at  $-55^{\circ}\text{C}$ , and at  $+85^{\circ}\text{C}$  to determine the resistance to fiber breakage and other cable damage at the temperature extremes. The objective is no fiber breakage or other cable damage.
  
- o Attenuation vs. Tension - The effect on fiber attenuation as a result of various tensile loads shall be determined. An optical signal shall be injected into the cable. Tension shall be applied and changes in transmission

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characteristics of each fiber in the cable shall be monitored individually as the load is incrementally increased from 50 pounds to 400 pounds. The cable shall be held in such a manner as to eliminate or properly account for compression induced attenuation.

- o Fatigue - The effect on fiber attenuation and jacket slippage as a result of continuous static tensile loading shall be determined. An optical signal shall be injected into the cable. A constant tensile load of 100 pounds shall be applied and changes in transmission characteristics of each fiber in the cable shall be monitored individually each day during the first week, and weekly thereafter for two months. Jacket slippage shall also be monitored at the same time. The cable shall be held in such a manner as to eliminate or properly account for compression-induced attenuation.
  
- o Roadway Survival - Cables shall be laid on a driveway carrying heavy vehicular traffic. Fiber continuity shall be measured each day during the first week and weekly thereafter for two months. Attenuation shall be measured initially and at the end of the two month period on each fiber in the cable.
  
- o High Temperature Attenuation - The effect on fiber attenuation as a result of exposure to elevated temperatures shall be

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evaluated. One cable shall be wound on a metal reel and another cable shall be coiled (no reel), and subjected to the High Temperature test per Method 501.1, Procedure I of MIL-STD-810. The temperature for Step 4 shall be 85°C. Attenuation of each fiber in the cable shall be measured initially and in Steps 5 and 7.

- o Low Temperature Attenuation - The effect on fiber attenuation as a result of exposure to low temperatures shall be evaluated. Cables prepared as in paragraph 2.1.7 shall be subject to the Low Temperature test per Method 502.1, Procedure I of MIL-STD-810. The temperature for Step 2 shall be -55°C. Steps 4 and 5 shall be omitted. Attenuation of each fiber in the cable shall be measured initially and in Steps 3 and 7.
  
- o Minimum Storage Radius - The minimum radius at which the cable may be stored shall be determined. The determination shall be based on evaluation at various radii under the conditions specified in paragraph 2.1.7 (High Temperature Attenuation) and paragraph 2.1.8 (Low Temperature Attenuation). The minimum storage radius should be optimized with respect to assuring no permanent degradation of optical and/or physical properties of the cable as a result of



storage on reels at high and low temperature.

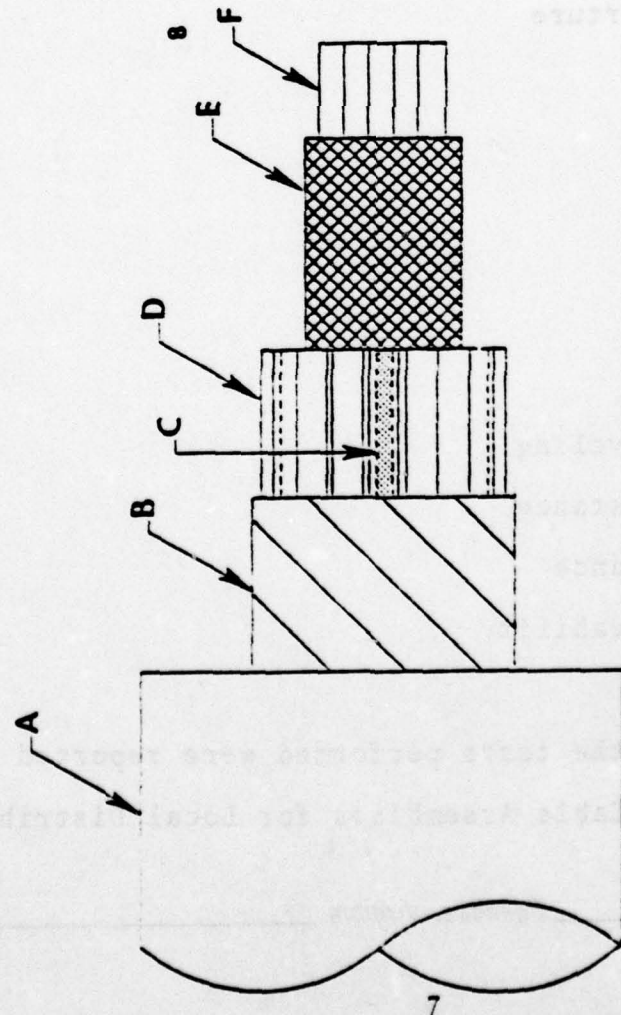
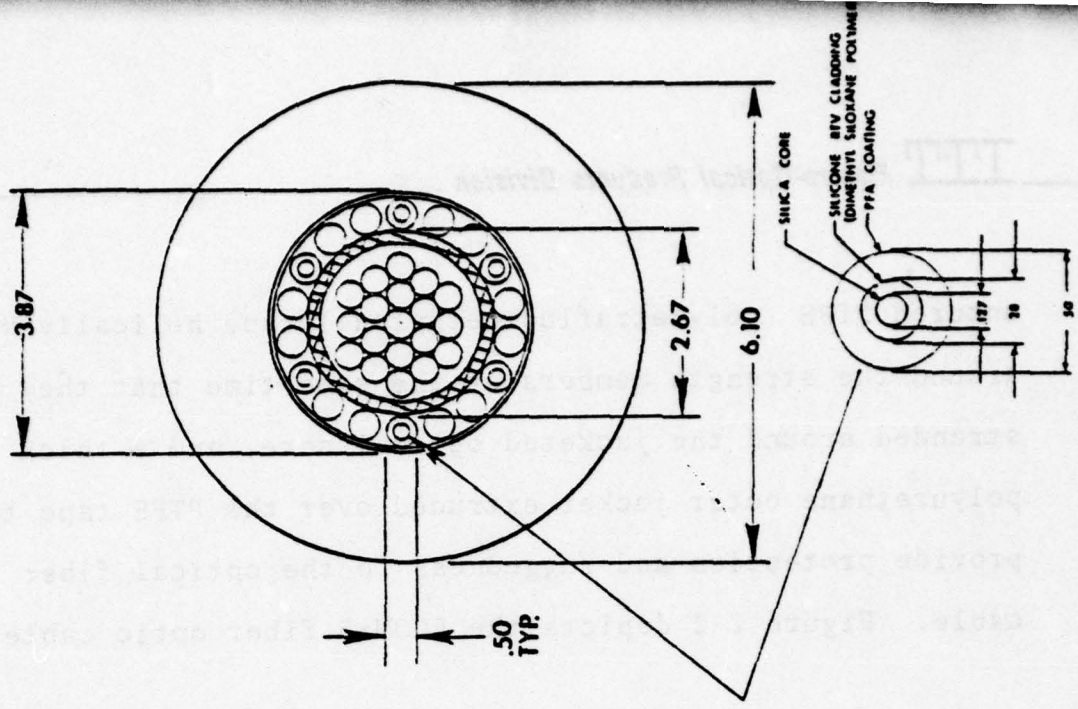
- o Gripping and Slippage - A tensile load of 400 pounds shall be applied to the cable using a suitable Kellems grip and a Preformed Line Products "dead-end" type grip. Jacket slippage shall be measured at one minute intervals for five minutes.

#### 2.1.1 Cable Types ECOM 1 and 3

These two low cost fiber optic cables were developed under contract No. DAAB07-75-1328.

ECOM-1 fiber optic cable design consists of a central strength member surrounded by six optical fibers, helically laid and spaced with two polyester fillers between each two adjacent fibers. This optical core is wrapped with an uncured PTFE tape, which keeps the cable components in the desired position before the outer polyurethane jacket is extruded on the cable. Figure 2-1 depicts the ECOM-1 low cost fiber optic design.

ECOM-3 fiber optic cable design consists of an optical core formed by seven helically laid fibers covered with a thin polyurethane jacket, eighteen yarns of Kevlar 49 (1420 deniers) helically laid around the jacketed optical core, an



- A - POLYURETHANE JACKET
- B - TFE TAPE
- C - PLASTIC CLAD SILICA FIBER (LAY LENGTH 4.2")
- D - POLYESTER FILLER LAY LENGTH 4.2"
- E - KEVLAR™ 29 BRAID
- F - KEVLAR™ 49 STRENGTH MEMBER

Figure 2-1

PLASTIC CLAD SILICA FIBER

CENTRAL STRENGTH MEMBER-SINGLE LAYER DESIGN

ECOM-1



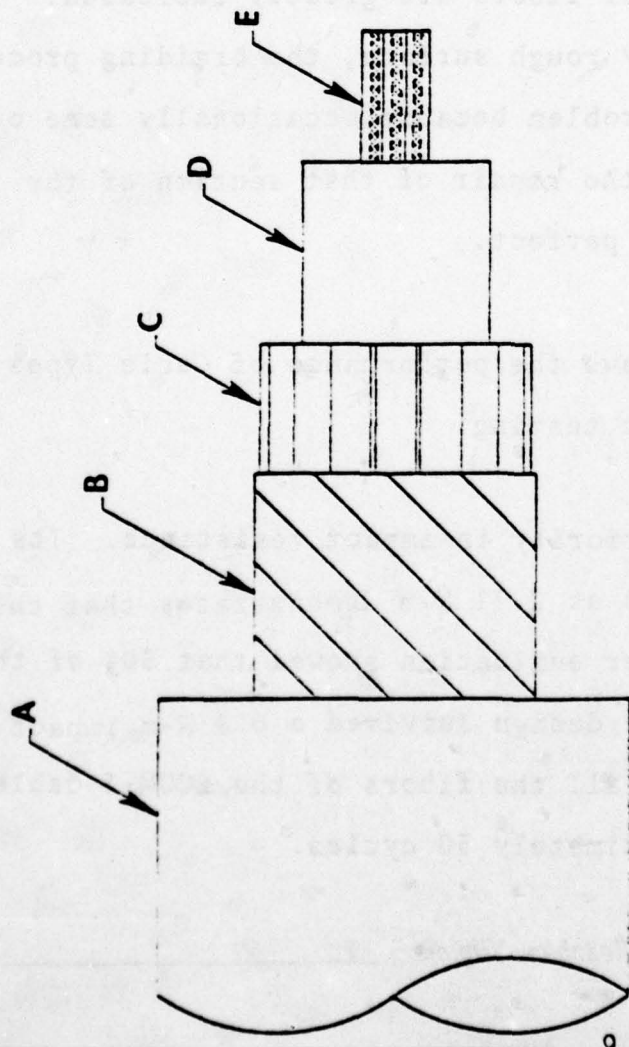
uncured PTFE (polytetrafluoroethylene) tape helically wrapped around the strength members at the same time that they are stranded around the jacketed optical core, and a thick polyurethane outer jacket extruded over the PTFE tape to provide protection and ruggedness to the optical fiber cable. Figure 2-2 depicts the ECOM-3 fiber optic cable design.

