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SHIELDING EFFECTIVENESS TESTS ON TYPICAL ACCESS FACILITY TELEPHONE CABLES

by

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ABSTRACT

This report summarizes work conducted in support of the Access Facility Study Program for the Defense Communications Agency. Six different types of telephone cables were tested to obtain information on their shielding quality and the electrical parameters affecting shielding. The shielding results were correlated with a lumped parameter model adequate for the cable lengths tested. Also, an initial investigation into standard grounding practices was conducted. The results of this study are analyzed from a system protection standpoint.

Work is continuing on other cable types and in correlating the responses on long and short cables of the same type.

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1. INTRODUCTION

The access facility study was conducted to determine the inherent hardness to an electromagnetic pulse (EMP) of the system of cables, repeaters, and protection devices in the facility. The access facility extends from the main distribution frames at the common-carrier node to the main distribution frame at the military installation, including all main-frame protection devices and guards. It is therefore essential to have a knowledge of typical telephone-cable shielding characteristics, shield-termination schemes, protection-device response, and many other fundamental response characteristics of elements or general practices used in the communications industry.

This interim report provides information on the shielding quality of six types of telephone cables, electrical parameters affecting the shielding, and an initial investigation into grounding practices. It is known that the six cables tested (table I) are representative of the different types of cables used in the access facilities.

Table I. List of simplex cables typically found in access facilities

Cable	Shield	No. pairs	Conductor Gauge	Comments
C1	Lead	26	19	
C2	Lead	202	22	
C3	Lead	300	19	Armor tape
C4	Steel and aluminum	100	22	Stalpeth
C5	Aluminum	100	22	Alpeth
C6	Steel and aluminum	600	24	Stalpeth

All of these cables were manufactured by Anaconda Wire and Cable Company. Each cable type was tested on the HDL 1020B cable driver.

Cable studies of types other than those described herein will be summarized in a subsequent report.

2. CABLE PREPARATION FOR TESTING

The cables are prepared for testing by

(1) Cutting each cable to a length of 4-1/2 feet;

(2) Connecting internal conductors together to form a shorted bundle at one end;

(3) Soldering a solid copper-cap to the shield on the same cable end and the shorted bundle is then terminated to the shield via the cap forming a short circuit (this end is connected to the cable driver current source);

(4) Soldering the shield on the opposite instrumentation end of the cable to a copper flange, which is used to connect the cable to the instrumentation box (fig.1);

(5) Shorting together the internal conductors at the instrumentation end and making measurements by terminating this bundle through a known impedance to the inside of the instrumentation box.