These two cable designs were evaluated in contract number DAAB07-75-1328, where the following tests were performed:

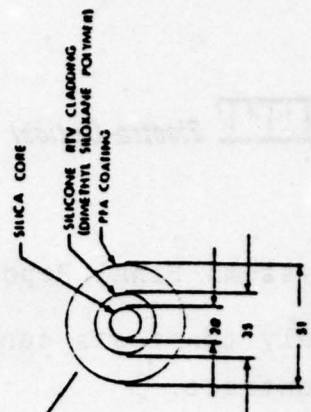
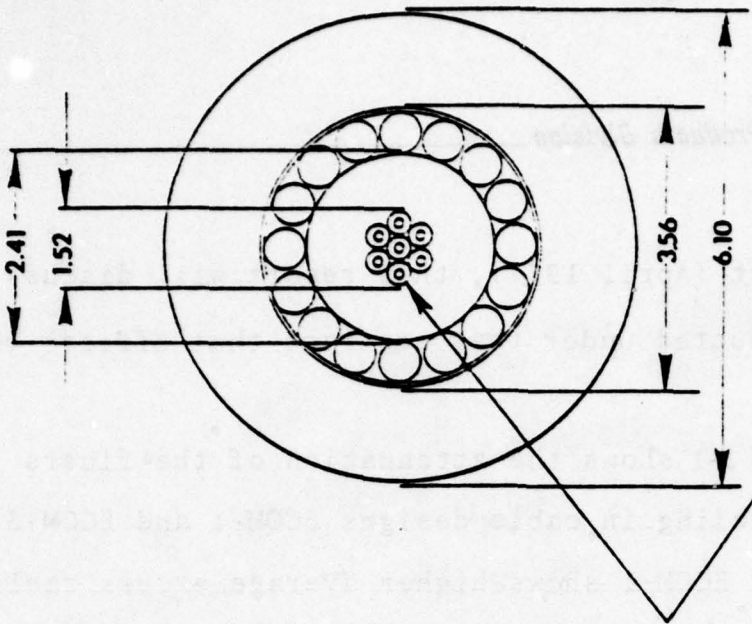
- o Attenuation
- o Numerical Aperture
- o Dispersion
- o Tensile Load
- o Impact
- o Twist
- o Bend
- o Vibration
- o Temperature Cycling
- o Moisture Resistance
- o Fungus Resistance
- o Nuclear Survivability

Since the results of the tests performed were reported in the Low Cost Fiber Optic Cable Assemblies for Local Distribution

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- A - POLYURETHANE OUTER JACKET
- B - TFE TAPE
- C - HELICALLY LAID KEVLAR™ 49 STRENGTH MEMBER YARNS (LAY LENGTH 4.2")
- D - POLYURETHANE INNER JACKET
- E - OPTICAL FIBER BUNDLE (LAY LENGTH 2.0 )



PLASTIC CLAD SILICA FIBER

307 11596

**EXTERNAL STRENGTH MEMBER DESIGN  
ECOM-3**

Figure 2-2

Systems Final Report (April 1977), this report will discuss only the tests conducted under that contract that affects this contract.

Attenuation - Table 2-1 shows the attenuation of the fibers before and after cabling in cable designs ECOM-1 and ECOM-3. It can be seen that ECOM-1 shows higher average excess cabling losses than ECOM-3. This difference in optical performance was attributed to the braided central strength member of ECOM-1. The braided surface is not smooth; therefore the chances of microbending the optical fibers are greatly increased. In addition to the relatively rough surface, the braiding process also presents a quality problem because occasionally some of the braiding yarns break and the repair of that section of the braided surface is seldom perfect.

Impact Test - Table 2-2 shows the performance of Cable Types ECOM-1 and 3 in the impact testing.

ECOM-1 shows a clear superiority in impact resistance. Its fiber survivability of 90% at 2.71 N-m demonstrates that this is a rugged cable. Further evaluation showed that 50% of the fibers of the ECOM-1 cable design survived a 6.8 N-m impact load for 200 cycles while all the fibers of the ECOM-3 cable type were broken at approximately 50 cycles.



TABLE 2-1

ATTENUATION - FINAL MODELS

<u>CABLE TYPE</u>	<u>LENGTH</u>	<u>FIBERS</u>	<u>ATTENUATION OF FIBERS BEFORE CABLING (dB/Km, .79μ)*</u>	<u>CABLING (dB/km, .79μ)</u>
ECOM-1	317 meters	1	8.2	8.5
		2	7.1	7.8
		3	6.1	7.4
		4	6.1	7.7
		5	5.9	7.5
		6	<u>5.4</u>	<u>7.5</u>
		Average	6.5	7.7
ECOM-1	1020 meters	1	13.1	19.3
		2	13.6	18.2
		3	17.5	18.0
		4	13.5	18.1
		5	14.9	15.8
		6	<u>13.1</u>	<u>17.2</u>
		Average	14.3	17.8
ECOM-3	336 meters	1	7.6	6.0
		2	6.7	6.8
		3	6.7	6.3
		4	6.8	7.1
		5	6.6	6.3
		6	6.8	8.3
		7	<u>6.7</u>	<u>8.3</u>
Average	6.8	7.0		
ECOM-3	520 meters	1	5.6	6.0
		2	5.7	6.6
		3	6.2	6.5
		4	7.0	6.6
		5	8.1	7.9
		6	6.3	6.5
		7	<u>11.2</u>	<u>10.6</u>
Average	7.2	7.2		
ECOM-3	1140 meters	1	17.0	14.8
		2	15.8	15.8
		3	19.9	24.4
		4	19.2	17.0
		5	17.4	16.5
		6	19.9	17.8
		7	<u>15.4</u>	<u>15.0</u>
Average	17.8	17.3		

\* Fibers Wound on 4" Diameter Spools

TABLE 2-2 - Impact Test

200 Cycles			
Cable Type	% of Fiber Transmitting		
	1.36 N-m	2.04 N-m	2.71 N-m
ECOM-1 (15 samples)	100%	100%	90%
ECOM-3	90%	Not tested	10%

Twist and Bend Tests - Both cable designs met the 2000 cycles, in accordance with MIL-C-13777, without fiber breakage.

2.1.2 Evaluation of ECOM Cable Types 1 and 3

The results shown in Tables 1 and 2 summarize the achievements of the initial contract. An objective of the follow-on contract is to indicate the performance of the cable under some specific circumstances such as extreme temperature (impact, bend and twist), Roadway Survival, etc. Therefore, it was necessary to fabricate additional cables for these tests. Table 2-3 shows the optical attenuation achieved on these cables.

TABLE 2-3 Attenuation (dB/km @ .82  $\mu$ )

Cable #072277-A-1		Cable #071777-AA-II	
Fiber #	ECOM-1 612m	Fiber #	ECOM-3 665m
1	10.7	1	11.5
2	18.3	2	10.5
3	13.3	3	9.7
4	12.3	4	10.7
5	11.4	5	11.9
6	10.9	6	12.2
		7	11.2
Average	12.8	Average	11.1

2.1.2.1 Impact Resistance

The cable types ECOM-1 and 3 were subjected to the Impact Resistance Test in accordance with the Cable Test Plan.

The test results are summarized in Tables 2-4 and 2-5.

Tables 2-4 and 2-5 show the percentage of surviving fibers, after the impact resistance test of cables ECOM-1 and 3. The specified low temperature of the impact test was -55°C, however,



**TABLE 2-4**  
**CABLE IMPACT RESISTANCE TESTING**  
**ECON-1 DESIGN**

No. of Samples Tested	Force (N-m)	Temp (°C)	Total No. of Breaks	No. of Impacts at each break	Comments
6	2.6	25	1	100	
6	2.9	25	3	53, 75, 176	One break in each of 3 samples
6	3.3	25	5	26, 67, 67, 75, 80	One break in each of 5 samples
6	2.7	-45*	0	0	Survived 200 impacts
6	3.0	-45*	0	0	Survived 200 impacts
6	3.4	45*	0	0	Survived 200 impacts
1	4.7	-45*	0	0	Survived 200 impacts
6	2.7	+85	0	0	Survived 200 impacts
6	3.0	+85	0	0	Survived 200 impacts
6	3.4	+85	0	0	Survived 200 impacts
5	4.7	+85	4	(25, 25), 45, 85	Break in each of 3 samples

\*Refer to Results Section

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**TABLE 2-5**  
**CABLE IMPACT RESISTANCE TESTING**

**ECOM-3 DESIGN**

<u>No. of Samples Tested</u>	<u>Force (N-m)</u>	<u>Temp (°C)</u>	<u>Total No. of breaks</u>	<u>No. of Impacts at each break</u>	<u>Comments</u>
6	1.2	25	0	--	Survived 200 impacts
6	1.6	25	0	--	Survived 200 impacts
6	1.9	25	0	--	Survived 200 impacts
1	2.6	25	7	53, 53, 80, 80, 120, 149, 149	All fibers broken
1	2.6	25	2	75, 75	
6	1.3	-45*	0	--	Survived 200 impacts
6	1.7	-45*	0	--	Survived 200 impacts
6	2.0	-45*	0	--	Survived 200 impacts
1	2.7	-45*	0	--	Survived 200 impacts
1	4.7	-45	0	--	Survived 200 impacts
6	1.3	+85	0	--	Survived 200 impacts
6	1.7	+85	0	--	Survived 200 impacts
6	2.0	+85	0	--	Survived 200 impacts
1	2.7	+85	0	--	Survived 200 impacts
1	3.4	+85	0	--	Survived 200 impacts

\*Refer to Results Section

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difficulties were experienced with the test equipment temperature control device that prevented attainment of  $-55^{\circ}\text{C}$ . For most samples, the lowest temperature achieved was  $-45^{\circ}\text{C}$ . In addition, frost deposits on the equipment caused some binding in the downward travel of the hammer at low energy levels resulting in questionable data. The data is believed to be valid at the higher energy values since no binding was noted.

#### 2.1.2.2 Bend Test

Both cables, ECOM-1 and ECOM-3, were subjected to the bend test in accordance with the Cable Test Plan, paragraph 2.0. Table 2-6 shows the test results at room temperature ( $26^{\circ}\text{C}$ ), low temperature ( $-45^{\circ}\text{C}$ ) and high temperature ( $+85^{\circ}\text{C}$ ).

All fibers of ECOM-3 survived the test at the different temperatures. Two fibers in one of the ECOM-1 samples failed simultaneously (882 cycles) when tested at  $+85^{\circ}\text{C}$ . This performance demonstrated high survivability for both cable designs over a wide temperature range.