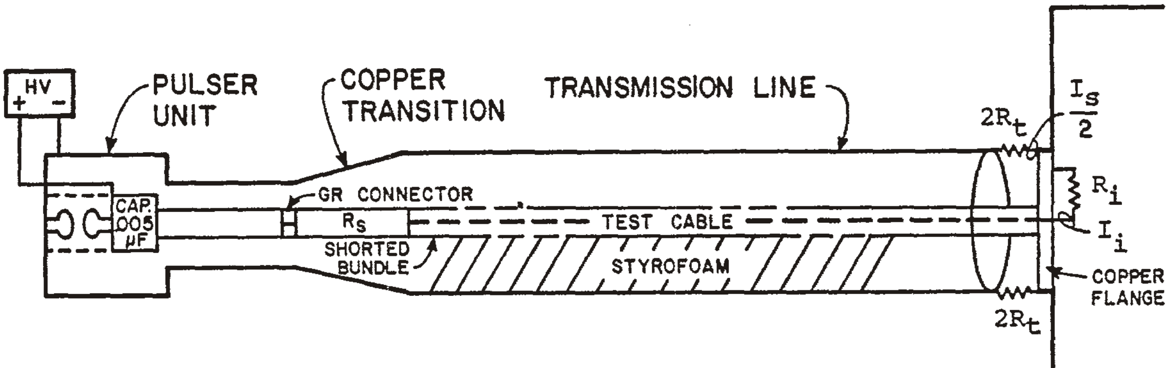

Figure 1. Short driver set-up

3. DRIVER TECHNIQUES

A cutaway view of the 1020B cable driver (pulser and transmission line) is shown in figure 1. The cable driver injects a current, I_s, on the external shield of the cable, as shown in figure 2. This sheath current, I_s, is measured with a CT2 current probe placed around the lead on one of the termination resistors, R_t, which carries one-half of the sheath current. The peak sheath current used for these tests is approximately 75 A. The internal current, I_i, was usually measured with a CTI current probe with a balanced resistive termination of either a 50- or 5-Ω impedance. In some instances, however, the voltage across the resistor had to be measured with a P6046 differential voltage probe because the internal current was below the sensitivity of the CTI current probe.

Both the external and the internal currents were recorded in the time domain (with a Tektronix 7904 oscilloscope) and in the frequency domain (with a Hewlett Packard 8553B/8552 spectrum analyzer). The techniques used in the time domain data collection are very straight forward and have been reported in the past.[1] However, it is felt that the data collection and reduction techniques used for the frequency domain information is fairly unique and worthy of further explanation here.

The frequency spectrum of both the internal and external current are taken over the range of 0.01 to 100MHz in four separate intervals (90.01 to 0.11 MHz; 0.1 to 1.1 MHz; 0 to 100 MHz). The spectral bandwidth used for each interval is 1, 10, 30, and 100 kHz, respectively.

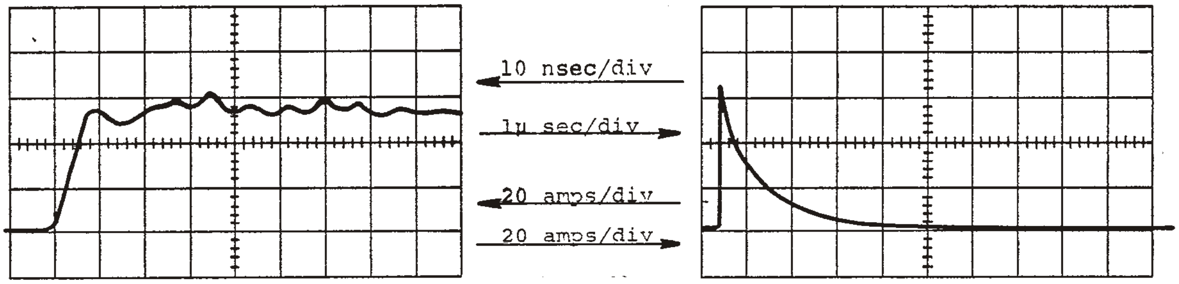

Figure 2: External sheath current

The driver pulser is adjusted to give about two pulses per second, and the analyzer is set at its slowest sweep rate of 10 sec/div, which gives a frequency resolution of about 1 percent of the center frequency. Care must be taken to insure that the IF section of the spectrum analyzer is not saturated. This is done by increasing the input attenuation until linear reductions of the spectrum are observed. The spectrums are recorded on 3000 speed polaroid flat back film with a Tektronix C30A camera.

These data are then reduced by hand to obtain the shielding effectiveness transfer function of the cable, $SE_{(\omega)}$, which is defined by equation 1.

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[1] USA Mobility Equipment Research and Development Center Report 1989, "Shielding Effectiveness of XM50 Firing System Cables," by Robert F. Gray, Oct. 1970.

$$\begin{aligned} S.E._{(\omega)} &= 20 \operatorname{Log}_{10} \left[F_{(\omega)} \; (I_i/I_s) \right] \\ &= 20 \operatorname{Log}_{10} \left[F_{(\omega)} \; (I_i/I_R) \right] - 20 \operatorname{Log}_{10} \left[F_{(\omega)} \; (I_s/I_R) \right] + K \\ &= Q_{i_{(\omega)}} - Q_{s_{(\omega)}} + K \end{aligned} \qquad (1)$$

Where I_i is the internal current
I_s is the external current
I_R is the standard reference current used in the H.P. spectrum analyzer
K is the scale factor in decibels (dB) for both current probes and the quantities $Q_{i_{(\omega)}}$ and $Q_{s_{(\omega)}}$ represent the Fourier spectrums in dB of the internal current and the external current respectively as measured by the spectrum analyzer.