#### 2.1.2.3 Twist Test

Samples of cable types, ECOM-1 and ECOM-3, were twist tested in accordance with the Cable Test Plan, paragraph 3.0

TABLE 2-6

BEND TEST

<u>Cable Type</u>	<u>Sample</u>	<u>Temperature</u>	<u># Cycles</u>	<u># Breaks</u>
ECOM 1	1	26°C	2000	0
	2	26°C	2000	0
	3	26°C	2000	0
ECOM 1	1	-45°C	1000	0
	2	-45°C	1000	0
	3	-45°C	1000	0
ECOM 1	1	85°C	1000	2*
	2	85°C	1000	0
	3	85°C	1000	0
ECOM 3	1	26°C	2000	0
	2	26°C	2000	0
	3	26°C	2000	0
ECOM 3	1	-45°C	1000	0
	2	-45°C	1000	0
	3	-45°C	1000	0
ECOM 3	1	85°C	1000	0
	2	85°C	1000	0
	3	85°C	1000	0

\* Break Location - 882 cycles for both breaks

Roanoke, Virginia

**TABLE 2-7**  
**TWIST TEST**

<u>Cable Type</u>	<u>Samples</u>	<u>(°C) Temperature</u>	<u># Cycles</u>	<u># Breaks</u>
ECOM 1	3	25	2000	0
ECOM 1	3	-45	1000	0
ECOM 1	3	85	1000	0
ECOM 3	3	25	2000	0
ECOM 3	3	-45	1000	0
ECOM 3	3	85	1000	0

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Table 2-7 lists the test data. The two cables survived the twist test with no fiber breakage over the temperature range of  $-45^{\circ}\text{C}$  - room temperature ( $25^{\circ}\text{C}$ ), and  $+85^{\circ}\text{C}$ . It must be noted that the desired low temperature was  $-55^{\circ}\text{C}$ , which could not be achieved because difficulties were experienced with the test equipment temperature control device.

The test equipment employed in the room temperature test allowed the cable to be twisted the specified  $180^{\circ}\text{C}$ . However, the test equipment employed for the high and low temperature tests, restricted the twist angle to approximately  $100^{\circ}$ .

The test data indicates that the goal of no fiber breakage at temperature extremes was achieved. Although the desired twist angle in the high and low temperature test was not achieved, it is believed that cable performance would have been comparable to that at room temperature.

#### 2.1.2.4 Attenuation vs. Tension

ECOM-1 and ECOM-4 cables were tested in accordance with the Cable Test Plan.

Two sets of data were taken. Short gauge length of cable and long gauge of cable (0.6 and 24.4 meters respectively).

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In addition to the test gauge, the cable ECOM-1 had an additional 400 m length and cable ECOM-3 had 100 meters length.

Cable types ECOM-1 and 3 showed no significant increase in attenuation when subjected to tensile loading up to 182 Kg as shown in Tables 2-8 and 2-9. The output signal levels for both, incremental and decremental loaded did not change within the experimental accuracy of the test equipment for either the long (24.4 m) or short (0.6 m) gauge length.

#### 2.1.2.5 Fatigue Test

The Fatigue Test was performed according to paragraph 5.0 of the Cable Test Plan.

A static load of 45 Kg was applied and the fiber attenuation and cable slippage of the samples was monitored. The test duration was two months. There was no observable jacket slippage, however, some fluctuations and decreases in attenuation were observed. The data substantiates these variations and decreases in attenuation, but there is no conclusions that can be reached from the analysis. Table 2-10 shows the attenuation performance during the Fatigue Test. Cable Type ECOM-3 showed a slightly higher loss during the test than the ECOM-1 type. All the optical fibers survived the two month tensile loading without optical fiber failure.

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ATTENUATION VS TENSION ECON 1

Gauge Length 24.4m & Cable Length 400m

Load (kg)	Fiber 1 $\alpha$ (dB)	Fiber 2 $\alpha$ (dB)	Fiber 3 $\alpha$ (dB)	Fiber 4 $\alpha$ (dB)	Fiber 5 $\alpha$ (dB)	Fiber 6 $\alpha$ (dB)	Average Attenuation (dB)
22.75	Broken	0.00	0.04	0	0.04	0.00	0.02
45.4	Broken	0.04	0.13	0.04	0.04	0.00	0.06
68.18	Broken	0	.04	0	0	0	0.01
90.91	Broken	0	0.13	0.04	0.04	0.04	0.05
115.64	Broken	0.04	0.18	0.04	0.09	0.04	0.08
150.56	Broken	0.15	0.27	0.09	0.13	0.09	0.14
159.09	Broken	0.15	0.18	0	0	0.09	0.08
181.82	Broken	0	0.13	.04	0	0	0.05

Gauge Length 0.6m & Cable Length 400m

Load (kg)	Fiber 1 $\alpha$ (dB)	Fiber 2 $\alpha$ (dB)	Fiber 3 $\alpha$ (dB)	Fiber 4 $\alpha$ (dB)	Fiber 5 $\alpha$ (dB)	Fiber 6 $\alpha$ (dB)	Average $\alpha$ (dB)
22.7	Broken	0	0	0.09	0.13	0.09	0.06
45.4	Broken	0.13	0	0.09	0.13	.09	0.09
68.2	Broken	0.13	0	0.09	0.18	0.09	0.10
90.9	Broken	0.09	0	0.09	0.15	0.09	0.08
115.6	Broken	0.09	0	0.09	0.3	0.09	0.08
156.4	Broken	0.13	0	0.09	0.13	0.09	0.09
159.1	Broken	0.09	0.13	0.22	0.13	0.09	0.13
181.8	Broken	0.13	0	0.09	0	0.13	0.07

Loss parameter is the output signal level referenced to the signal level with minimal tension (5kg).



TABLE 2-9

ATTENUATION VS TENSION ECOM 3

Gauge Length 24.4m & Cable Length 100m

Load	Fiber 1 α(dB)	Fiber 2 α(dB)	Fiber 3 α(dB)	Fiber 4 α(dB)	Fiber 5 α(dB)	Fiber 6 α(dB)	Fiber 7 α(dB)	Average Atten. (db)
22.7	0	0.04	0	0.22	0	0	0.04	0.04
45.4	0.04	0.18	0	0.09	0.09	0	0.04	0.06
68.2	0	0.22	0	0.09	.09	0	0.13	0.08
90.9	0	0.04	0	0.29	0.09	0	0.04	0.07
113.6	0	0.04	0	0.22	0.09	0	0.04	0.06
136.4	0	0.18	0	0.22	0.09	0	0	0.07
159.1	0	0.18	0	0.22	0.09	0	0.13	0.09
181.8	0.04	0.04	0	0.13	0.09	0	0.04	0.05

Gauge Length 0.6m & Cable Length 100m

22.7	0	0.04	0.04	0.04	0	0	0	0
45.4	0.04	0	0.04	0.04	0	0	0.04	0.02
68.2	0.04	0.04	0.09	0.09	0.09	0.13	0.09	0.08
90.9	0.09	0.04	0.09	0.04	0.04	0.09	0.09	0.07
113.6	0.04	0	0.09	0.04	0	0.04	0.04	0.04
136.4	0.04	0.09	0.04	0	0.09	0	0	0.04
159.1	0.09	0.13	0.09	0.09	0.13	0.09	0.04	0.09
181.8	0.09	0.04	0.04	0	0.04	0.04	0.04	0.04

Loss parameter is the output signal level referenced to the signal level with minimal tension (5kg).

Conditions of Test  
 $\lambda = .82 \mu\text{m}$   
 $NA = .124$   
 Gauge length = 24m  
 Cable length = 80m

FATIGUE TEST

ATTENUATION OF SAMPLE (-dB)

FIBER NUMBER	CABLE SLIPPAGE (cm)	INITIAL (T=0)	T=45.kg	1st wk.	2nd wk.	6th wk.	8th wk.	FINAL(T=0)
1	0	1.3	0.73	0.92	0.94	1.69	0.93	1.0
2	0	1.11	0.88	0.81	0.53	0.93	0.95	1.11
3	0	1.27	1.57	1.40	1.42	1.91	1.30	2.39
4	0	1.59	1.23	1.48	1.30	1.74	1.47	1.23
5	0	1.00	1.08	1.19	1.34	1.54	1.51	1.52
6	0	<u>1.37</u>	<u>0.78</u>	<u>1.72</u>	<u>1.53</u>	<u>1.9</u>	<u>1.73</u>	<u>1.86</u>
AVERAGE	0	1.27	1.05	1.25	1.18	1.62	1.32	1.52

FIBER NUMBER	CABLE SLIPPAGE (cm)	INITIAL (T=0)	T=45.kg	1st wk.	2nd wk.	6th wk.	8th wk.	FINAL(T=0)
1	0	1.38	*	2.63	2.73	3.29	2.12	1.08
2	0	1.01	0.58	1.3	1.59	1.59	1.46	1.42
3	0	0.91	0.49	1.44	2.26	2.05	2.11	2.20
4	0	0.86	1.03	0.79	*	0.99	1.43	1.22
5	0	1.13	0.92	0.98	1.22	1.33	1.21	1.31
6	0	0.97	0.62	0.98	1.20	2.26	1.57	2.15
7	0	<u>0.93</u>	<u>0.83</u>	*	*	<u>1.57</u>	<u>1.96</u>	<u>1.81</u>
AVERAGE	0	1.03	.75	1.30	1.80	1.87	1.69	1.60

\* NO MEASUREMENT

T = TENSION



#### 2.1.2.6 Roadway Survival Test

This cable survival test was performed on ECOM-1 and 3 cable designs during a two month period. Heavy vehicular traffic traveled over each cable type (10,390 vehicles per month average).

Table 2-11 lists the data obtained during the eight week testing period.

All the fibers of both designs survived the first two weeks without fiber damage. One fiber of the ECOM-1 cable ceased transmitting in the third week. An inspection of the testing site showed tire tracks due to intentional acceleration over the cables (See Figure 2-3). However, the ECOM-3 cable had all the fibers transmitting.

During the fourth week, one more fiber of the ECOM-1 design failed to transmit light. All seven fibers of the ECOM-3 cable continued transmitting.

The inspection at the beginning of the sixth week showed four broken fibers in the ECOM-3 design and one more in ECOM-1. During the sixth week all remaining fibers of the ECOM-3 design broke. In the ECOM-1 cable, only three fibers survived the eight weeks test.

TABLE 2-11

ROADWAY SURVIVABILITY

CABLE TYPE	Fiber #	Pre-test Attenuation (dB/km)	Post-test Attenuation (dB/km)	Continuity									
				1st	2nd	3rd	4th	5th	6th	7th	8th		
CABLE TYPE ECOM 1	1	—	Broken	T	T	T	NT	NT	NT	NT	NT	NT	NT
	2	—	Broken	T	T	T	T	T	NT	NT	NT	NT	NT
	3	—	Broken	T	T	T	T	T	NT	NT	NT	NT	NT
	4	10.89	10.1	T	T	T	T	T	T	T	T	T	T
	5	11.38	16.1	T	T	T	T	T	T	T	T	T	T
	6	12.34	16.1	T	T	T	T	T	T	T	T	T	T
CABLE TYPE ECOM 3	1	—	Broken	T	T	T	T	T	T	T	T	T	NT
	2	—	Broken	T	T	T	T	T	T	T	T	T	NT
	3	—	Broken	T	T	T	T	T	T	T	T	T	NT
	4	—	Broken	T	T	T	T	T	T	T	T	T	NT
	5	—	Broken	T	T	T	T	T	T	T	T	T	NT
	6	—	Broken	T	T	T	T	T	T	T	T	T	NT
	7	—	Broken	T	T	T	T	T	T	T	T	T	NT

T - Transmitting  
NT - Not Transmitting

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Figure 2-3  
Roadway Survival



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Except for the broken fibers, there was no visible damage to either cable.

It must be noted that both cables demonstrated resistance to vehicular traffic during the first three weeks of the test. Because of suspected intentional damage, the test results are inconclusive.