The shielding effectiveness transfer function of the cable has proved to be an extremely useful technique in determining the relative shielding provided by cable shields. This technique has been used to resolve as little as 2 dB across the band increases in shielding effectiveness in carefully controlled tests. Also, the transfer function obtained by the above method does not have the frequency limitation problems that a Fast Fourier Transform (FFT) on a computer has (the upper-frequency limit in FFT is equal to the number of data pairs divided by the pulse width and the lower frequency limit is the reciprocal of the pulse width).

4. MODEL DEVELOPMENT

A computer program was written to predict theoretical values of transfer impedance and shielding efficiency for the cables being tested. The following equation* was used in the program for the transfer impedance, Z_t of a solid shield.

$$\text{Transfer impedance, } |Z_t| \,, = \ell \cdot \frac{\sqrt{\mu \cdot f}}{\sqrt{\pi \cdot g \cdot A \cdot B \,(\cosh u - \cos u)}} \qquad (2)$$

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* These equations were suggested by S.A. Schelkunoff in a Bell System Technical Journal Vol. 13, dated October 1934.

where $u = t\sqrt{2.g.\omega.\mu}$
ℓ = length of cable,
t = thickness of shield,
A = radial distance to inner surface of shield,
B = radial distance to external surface of shield,
μ = permeability of shield,
g = conductivity of shield, and
f = frequency

An equivalent circuit for the cables being tested is shown below.

I_p - Source current
I_s - Sheath current
I_i - Internal current

R_t - Internal termination
Z_t - Shield transfer impedance

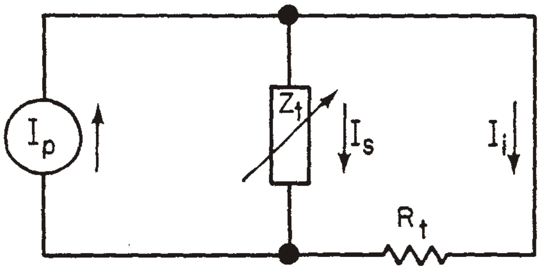

Figure 3. Equivalent circuit for solid shield cable

Solving for the ratio of internal current to external current we find:

$$\frac{I_i}{I_s} = \frac{Z_t}{R_t} \qquad (3)$$

and, therefore, the shielding effectiveness for the cable is given by

$$SE_{(\omega)} = 20 \text{ Log}_{10} \left|\frac{I_i}{I_s}\right| = 20 \text{ Log}_{10} \frac{|Z_t|}{R_t} ,$$

or $\qquad (4)$

$$SE_{(\omega)} = 20 \text{ Log}_{10} \frac{\ell \sqrt{\mu \cdot f}}{R_t \sqrt{\pi \cdot g \cdot A \cdot B} \, (\cosh u - \cos u)}$$

These equations were solved for each cable at frequencies from 0.01 to 10 MHz, and the results plotted along with the experimental results presented in figures 4 through 9.

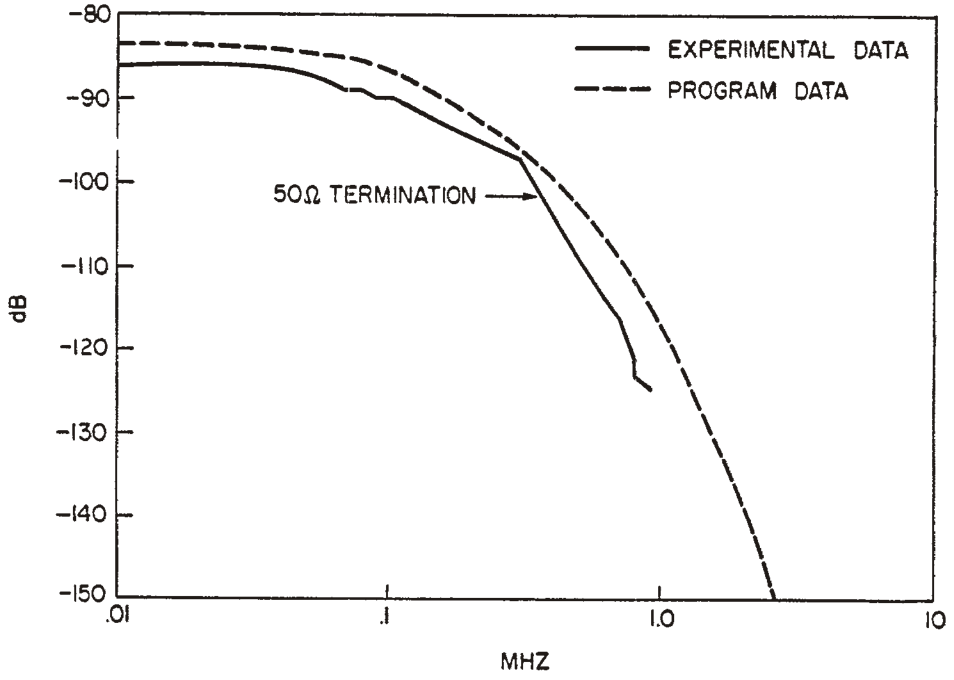

Figure 4. Experimental results for cable C1

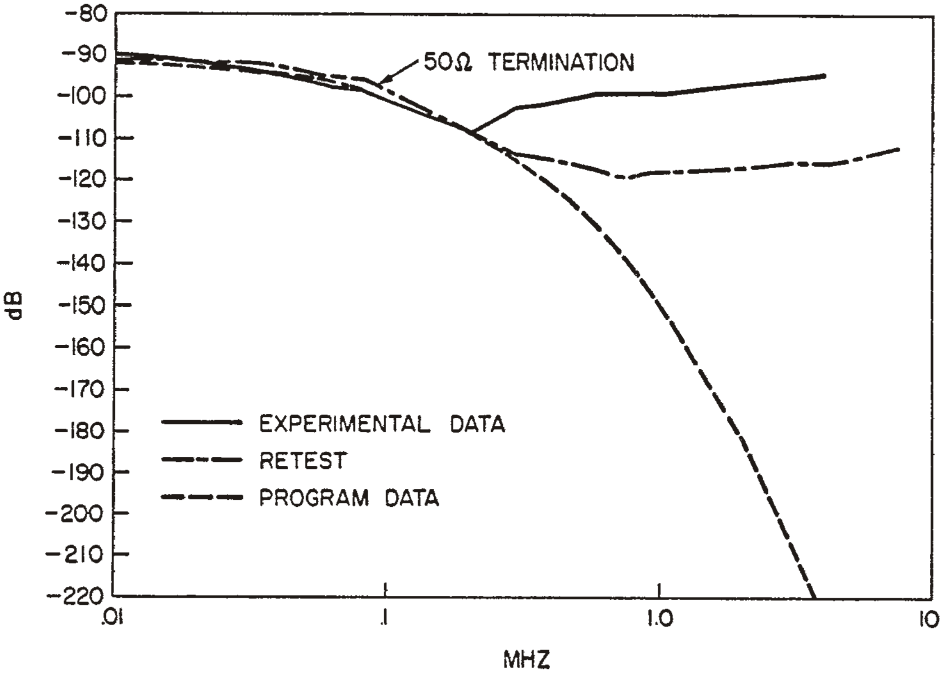

Figure 5. Experimental results for cable C2

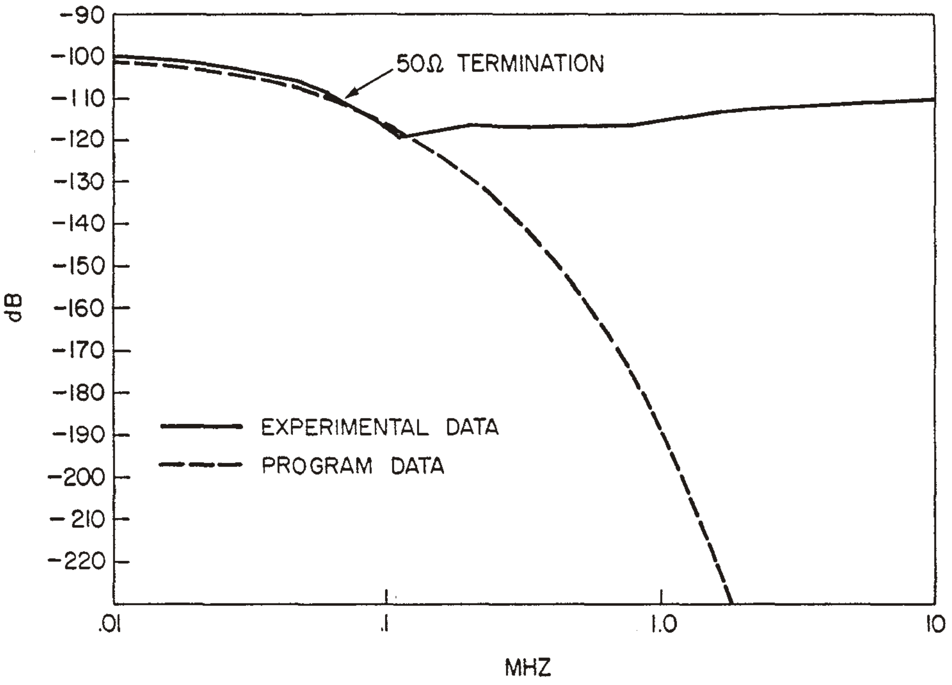

Figure 6. Experimental results for cable C3

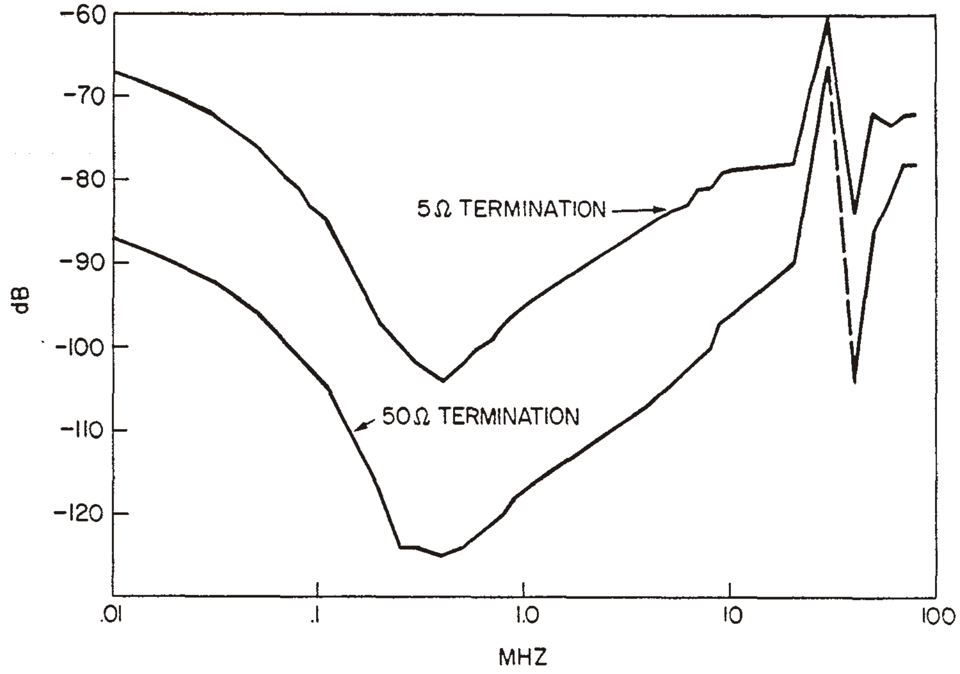

Figure 7. Experimental results for cable C4