#### 2.1.2.7 High Temperature Attenuation

ECOM 1 and ECOM 3 cables were tested in accordance with the Cable Test Plan with the exception that each fiber was individually injected and detected instead of bundle injections as originally proposed in the Cable Test Plan.

Test data for cable types ECOM 1 and ECOM 3 are listed in Tables 2-12 and 2-13 . Neither cable type exhibited significant increases in attenuation when exposed to high temperature. The storage configuration appeared to have no influence on the results since average optical performance was nearly the same in a loose coil configuration as on a spool, but some fibers incurred significant increases in attenuation. This may be attributed to cable effects rather than reel configuration.

The results indicate that at a high temperature the cabled fibers have minor degradation. Both the ECOM 1 and ECOM 3 cables had

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TABLE 2-12

HIGH TEMPERATURE ATTENUATION

ECOM 1

Attenuation (dB/km @ 0.82  $\mu$ m & Inj NA = 0.124)

Fiber#	Pre-Test @ 24°C	Test @ +85°C	Post-Test @ 24°C
1	17.56	13.81	17.31
2	10.95	11.48	13.36
3	13.52	14.22	18.62
4	16.25	14.18	18.01
5	12.37	11.85	15.18
6	13.29	13.42	16.55
Average	13.99	13.16	16.51
1	14.34	12.34	14.09
2	10.66	17.09	15.72
3	15.35	13.89	18.63
4	12.07	*	15.37
5	14.50	13.30	17.23
6	14.77	13.51	17.17
Average	13.62	14.03	16.37

15 cm metal reel, 265 m cable length

15 cm coil, 140 m cable length

\* No Measurement

Roanoke, Virginia

TABLE 2-13

HIGH TEMPERATURE ATTENUATION

ECOM 3

Attenuation (dB/km @ 0.82  $\mu$ m & Inj NA = 0.124)

Fiber #	Pre-Test @ 24°C	Test @ +85°C	Post-Test @ 24°C
1	9.59	10.33	10.60
2	10.75	11.48	13.19
3	9.80	15.00	8.15
4	8.36	8.77	13.56
5	11.46	10.39	9.45
6	10.74	12.71	15.13
7	8.91	10.48	10.96
Average	9.94	11.31	11.58
1	9.56	13.24	14.39
2	11.23	18.76	20.13
3	9.04	10.63	11.31
4	9.99	10.07	10.35
5	9.35	11.63	13.41
6	12.11	13.19	12.52
Average	10.23	12.71	13.80

15 cm metal reel, 200 m cable length

15 cm coil, 200 m cable length

Roanoke, Virginia



post-test attenuations above pre-test values. The metal reel vs loose coil showed only slight differences in attenuation for both cable designs.

#### 2.1.2.8 Low Temperature Attenuation

The cable types ECOM-1 and ECOM-3 were tested in accordance with the Cable Test Plan with the exception that each fiber was individually injected instead of bundle injected.

Tables 2-14 and 2-15 show that neither ECOM-1 nor ECOM-3 cables had detectable light transmission at  $-55^{\circ}\text{C}$  (attenuation equipment dynamic range  $\sim 87$  dB). The post-test attenuation, at  $24^{\circ}\text{C}$ , indicated a complete recovery of the optical transmission characteristics for both, the spooled and coiled test cables.

The test was repeated at  $-45^{\circ}\text{C}$ , Tables 2-16 and 2-17 show the data obtained for cables ECOM-1 and ECOM-3, respectively, on metal reels and coils.

ECOM-3 showed a clear transmission superiority at this testing temperature. ECOM-1 cable had more than double its room temperature attenuation when tested at  $-45^{\circ}\text{C}$ , both cables had an almost complete recovery when the temperature was returned to  $+24^{\circ}\text{C}$ .

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TABLE 2-14  
 LOW TEMPERATURE ATTENUATION  
 ECOM 1  
 Attenuation (dB/km @ 0.82 μm & Inj NA = 0.124)

Fiber #	Pre-Test @ 24°C	Test @ -55°C	Post-Test @ 24°C
1	17.31	*	17.35
2	13.36	*	12.31
3	18.62	*	16.92
4	18.01	*	17.46
5	15.78	*	13.74
6	16.55	*	13.79
Average	16.61		15.26
1	14.09	*	17.90
2	15.72	*	11.01
3	18.63	*	17.11
4	15.37	*	12.62
5	17.23	*	17.50
6	17.17	*	17.12
Average	16.37		15.54

15 cm metal reel, 265 m cable length

15 cm coil, cable length 140 m

\* No Detectable Light Transmission

TABLE 2-15

LOW TEMPERATURE ATTENUATION  
ECOM 3

Attenuation (dB/km @ 0.82  $\mu$ m & Inj NA = 0.124)

Fiber #	Pre-Test @ 24°C	Test @ -55°C	Post-Test @ 24°C
1	10.60	*	11.38
2	13.19	*	12.09
3	8.15	*	14.42
4	13.56	*	12.55
5	9.45	*	13.00
6	15.13	*	13.90
7	12.52	*	11.73
Average	11.80		12.72
1	14.39	*	14.17
2	20.13	*	10.73
3	11.31	*	13.58
4	10.35	*	13.87
5	13.41	*	14.18
6	14.46	*	8.46
7	11.73	*	12.26
Average	13.68		12.45

15 cm metal reel,  
cable length  
200m

15 cm coil, cable  
length 200 m.

\* No detectable light transmission



**TABLE 2-16**  
**LOW TEMPERATURE ATTENUATION**  
**ECOM 1**  
**Attenuation (dB/km @ 0.82 μm & Inj NA = 0.124)**

Fiber #	Pre-Test @ 24°C	Test @ -45°C	Post-Test @ 24°C
1	17.35	50.07	18.47
2	12.31	29.73	13.04
3	16.92	47.76	18.15
4	17.46	49.23	19.86
5	13.74	31.56	21.52
6	13.79	20.03	12.41
Average	15.26	38.06	17.24
1	17.90	35.70	14.88
2	11.01	28.01	11.17
3	17.11	48.74	17.05
4	12.62	31.85	15.26
5	17.50	45.40	18.62
6	17.12	53.03	18.94
Average	15.54	40.46	15.99

15 cm metal reel,  
cable length  
265 m

15 cm coil,  
cable length  
140 m

**TABLE 2-17**  
**LOW TEMPERATURE ATTENUATION**  
ECOM 3  
Attenuation (dB/km @ 0.82 μm & Inj NA = 0.124)

Fiber #	Pre-Test @ 24°C	Test @ -45°C	Post-Test @ 24°C
1	11.38	21.13	17.31
2	12.09	19.86	15.13
3	14.42	23.15	15.52
4	12.55	23.38	18.51
5	13.00	14.88	14.28
6	13.90	23.50	16.66
7	11.73	18.56	16.30
Average	12.72	20.65	16.24
1	14.17	36.19	14.31
2	10.13	15.01	13.11
3	13.58	15.46	15.26
4	13.87	17.58	16.27
5	14.18	15.21	12.77
6	8.46	12.92	10.79
7	12.26	13.98	7.06
Average	12.38	15.02	13.75

15 cm metal reel, cable length 200 m

15 cm coil, cable length 200 m

Roanoke, Virginia

The failure to transmit light at  $-55^{\circ}\text{C}$  and increased attenuation at  $-45^{\circ}\text{C}$  is attributed to a change of density of the RTV silicone, cladding material resulting in a significant change of its refractive index.

The difference in performance of both cables at  $-45^{\circ}\text{C}$  is related to cable design. The Kevlar central strength member, of the ECOM-1 cable design, expand with the lower temperature, while the optical fibers and outer jacket contract, forcing the fibers into microbending. The optical fibers are isolated from the Kevlar strength members in the ECOM-3 design. Furthermore, in ECOM-1, all the Kevlar yarns are stranded and braided in a single strength member, while in ECOM-3, each yarn is a flexible (Neoprene impregnated) cable component.

#### 2.1.2.9 Minimum Storage Radius

ECOM-1 and ECOM-3 type cables were evaluated to determine the effect of storage on small diameter reels at temperature extremes. In addition, the smallest diameter reel at which optical and mechanical degradation is negligible was to be determined.

Reel diameters of 11 cm, 15 cm, and 25 cm, were selected for evaluation. The attenuation for each cable type as a function of reel diameter is listed in Table 2-18.

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TABLE 2-18

MINIMUM STORAGE RADIUS

Fiber #	Original Attenuation -dB/km	Post HT** Atten Test (Pre LT** Atten Test)		Post LT Atten Test -dB/km
		dB	-dB/km	
ECOM 3 with 11 cm metal reel, 97 m cable length	1.39	1.24	12.75	1.20
	1.39	1.23	12.66	1.20
	1.00	.90	9.32	1.13
	1.22	1.61	16.59	1.53
	1.21	1.53	15.76	1.93
	1.09	.89	9.14	1.26
	1.03	1.77	18.20	1.81
Average	1.19	1.31	13.49	1.44
ECOM 1 with 15 cm metal reel, 258 m cable length	4.53	4.47	17.31	4.48
	2.83	3.50	13.36	3.18
	3.49	4.80	18.62	4.37
	4.19	4.65	18.01	4.50
	3.19	3.92	15.18	3.54
	3.43	4.27	16.55	3.56
	Average	3.61	4.27	16.51
ECOM 3 with 15 cm metal reel, 200 m cable length	1.92	2.12	10.60	2.28
	2.15	2.64	13.19	2.42
	1.96	1.63	8.15	2.88
	1.67	2.71	13.56	2.51
	2.29	1.89	9.45	2.60
	2.15	3.03	15.13	2.78
	1.78	2.19	10.96	2.35
Average	1.99	2.32	11.58	2.55
				15.26
				11.38
				12.09
				14.42
				12.55
				13.00
				13.90
				11.73
				12.72

\*HT = High Temperature (+85°C)  
\*\*LT = Low Temperature (-55°C)

TABLE 2-18 (cont.)

MINIMUM STORAGE RADIUS

	<u>Fiber #</u>	<u>Original Atten.</u>	<u>Atten. After 85°C</u>	<u>Atten. After -55°C</u>
ECOM-1 15 cm metal reel 264 m	1	17.56	17.31	17.35
	2	10.95	13.36	12.99
	3	13.52	18.62	16.92
	4	16.25	18.01	17.46
	5	12.37	15.18	13.74
	6	13.29	16.55	13.79
	Average	13.99	16.51	15.38
ECOM-1 15 cm coil 139 m	1	14.34	14.09	17.90
	2	10.66	15.72	11.01
	3	15.35	18.63	17.11
	4	12.07	15.37	12.62
	5	14.50	17.23	17.50
	6	14.77	17.17	17.12
	Average	13.62	16.36	15.54
ECOM-3 15 cm metal reel 199 m	1	9.59	10.60	11.38
	2	10.75	13.19	12.09
	3	9.80	8.15	14.42
	4	8.36	13.56	12.55
	5	11.46	9.45	13.00
	6	10.74	15.13	13.90
	7	8.91	10.96	11.73
Average	9.94	11.58	12.72	

TABLE 2-18 (cont.)

MINIMUM STORAGE RADIUS

	<u>Fiber #</u>	<u>Original Atten.</u>	<u>Atten. After 85°C</u>	<u>Atten. After -55°C</u>
ECOM-3 15 cm coil	1	9.56	14.39	14.17
	2	11.23	20.13	10.13
	3	9.04	11.31	13.58
	4	9.99	10.35	13.87
	5	9.35	13.41	14.18
	6	12.11	14.46	8.46
	7	10.31	12.52	12.26
	Average	10.22	15.80 12.74*	12.38

Attenuation is expressed in dB/km. It was measured at .82 μm with .124 injection N.A.

\*Average of six fibers, not including fiber #2 (20.13 dB/km).



TABLE 2-18 (CONT.)

MINIMUM STORAGE RADIUS

Fiber #	Original Attenuation dB	Post HT** Atten Test (Pre LT** Atten Test) dB	Post LT Atten Test dB	Post LT Atten Test -dB/km
ECOM 1	1.10	1.66	2.40	26.70
with	1.14	1.76	2.11	23.40
25 cm	1.25	1.84	2.57	28.55
metal	1.07	1.56	1.57	17.40
.90 m	1.17	1.50	1.63	18.15
cable	.98	1.85	2.26	25.14
length				
Average	1.12	1.70	2.09	23.22
ECOM 3	.88	1.45	.99	11.00
with	.80	1.44	1.69	18.82
25 cm	1.00	1.33	2.48	27.51
metal,	.84	1.44	.91	10.16
90 m	.79	1.21	1.02	11.35
cable	.99	1.32	3.11	34.60
length	.91	1.67	.86	9.52
Average	.89	1.41	1.58	17.57

\*HT = High Temperature (+85°C)  
 \*\*LT = Low Temperature (-55°C)

2.1.2.10 Gripping and Slippage

Two types of gripping devices were used in this test, Kellems Grips and Dead End Grips.

Table 2-19 shows the data from the test on cable types ECOM-1 and ECOM-3. Two loading levels were used: 445N was used with the Kellems Grips. At this load level, the ECOM-1 cable slipped 1.3 cm after 1 minute, the test was discontinued because it continued slipping. The ECOM-3 cable exhibited better performance, although still unsatisfactory.

The level of 1114N was reached with the Dead End Grips. Both cables exhibited a small slippage ~ .1 and .3 cm for ECOM-1 and ECOM-3 respectively.

2.1.3 Summary of ECOM-1 and ECOM-3 Cable Test Results

Table 2-20 shows a comparison of the performance of ECOM-1 and ECOM-3 cables.

TABLE 2-19  
GRIPPING AND SLIPPAGE

CABLE TYPE	GRIP TYPE	LOAD (N)	GAUGE LENGTH (cm)	CABLE ELONGATION % @ load	SLIPPAGE (2) (cm)				
					After 1 minute	2	3	4	5
ECON 1	KELLEMS *	445	61	0	1.3	(1)	(1)	(1)	(1)
ECON 3	KELLEMS	445	61	0	0.6	1.0	1.3	1.6	2.0
ECON 1	Dead End*	1114	64	0.9	0.1	0.1	0.1	0.1	0.1
ECON 3	Dead End	1114	65	0.9	0.3	0.3	0.3	0.3	0.3

\* 0.187" - 0.25" KELLEMS Grip

\* 1/4" Dead End Grip

(1) Cable slipped at this load

(2) Total slip length after each time interval



TABLE 2-20

Test	ECOM-1	ECOM-3
Impact Resistance Test	2.6 N-m G	1.9 N-m G
Bend Test	G	G
Twist Test	G	G
Attenuation vs Tension	G	G
Fatigue Test	G	G
Roadway Survival	F <sup>1</sup>	F <sup>1</sup>
High Temperature Attenuation	F	F
Low Temperature Attenuation	-45°C P -55°C P	-45°C F -55°C P
Minimum Storage Radius	I	F
Gripping and Slippage	P	P
G = Good      F = Fair      P = Poor      I = Inconclusive		

<sup>1</sup>Results may have been affected by suspected intentional damage.

2.1.3.1 Impact Resistance Test

The results of the test performed at Room Temperature (25°C) confirm that the central strength member cable (ECOM-1) is more impact resistant than the external strength member cable (ECOM-3). This superiority is not clear at either low (-45°C) or elevated temperature (+85°C). There was no fiber break in either design at -45°C up to an impact load of 4.7 N-m and at +85°C up to a load of 3.4 N-m.

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2.1.3.2 Bend Test

The goal of no fiber breakage was achieved for all samples of the ECOM-3 design and all but one sample of the ECOM-1 design. These tests were performed at room temperature (26°C), low temperature (-45°C) and elevated temperature (+85°C).

2.1.3.3 Twist Test

There was no fiber break in this test over a wide temperature range.

2.1.3.4 Attenuation vs Tension

There was no measurable increase in attenuation when the cable was subjected to a load of 182 kg.

2.1.3.5 Fatigue

With a static tensile load of 45 kg applied to the cable, the fiber attenuation and cable jacket slippage were monitored. The ECOM-1 and ECOM-3 cables survived for two months without fiber breakage. There was no observable jacket slippage.

2.1.3.6 Roadway Survival

The ECOM-1 and ECOM-3 cables were tested for cable integrity during a two month test. The results of this test are inconclusive because of suspected intentional damage.

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2.1.3.7 High Temperature Attenuation

The ECOM-1 and ECOM-3 cables were tested in accordance with the Cable Test Plan, except that the fibers were individually tested for attenuation. The post test fiber attenuation showed a slight increase over the pre-test values.

2.1.3.8 Low Temperature Attenuation

Neither ECOM-1 nor ECOM-3 had light transmission at  $-55^{\circ}\text{C}$ , however, at  $-45^{\circ}\text{C}$  both transmitted light; ECOM-1 had a higher attenuation increase (15 to 30 dB/km compared to 5-10 dB/km for ECOM-3).

2.1.3.9 Minimum Storage Radius

Cable designs ECOM-1 and 3 were evaluated to determine the effect of storage, on small diameter reels at temperature extremes.

Tables 2-21 and 2-22 show the effect of the reel diameter on attenuation, which was measured at room temperature, before and after exposure to the temperature extremes.

Tables 2-21 and 2-22 show the attenuation in absolute "dB" and in "dB/km". Since the length of the cables in the 11 cm and 25 cm reels are short, the accuracy of the test is affected, and the measurement uncertainty becomes a factor to be considered when analyzing the test results.

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Tables 2-23 and 2-24 show the attenuation of cables ECOM-1 and ECOM-3 respectively, before and after they have been in 15 cm coils. The similar behavior of the coiled and reeled cables eliminates factors such as spool expansion.

The strange behavior of the cables wound on the 25 cm reels has not been satisfactorily explained. Factors such as cable length, measurement uncertainty, quality of core/clad interface could be interacting and helping to distort the final results. ITT has conducted temperature cycling test on glass core/glass clad fiber optic cables, of closely related designs at the temperatures of +85°C, 25°C and -50°C and found that during the low temperature cycle, the optical loss increases 1.5 dB/km, however, this attenuation increase is reversible at room temperature. Therefore, this evaluation on 25 cm reels has been considered inconclusive.

A slight set was observed in the cables from all spools. The cables can be wound in reel diameters as small as 11 cm experiencing a modest increase in attenuation after exposure to extreme temperatures.

The results require further study since selected fibers exhibited greater attenuation increases than others.

2.2 Phase II - Optimized Cable Design

This section addresses the design and testing of an optimized low cost cable.

2.2.1 Requirements

The contract technical guidelines requires compliance with the requirements in the following subsections.

2.2.1.1 Attenuation

The attenuation of all fibers in the cable must be less than 12 dB/km when measured at a minimum of 4 selected wavelengths between 6,000 and 10,600 A°.

2.2.1.2 Impact

Cables will be tested at room temperature, at -55°C and at +85°C. 90% of the fibers must survive a load of 4 N-m after 200 impacts when tested to MIL-C-13777.

2.2.1.3 Fatigue

The effect on fiber attenuation and jacket slippage as a result of continuous static tensile load shall be determined. A load of 45 kg shall be applied and changes in transmission characteristics shall be monitored in each fiber daily during the first week, and weekly thereafter for two months. Jacket slippage shall also be monitored at the same time.

2.2.1.4 Bend

The cables shall be tested in accordance with MIL-C-13777. The objective is no fiber break or other cable damage. Changes in attenuation after each temperature condition shall be recorded.

2.2.2 Performance of ECOM 1 and 3 vs Optimized Cable Specification

2.2.2.1 Attenuation

The ECOM 3 cable has no problems meeting the 12 dB/km maximum attenuation, however the attenuation of the ECOM 1 design depends on the quality of the surface of



the internal strenght member. Since ITT has experienced problems buying the strength member with a consistently smooth surface, the ECOM 1 design is not favored for low loss performance.

2.2.2.2 Impact

ECOM 1 has demonstrated superior impact resistance over ECOM 3, however, ECOM 1 does not meet the optimized specification. This characteristic is a prime target for improvement.

2.2.2.3 Fatigue

Neither design showed any significant increase in attenuation due to static fatigue. There was no jacket slippage at the specified load of 445 N (100 lbs). During the gripping and slippage test, where the load is specified at 1782 N (440 lbs), the jacket slips when the load reaches 445 with Kellems Grips and 1114 N with Dead End Grips. This is another characteristic that is targeted for improvement.

2.2.2.4 Bend

Both designs met this requirement, this characteristic is not expected to change in the optimized cable design.

2.2.2.5 Minimum Storage Radius

The ECOM 1 and ECOM 3 cables were evaluated to determine the effect on the cable of storage on small diameter reels at temperature extremes. Reels with drum diameters of 11, 15, and 25 cm were used. A slight set was observed in the cables after storage on all spools sizes. The optical behavior of the cables is difficult to interpret since the highest loss occurred on the 25 cm spool.

2.2.2.6 Gripping and Slippage

The ECOM 1 and ECOM 3 cables had jacket slippage with Kellems grips at 445N and with "Dead End Grips" at 1114N. The required load was 1782 N.

2.3 Phase II Optimized Cable Designs

2.3.1 Design Parameters

It was established from the Technical Guidelines, that the following improvements were required:

- o Lower the attenuation of the fibers to 12 dB/km
- o Improve impact resistance level to 4 N-m
- o Reduce jacket slippage (1782 N required)

It was also the intent of this contract to retain the following, already achieved, cable characteristics:

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- o Tensile strength 182 kg
- o Flexing and twisting, per MIL-C-13777, performance.
- o Fungus Resistance
- o Operating temperature range  $-55^{\circ}\text{C}^*$  to  $+85^{\circ}\text{C}$
- o Nuclear survivability
- o Metallic cable components not allowed

### 2.3.2 Cable Design

#### 2.3.2.1 Attenuation

The attenuation goal of 12 dB/km can be achieved because of the dramatic improvement of the transmission characteristics of the plastic clad silica fibers. It is necessary to minimize the excess cable losses which results primarily from micro-bending and fiber diameter variations.