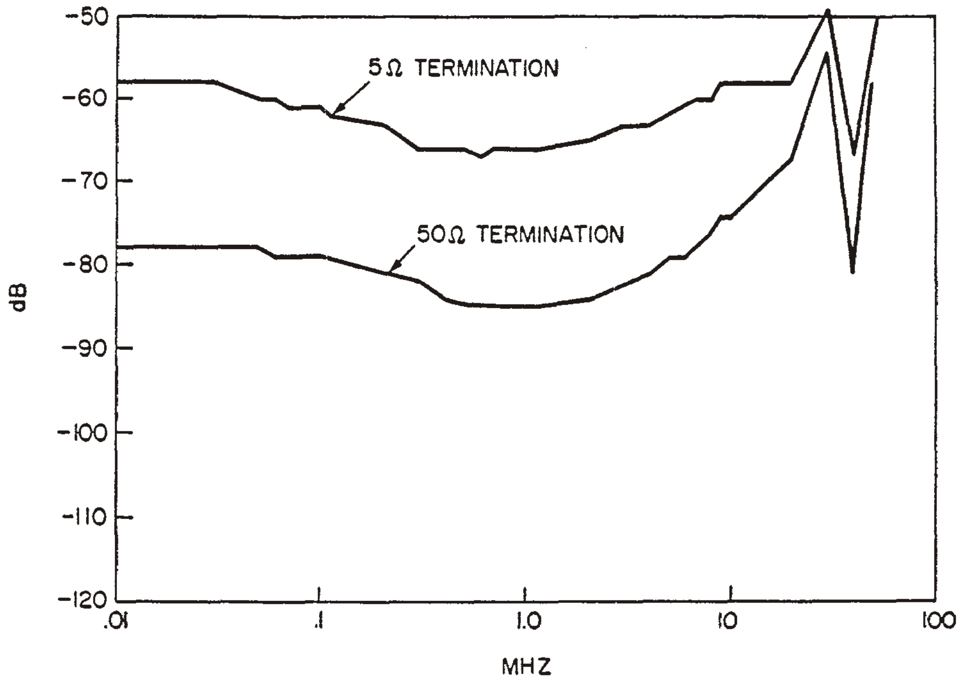

Figure 8. Experimental results for cable C5

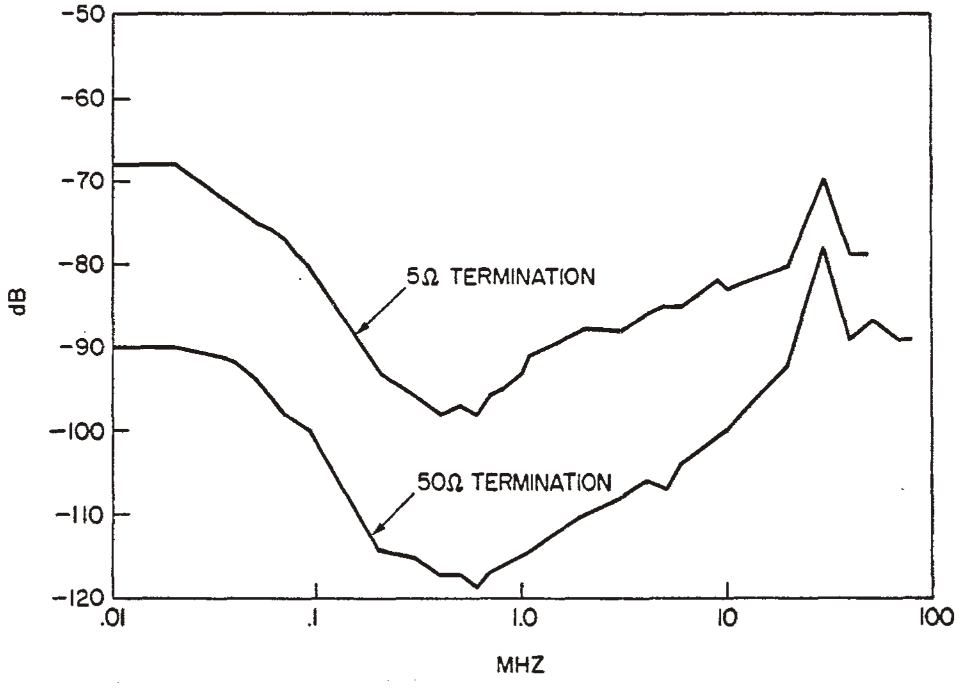

Figure 9. Experimental results for cable C6

The data generated by the program and the experimental data were in very close agreement for the shielded lead cables, up to frequencies of 0.5 MHz. After this point the observed shielding efficiency was less than the predicted value. Two possible reasons for this behavior were (1) that there was rf leakage around the joints formed by the termination of the copper flange to the instrumentation box which would give rise to the decrease in shielding effectiveness at the higher frequencies, or (2) that the limitation of the instrumentation had been reached which is around 120 dB.