The sensitivity of the fiber to microbending losses, in general, can be reduced by:

- a) increasing the numerical aperture
- b) reducing the fiber core diameter
- c) increasing the overall fiber diameter
- d) use of a soft fiber buffer coating and a hard extruded jacket

---

\* The fibers do not transmit light at  $-55^{\circ}\text{C}$ .



Since the numerical aperture and fiber core diameter should not change, fiber diameter uniformity and the use of a soft/hard combination fiber coating are the elements which can be changed to control the sensitivity of the fiber to microbending losses. The fiber diameter uniformity has been greatly improved through the use of optical diameter monitors. The coated diameter of the fiber has been increased to 1 mm. The fiber consists of a high purity synthetic silica core, an RTV silicone cladding and a polyester elastomer (Hytrel<sup>®</sup>) jacket.

#### 2.3.2.2 Impact Resistance

The failure of a fiber during the impact test is produced by one of the following mechanisms:

- a) propagation of a microcrack or
- b) the fiber is forced to suddenly elongate, in excess of its maximum elongation

The improvements of impact resistance can be achieved through the use of

- a) Fibers with high mechanical strength
- b) A resilient buffer coating of a sufficient thickness to support the fiber and absorb part of the impact
- c) A hard outer jacket with a low friction surface
- d) As much mechanical protection as the cable diameter permits

2.3.2.3 Reduce Jacket Slippage

The major reason for jacket slippage in the ECOM 1 and 3 cable designs is that the jacket is applied over a TFE tape wrapped core. That tape was used primarily, in ECOM 1, to isolate the fibers from the jacket and in ECOM 1 and 3, to keep all the cable components in the proper position. It has been found that the tape is not necessary and has been eliminated.

The strength member was changed from neoprene impregnated Kevlar<sup>®</sup> to non-impregnated Kevlar<sup>®</sup>. This change allows some filaments to be embedded in the Polyurethane jacket, resulting in a reinforced jacket with less tendency to slip.

2.3.2.4 Already Achieved Cable Characteristics

The design improvements may affect the following cable characteristics:

- a) Tensile Strength - The non-impregnated Kevlar<sup>®</sup> strength member consists of loose parallel filaments (1000 per yarn). Slight variations in tension in these filaments will cause some of them to take more load than others and reach their break point earlier. Because of this characteristic, it is not recommended to exceed 70% of the breaking load. The breaking load in this case is in excess of 270 kg. The tensile strength requirement is 182 kg, it has been

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already demonstrated and the cable meets it without difficulty.

b) Flexing and Twisting per MIL-C-13777 - Limited testing indicates that the Optimized Design meets both, flexing and twisting, requirements per MIL-C-13777.

c) Temperature Range - It has been found that the plastic clad silica fiber optic waveguides will not transmit light at  $-55^{\circ}\text{C}$  because the refractive index of RTV silicone increases and matches the refractive index of the silica, however attenuation increases at  $-45^{\circ}\text{C}$ , in the ECOM 3 cable design, is only 5 to 10 dB/km.

A study, aimed to increase the light transmission at low temperatures, was performed using a plastic cladding consisting of a mixture of 50% GE-670 and 50% Shin-Etsu KE-103 RTV Silicones. The performance of this mixture at low temperature was slightly better than the performance of fibers with Shin Etsu cladding. Therefore, the mixture of GE-670 and Shin Etsu RTV Silicones was initially selected to clad the optical fibers of the deliverable cables. The decision was later changed because it was found that the cables made with the RTV silicone mixture exhibited too much excess cabling losses.

Appendix B shows the evaluation of fibers cladded with the GE-670/Shin Etsu mix and fibers cladded with Shin Etsu RTV silicone.

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The ECOM 3 cable design experienced a slight increase in attenuation at 85°C. This higher loss was attributed to shrinkback of the strength member which in turn compressed the optical core. The optimized cable design has fibers with a heavier plastic jacket which is expected to reduce microbending.

- d) Nuclear Survivability - This characteristic is a function of the radiation resistance of the materials used, especially of the core and cladding of the optical fiber. Since these materials have not been changed, the optimized cable is expected to retain the performance of the cables developed in the prior contract.

### 2.3.3 Cable Components

Almost all the cable components in the Optimized, Low Cost Cable Design were used in the ECOM-3 cable design. They are:

- a) Optical Fiber - Table 2.3-1 below compares the fibers used in ECOM 3 to those used in the Optimized Cable Designs. Table 2.3-1

	ECOM 3	Optimized Design
Silica	Suprasil 2	Suprasil 2
RTV Silicone	Shin Etsu	Shin Etsu
Jacket Diameter	.5 mm	1 mm
Jacketing Material	Tefon PFA	Hytrel

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The differences are in the jacket material and the outside diameter. These changes were made for the following reasons:

- o The larger diameter fiber is a key element in achieving the mechanical properties already described.
  - o The heavy wall with the small fiber core is not easy to achieve consistently with a tubing extrusion. Teflon PFA does not lend itself to pressure extrusion.
  - o Hytrel processes easier by both pressure and tubing extrusion methods and does not corrode processing equipment.
  - o Hytrel meets the operating temperature range of the cable.
- b) Strength Members - Kevlar is an aramid yarn developed and produced by Dupont. Kevlar was selected in the prior contract because it has the highest Young Modulus of the non-conductive, readily available materials and because it is capable of operating in the specified temperature range.

Kevlar 49 is commercially available in several yarn sizes (195, 380, 1420 and 7100 deniers). It is sold either as a raw (non-impregnated) yarn or as a twisted and impregnated yarn.

ITT EOPD has selected non-impregnated Kevlar 49 (1420 denier) because it can meet and exceed the required tensile strength at the lowest cost while allowing adhesion to the jacket to reduce or eliminate jacket slippage.

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- c) Polyurethane Jacket -Thermoplastic polyurethanes have a unique combination of properties. They combine the resiliency of elastomers with the toughness of thermoplastics. Their abrasion and tear resistance exceed those of neoprene. The polyester grades of polyurethanes are sensitive to hydrolysis while the polyether grades are not. A polyether grade has been selected for this application.

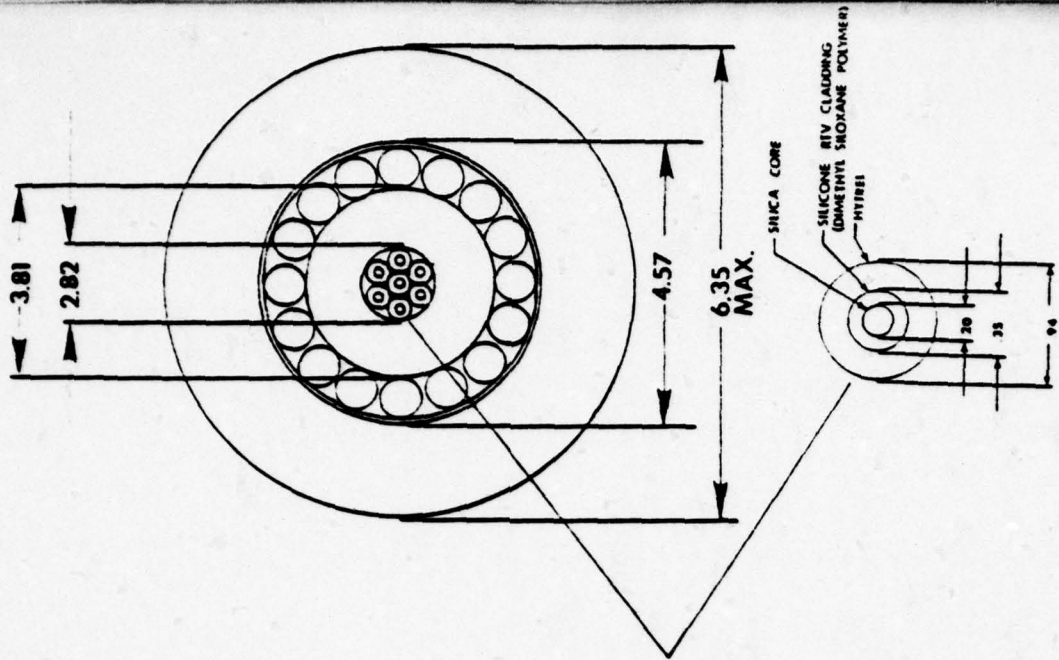
#### 2.3.4 Optimized, Low Cost Fiber Optic Cable Design

Figure 2.3-1 depicts the cable designed to meet the technical guidelines of this contract. Its optical core consists of seven plastic clad silica fibers with a heavy Hytrel<sup>®</sup> jacket. This bundle has a polyurethane jacket (polyether grade). The strength members are 18 yarns of Kevlar 49<sup>®</sup> (1420 deniers). These yarns are non-impregnated to reduce jacket slippage and lower cost. The Kevlar yarns are helically laid around the polyurethane jacketed optical core. A final polyurethane jacket provides mechanical protection against abrasion, impact, and the environment. This outer polyurethane jacket is a flame retardant polyether grade. This type jacket will reduce the gloss of the cable.

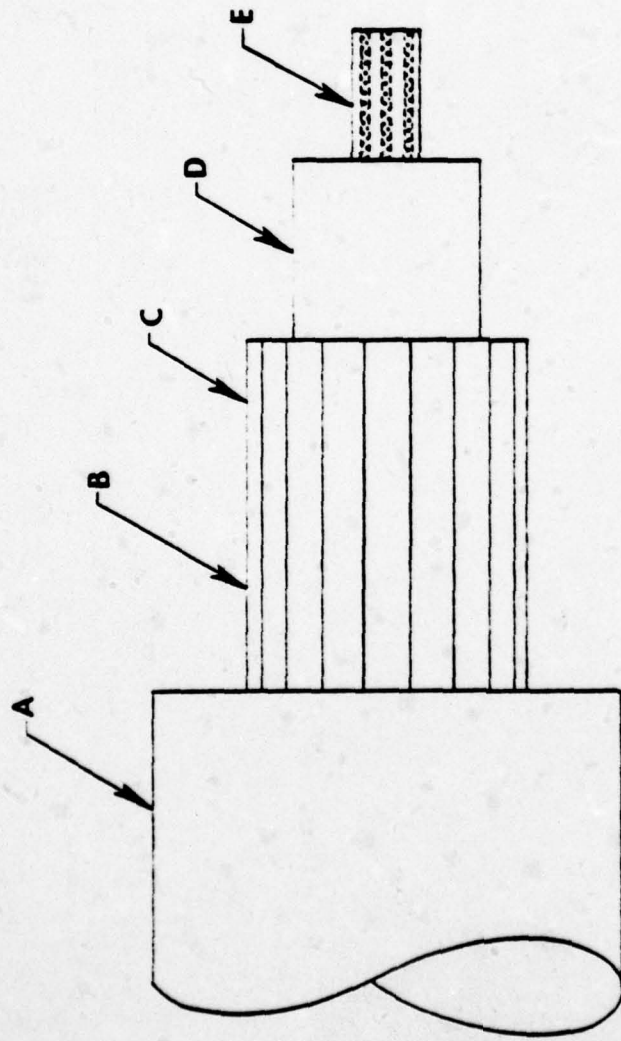
This cable has sufficient tensile strength to meet or exceed the requirement in the technical guidelines.

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PLASTIC CLAD SILICA FIBER



- A - POLYURETHANE OUTER JACKET
- B - TFE TAPE
- C - HELICALLY LAID KEVLAR 49 STRENGTH MEMBER YARNS (LAY LENGTH 4.2')
- D - POLYURETHANE INNER JACKET
- E - OPTICAL FIBER BUNDLE (LAY LENGTH 2.0')

# OPTIMIZED LOW COST FIBER OPTIC CABLE

Figure 2.3-1

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3.0 CABLE FABRICATION

Several cables of the ECOM-1 and ECOM-3 designs were made to be used in the mechanical evaluation (Phase I) of this program.

They are:

<u>ECOM-1</u>	<u>ECOM-3</u>
072277 -A-I 600m	071777 -AA-II 650m
072500 -A-I 500m	091677 -AA-II 545m
101177 -A-I 400m	101477 -BB-II 400m

The optimized fiber optic cable design cable was fabricated for both design evaluation and deliverable cables. They are:

102777 -AA- II	Two short sections (with & without TFE tape)
122277 -AA- II	225m
061378 -22- II	379m
061478 -22- II	515m
061578 -22- II	390m
110678 -CA- II	370m
110778 -BA- II	378m

Cables 061378 -22- II, 061478 -22- II and 061578 -22- II were made using the GE-670/Shin Etsu coated fibers. Their attenuation at .82  $\mu$ m before and after cabling is shown in Table 3-1 .

Table 3-1

Attenuation @ .82  $\mu$ m

Cable Batch	Fiber No.	Before Cabling	After Cabling	Cable Length
061378-ZZ-II	1	16.14 dB/km	19.45 dB/km	379 m
	2	11.55	18.47	
	3	11.55	20.86	
	4	11.67	20.37	
	5	11.55	21.39	
	6	11.67	23.01	
	7	11.67	21.81	
	Average	12.26 dB/km	20.77 dB/km	
061478-ZZ-II	1	10.67 dB/km	15.30 dB/km	519 m
	2	10.33	13.50	
	3	10.03	14.38	
	4	8.90	14.69	
	5	10.56	12.05	
	6	10.79	18.13	
	7	8.16	12.94	
	Average	9.92 dB/km	14.43 dB/km	
061578-ZZ-II	1	10.67 dB/km	19.35 dB/km	389 m
	2	10.33	28.50	
	3	10.03	14.23	
	4	8.90	18.31	
	5	10.56	17.07	
	6	10.03	14.95	
	7	10.56	21.78	
	Average	10.15 dB/km	19.17 dB/km	

NOTE: Cables 061378-ZZ-II, 061478-ZZ-II and 061578-ZZ-II were made with fibers having a 50% blend GE-670 and Shin-Etsu RTV Silcione Cladding.



Cable 061377-22-II was fabricated for the mechanical evaluation of the optimized, low cost, fiber optic cable design, and cables 061477-22-II and 061577-22-II were fabricated as deliverable cable.

The unexpectedly high excess cabling losses required an explanation. Since this cable design is very similar to ECOM-3, the only difference is the diameter of the coated fiber; and ECOM-3 had low excess cabling losses, it is believed that the silica core/plastic cladding interface has been affected during the cabling operations.

It is also believed that the GE-670/Shin Etsu mixture has less adhesion to the silica core than Shin Etsu RTV silicone, therefore, during handling or processing the silica core/silicone clad interface would be affected, causing higher attenuation.

It was decided to abandon the GE-670/Shin Etsu RTV silicone mixture and use only Shin Etsu RTV silicone as cladding material. It was also decided to fabricate two more cables with the Shin Etsu coated fibers.

### 3.1 Optimized Fiber Optic Cable Evaluation

The evaluation of the Optimized Fiber Optic Cable Design was

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performed in accordance with the Technical Guidelines of this contract.

3.1.1 Attenuation

The optical attenuation was measured at four different wavelengths and the results are shown in Table 3-2. It can be seen that the 12 dB/km goal was met at the following wavelengths: .65 - .79 and .82  $\mu\text{m}$ , but it was not achieved at 1.05  $\mu\text{m}$ . Figure 3-1 shows the spectral attenuation of a Suprasil 2 plastic clad silica fiber. There is a typical increase of 5 to 6 dB/km at 1.05  $\mu\text{m}$  wavelength over the attenuation at .82  $\mu\text{m}$  wavelength.

Table 3-2

Cable Batch #	Fiber #	Attenuation (dB/km)				Cable Length
		.65 $\mu\text{m}$	.79 $\mu\text{m}$	.82 $\mu\text{m}$	1.05 $\mu\text{m}$	
110678-CA-II	1	8.02	5.80	9.40	13.54	367m
	2	9.53	6.63	10.56	16.41	
	3	8.81	6.80	10.66	17.11	
	4	8.09	6.76	10.50	14.84	
	5	8.67	6.98	10.84	15.09	
	6	7.62	5.79	9.51	14.52	
	7	7.45	5.84	9.46	14.30	
	Average		8.31	6.37	10.31	
110778-BA-II	1	7.48	6.04	9.61	13.53	378m
	2	11.16	8.28	11.97	19.97	
	3	8.74	6.82	10.61	16.63	
	4	7.85	6.06	9.89	16.77	
	5	7.54	6.07	9.84	17.20	
	6	8.79	6.94	10.88	18.29	
	7	8.43	6.98	10.62	15.67	
	Average		8.57	6.74	10.48	

\*Note: The fibers of cables 110678-CA-II and 110778-BA-II were made with fibers having Shin Etsu RTV silicone cladding.

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Fiber Spectral Loss

Fiber No.: 050977D-5

Fiber Type: SS2

Buffer: Shin-Etsu RTV silicone

Length: 500 meters

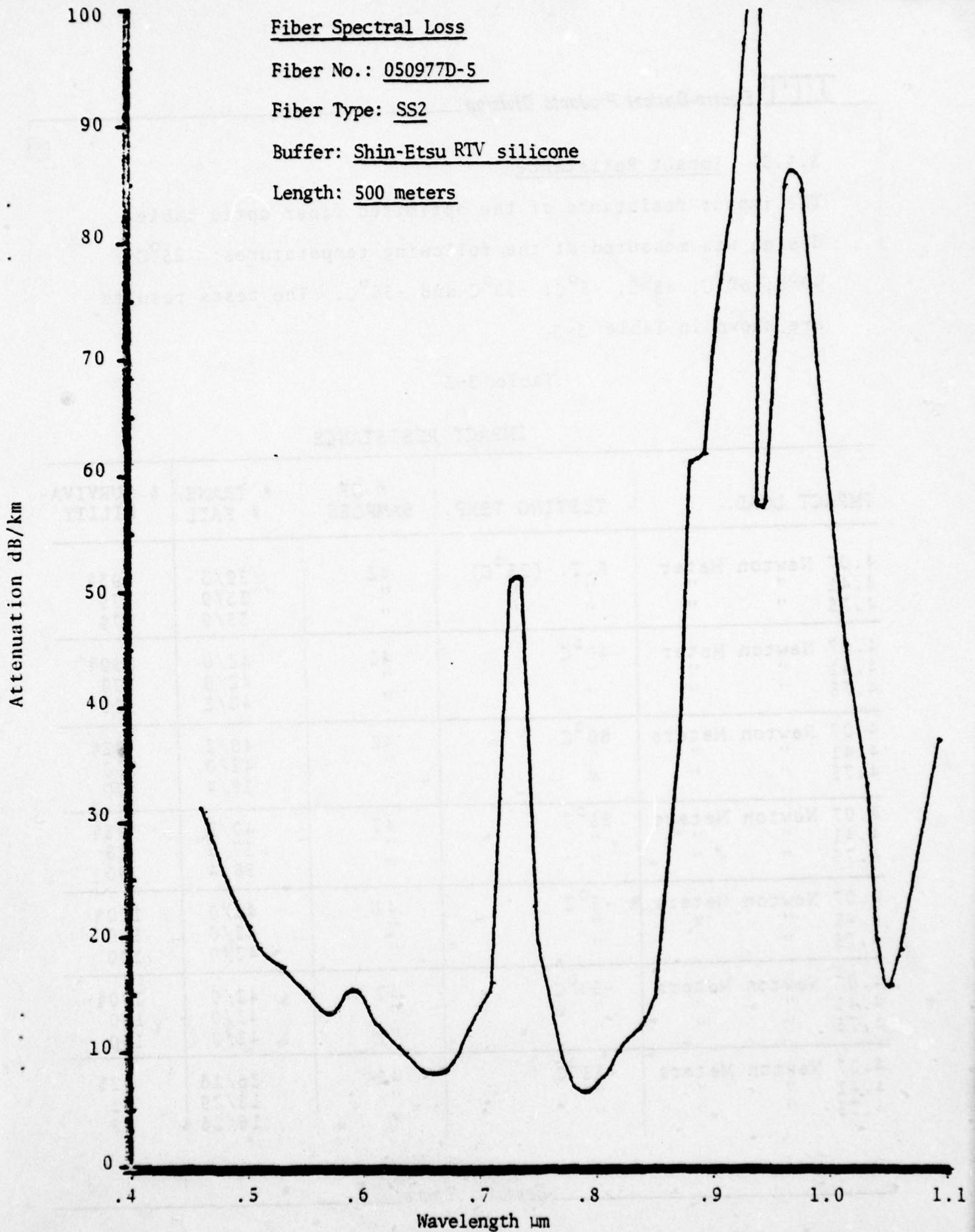


Figure 3.1 Plastic Clad Silica Optical Fiber



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3.1.2 Impact Resistance

The impact resistance of the optimized fiber optic cable design was measured at the following temperatures: 25°C; 40°C; 60°C; 85°C; -5°C; -30°C and -55°C. The tests results are shown in Table 3-3.

Table 3-3

IMPACT RESISTANCE

IMPACT LOAD	TESTING TEMP.	# OF SAMPLES	# TRANS/ # FAIL	% SURVIVABILITY
4.07 Newton Meter	R.T. (25°C)	42	39/3	93%
4.41 " "	" "	"	33/9	79
4.75 " "	" "	"	33/9	79
4.07 Newton Meter	40°C	42	42/0	100%
4.41 " "	" "	"	42/0	100
4.75 " "	" "	"	40/2	95
4.07 Newton Meters	60°C	42	40/2	95%
4.41 " "	" "	"	42/0	100
4.75 " "	" "	"	38/4	90
4.07 Newton Meters	85°C	42	40/2	95%
4.41 " "	" "	"	37/5	88
4.75 " "	" "	"	38/4	90
4.07 Newton Meters	-5°C	42	42/0	100%
4.41 " "	" "	"	42/0	100
4.75 " "	" "	"	42/0	100
4.07 Newton Meters	-30°C	42	42/0	100%
4.41 " "	" "	"	42/0	100
4.75 " "	" "	"	42/0	100
4.07 Newton Meters	-55°C	42	26/16	62%
4.41 " "	" "	"	13/29	31
4.75 " "	" "	"	16/26	33

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Table 3-3.1

IMPACT RESISTANCE

Energy Level/ Sample #	Room Temperature Break Location/ Fiber Trans	+85°C Break Location/ Fiber Trans	+60°C Break Location/ Fiber Trans	+40°C Break Location/ Fiber Trans	5°C & -30°C
4.07 Newton Meter	S1	--/7	116/6	--/7	No fiber breakage at these two temp. levels. The outer polyurethane jacket had a slight indent- ation. -30°C seems to be the light trans- mittance transition level, because output oscillated as the temp. changed from -25°C to -35°C.
	S2	--/7	--/7	--/7	
	S3	149, 192/5	144/6	173/6	
	S4	--/7	--/7	--/7	
	S5	--/7	--/7	--/7	
	S6	*/6	--/7	--/7	
4.41 Newton Meter	S7	--/7	151, 182/5	--/7	Impact Resistance at -55°C was measured by the number of trans- mitting fibers, after temperature was increased to 25°C.
	S8	127/6	82/6	--/7	
	S9	108, 135/5	--/7	--/7	
	S10	49, 69/5	65, 67/5	--/7	
	S11	49, 69/5	--/7	--/7	
	S12	116, 132/5	194/6	--/7	
4.75 Newton Meter	S13	95/6	67, 167/5	48/6	See Table 3- 3 for surviving fibers.
	S14	--/7	91/6	--/7	
	S15	89(2)/5	--/7	82/7	
	S16	19(2), 89/4	--/7	--/7	
	S17	68/6	158/6	150/6	
	S18	57, 62/5	--/7	126/6	

\*Only 6 fibers were transmitting  
before testing.