We attempted to resolve this point by retesting cable C5 after a concerted effort was made to block all paths of possible leakage. The results of this retest showed marked improvement over the original test. This led us to conclude that leakage was a major problem that had to be considered in further testing of these cables.

The multiple shielded cables posed a calculational problem that is still unsettled. Originally, an attempt was made to combine the permeability and conductance of the two metals and arrive at an average value that could be used in the above equations. When the values of shielding efficiency obtained from the program were combined with the values obtained experimentally, there was a large difference. The experimental values of shielding efficiency were much less than those predicted by using the program. Since the same test setup was used for the lead cables and all the other parameters were held constant, it was assumed that the error was with the program, specifically in the values that had been assumed for μ and g. After determining new values for these two parameters, the program was used to calculate the shielding efficiency again. The new values gave somewhat better results but we were not able to obtain the close agreement that we had for the lead shielded cables. It has been concluded that in dealing with multiple shields the previously used equation for Z_t is not valid. More work is necessary if this problem is to resolved.

The experimentally obtained shielding effectiveness transfer functions and the analytical curves are plotted in figures 4 through 9. The cable parameters used in the computer program are tabulated in table II.

Table II. Data for cables tested

CABLE SHIELD	THICKNESS (cm)	A (cm)	B (cm)	LENGTH (cm)	μ (H/cm)	g (mhos/cm)	R_D-C (ohms/cm)
C1 LEAD	0.159	0.787	0.946	137.3	12.57×10^{-9}	4.3077×10^{4}	1.915×10^{-5}
C2 LEAD	0.2285	1.397	1.625	137.3	12.57×10^{-9}	4.8077×10^{4}	1.02×10^{-5}
C3 LEAD	0.318	2.872	3.19	137.3	12.57×10^{-9}	4.8077×10^{4}	1.24×10^{5}
C4 ALUMINUM STEEL	0.361 0.606	0.964	1.06	137.3	12.57×10^{-9}	0.33×10^{6}	2.53×10^{-5}
C5 ALUMINUM	0.566	1.154	1.21	137.3	12.57×10^{-9}	0.33×10^{6}	3.38×10^{-5}
C6 ALUMINUM STEEL	0.0509 0.0844	2.245	2.380	137.3	12.57×10^{-9}	0.33×10^{6}	

5. ANALYSIS OF RESULTS

A comparison of the high-frequency shielding ($f > 1 \text{MHz}$) of the lead-shielded cables with that of the steel and aluminum and all-aluminum shields shows that the solid-lead shields all exhibit greater shielding at these frequencies. It is also seen that the analytical model does not predict the characteristic leveling off around 110 to 120 dB of the transfer function of the lead shields at higher frequencies. As stated, it is felt that this deviation from the predicted curve is due to inherent leakage of the test facility. This was demonstrated in the retest of cable C2 in which a reworking of the test facility joints caused a significant reduction in the transfer function. We will therefore consider 110 to 120 dB to be the noise level of the testing system and only signals above this noise level will be considered legitimate for frequencies 1 and 10 megahertz. Therefore, it was felt that the transfer function of the C4, C5 and C6 are accurate and their decrease in shielding compared to the lead-shielded cable is due to leakage through the split in the shields that are not soldered or continuously welded. Both the steel and aluminum shields are formed by rolling a corrugated strip of the material around the cable bundle and overlapping the ends by about 1/2 in.

This effect can be modeled by adding a reactive component ($j\omega L_s$) to the shield transfer impedance. At the higher frequencies, this reactance would dominate the transfer impedance, making a calculation of its magnitude simple.