DATA DISTRIBUTION  
Optimized Low Cost Fiber Optic Cable

3.1.3 Bend

The Flex Test, per MIL-C-13777, was performed at 25°C; 85°C; and -55°C with no fiber failure, or any visible degradation.

3.1.4 Fatigue

Table 3-4 shows the performance of the optimized fiber optic cable when submitted to the Fatigue Test in accordance with the Cable Test Plan.

Table 3-4

FATIGUE TEST - ATTENUATION dB/km (@ .82 μm)

DATE	8/25/78	8/25/78	9/1/78	9/9/78	10/6/78	10/24/78	10/25/78
Load (kg)	0	50.45	47.27	45.45	46.60	46.60	0
Fiber (Central)							
#1	28.76	29.15	29.39	29.33	30.54	14.19	29.82
2	25.17	25.17	23.90	23.09	27.78	26.87	23.67
3	20.57	21.49	21.74	21.07	23.86	21.83	22.84
4	24.76	26.69	26.58	26.87	28.57	28.39	26.21
5	22.62	23.66	23.03	26.62	26.38	28.29	23.02
6	20.64	22.04	21.82	24.27	23.08	23.84	22.50
7	27.83	28.77	28.97	29.16	22.13*	28.67	29.03
Average	24.34	25.28	25.06	25.77	26.70	26.31	25.30

\*Fibers #7 10/6/78 and #1 10/24/78 exhibit lower attenuation than expected. They have not been included in the calculation of the average attenuation.



It must be noted that the high attenuation of this cable is attributed to the GE-670/Shin Etsu RTV silicone cladding of the optical fibers.

4.0 COMPARATIVE COST-FIBER OPTIC CABLE VS. CONVENTIONAL  
ELECTRO-MAGNETIC CABLE

One of the objectives of this contract was to develop a fiber optic cable that will be cost competitive with conventional cables when manufactured in large volumes. This section briefly compares the dimensional characteristics and projected costs of cables developed under this contract with the presently used conventional WM-130 cable, used in the CX-4566 cable assemblies.

A comparison of dimensional characteristics for both cable types is shown in Table 5.1.

Table 5.1

	<u>OPTIMIZED FIBER OPTIC CABLE</u>	<u>WM-130</u>
Diameter	.250"	.503"
Weight	30 kg/km	219 kg/km
Length/Spool	1 km	76 meters

The above data clearly shows the space and weight savings offered by fiber optic cables.

Fiber optic cables similar in structure to those developed under this program which incorporate 6 plastic clad silica fibers and have an attenuation of 12 dB/km, are commercially available for \$6.50/meter. Comparable WM-130 cable (26-pair) is priced

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at approximately \$7.55/meter in similar quantities (10-20 km)

This cost comparison indicates that optical cables are already cost competitive with multipairs copper cables. Further improvements in optical fiber and cable fabrication equipment and processes will achieve even greater cost reductions.

Substantial progress toward cost reduction of all-glass optical fibers is also expected during the 1979-1982 time frame.

The cost of the WM-130 cable will be progressively higher due to inflationary pressures. Since the plastic clad silica cables are already cost competitive, time will only make them more attractive.

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## 5.0 SUMMARY

The three phases of this cable development contract have been completed. Their results can be summarized as follows:

### Phase I - Evaluation of ECOM Cable Types 1 and 3 -

While the ECOM 1 cable design was superior in mechanical performance, the ECOM-3 cable demonstrated superior optical performance.

The performance of the ECOM-1 and 3 cables at temperature extremes was surprisingly better than the room temperature results except for the low temperature increase of optical attenuation.

### Phase II - Optimized Fiber Optic Cable Design

Since the ECOM-3 design had better optical performance than the ECOM-1 design, it was selected for mechanical optimization. It was found that the heavier buffer of the optical fiber was a major factor in achieving the specified cable parameters. One millimeter fibers were selected for this task because of their compatibility with existing connectors.

### Phase III - Cable Fabrication

The optimized cable design was first fabricated with GE-670/Shin Etsu clad fibers. The excess cabling losses were too

high; this problem was corrected when fibers clad with Shin Etsu RTV Silicone were used.

Better than the required 90% survivability was achieved in the specified impact testing, except at  $-55^{\circ}\text{C}$  where the fiber breakage due to jacket brittleness, was only 62% at 4.07 newton-meters. The final deliverable cables were fabricated with Roylar E-9B jacket, which had exhibited superior performance in the low temperature impact test.

The objective for all fibers in the cable to have attenuation less than 12 dB/km, at a minimum of four selected wavelengths, was met at the following wavelengths:

.65  $\mu\text{m}$ , .79  $\mu\text{m}$ , and .82  $\mu\text{m}$ . The goal was not met at 1.05  $\mu\text{m}$  due to the optical characteristics of the Suprasil 2 silica. See the spectral curve shown in Figure 3.1.

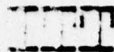
The cable met the Flex Test of MIL-C-13777 at the temperature extremes as well as at  $25^{\circ}\text{C}$ .

The cable exhibited only a minor variation of attenuation during the two months it was under load in the Fatigue Test.

The Optimized Low Cost Fiber Optic Cable Design has substantially reduced the materials and fabrication cost.

Examples of the efforts in cost reduction are:

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- o Use Non-Impregnated Kevlar 49 - 1420 deniers instead of Impregnated Kevlar 49 - 1420 deniers. (Non-Impregnated Kevlar 49 - 1420 deniers costs \$8.50/lb and each pound yields 2800 meters approximately, while Impregnated and twisted Kevlar 49 - 1420 deniers costs \$25.25/lb and each pound yields 2300 meters approximately.)
- o Elimination of TFE tape (It costs \$7.50/lb.) This step also allows the production rate to be increased substantially.



## 6.0 CONCLUSIONS

Rugged fiber optic cables were produced meeting most of the requirements for tactical field applications. The following conclusions have been reached at the end of this contract.

- o Rugged optical fiber cables employing plastic clad silica fibers have been fabricated with optical attenuation meeting the 12 dB/km goal at the following wavelengths: .65, .79. and .82  $\mu\text{m}$ .
- o The contract goal of 90% fiber survivability at a load of 4.07 Newton-Meter was achieved when testing per MIL-C-13777 at the following temperatures: 85, 60, 40, 25, -5 and -30°C. But it was not achieved at -55°C due to jacket brittleness. This problem can be easily corrected by changing the grade of the outer polyurethane jacket, which was done in the final deliverable cables. No secondary effects are expected in other cable properties.
- o Optical cables can be fabricated with tensile strengths required for field applications.
- o Cycling, bending and twisting have no adverse effects on optical continuity of the fiber optic cables.
- o With present fibers, the attenuation of plastic clad silica fiber cables increases to a level that limits their usefulness.
- o It is recommended that glass core/clad fibers, with core size of 100  $\mu\text{m}$  be considered for this application. Cables using the optimized design and these fibers should be fabricated and evaluated against this contract's goals.
- o Large core glass fibers will still allow the use of low cost light sources.
- o Optical fiber cables are already cost competitive with cable WM-130 (26 pairs).

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APPENDIX A

REPORT ON PERFORMANCE OF PLASTIC  
CLAD SILICA FIBERS IN LOW TEMPERATURE ATTENUATION TEST

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Five PCS fibers with different cladding and jacketing materials were tested for low temperature attenuation effects. Three attenuation vs. temperature tests were performed because of inconsistent results attributed to inadequate thermal settling time and in-chamber frost accumulation, respectively, in the first two tests. The attenuation of each fiber was monitored at successive ambient temperatures of +25°C, -40°C, -45°C, -40°C, and +25°C with a minimum settling time of 19 hours between measurements (see attached temperature profile). Each fiber was coiled in a 12.5 inch diameter loop during the test period. Test results are shown in Table 1.

Of the five fibers tested, Fiber 4 (Shin-Etsu/GE RTV) and Fiber 1 (Shin Etsu/GE RTV .040" Hytrel) performed the best, with  $\Delta\alpha = -2.7$  and 46.8 dB/km, respectively, at -45°C. Fiber 3 transmitted to -40°C with  $\Delta\alpha = -3.7$  dB/km, while fibers 2 and 5 failed to transmit at -40°C. None of the fibers transmitted 0.79  $\mu\text{m}$  radiation at -50°C.

Observation of the fibers injected with .63  $\mu\text{m}$  light at -45°C revealed that the fibers not transmitting (2, 3, 5) suffered excess jacket loss prior to entry into the test chamber, with the remaining light being lost in the first few meters within the chamber, while Fiber 4 showed no excess loss.



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All the fibers tested showed a different characteristic during the increasing temperature readings. Only Fiber 1 transmitted at  $-40^{\circ}\text{C}$  and no fibers at  $-45^{\circ}\text{C}$ , indicating possible hysteresis in the thermal characteristic.

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TABLE I - PCS Low Temperature Attenuation Test Results

Attenuation dB/km (.124 NA, 0.79 μm)

Fiber	Cladding	Jacket	Length M	T <sub>A</sub> °C	Attenuation dB/km						
					+25	-40	-45	-50	-45	-40	+25
1. 030778-(DE)EK-3	Shin-Etsu/ GE RIV 670	.040" Ilyrel	505	8.4	34.1	55.2	*	*	*	57.5	8.6
2. 030778-(DE)EK-4	Shin-Etsu	.040" Ilyrel	556	17.8	*	*	*	*	*	*	12.1
3. 030878-D-6	Shin-Etsu	None	649	4.6	8.3	*	*	*	*	*	4.6
4. 030878-D-5	Shin-Etsu/ GE RIV 670	None	549	6.1	8.7	8.8	*	*	*	*	5.6
5. 030678-(DE)-3	Shin-Etsu/ GE RIV 670	.020" Ilyrel	1200	11.3	*	*	*	*	*	*	9.9

\*No transmission

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