For $f > 1 \text{MHz}$ $$SE_{(\omega)} \simeq 20 \text{ Log } \frac{\omega L_s}{R_t}$$

The above approximation gives the following results for the reactive term of the transfer impedance:

(H/m)

$L_{C4} = 7.3 \times 10^{-12}$

$L_{C5} = 1.2 \times 10^{-10}$

$L_{C6} = 6.0 \times 10^{-12}$

The two steel-aluminum sheathed cables exhibit approximately the same amount of leakage due to their similar construction, However, the single-aluminum shield has more than an order of magnitude greater leakage because of the single shield.

This leakage inductance term would then be added to the transfer impedance given earlier to compensate for the high frequency leakage through the seam.

6. SHIELD TERMINATION TEST

A termination test was conducted using cable C2 with the following modification. The cable external shield was insulated from the flanged connector and a copper jumper strap measuring 2 in. long, 1/2 in. wide, and 10 mil thick was then used to make the electrical connection from the flange to the lead shield, Except for this modification, the normal short-driver setup diagramed in figure 1 was used. A detailed schematic diagram of the jumper setup used is given in figure 10.

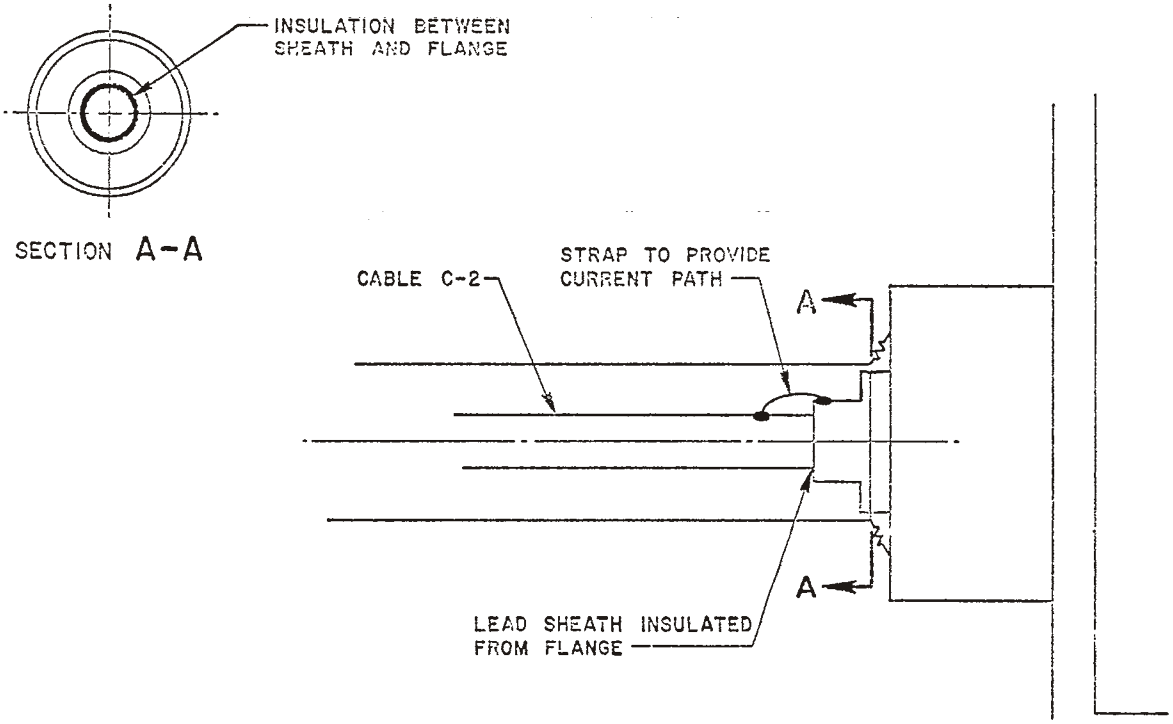

Figure 10. Simulated telephone shield termination

Although much shorter in length, this configuration is similar to that used in the cable pit or vaults of the access facilities where the ground termination is typically made by a 3/8-inch strap attached to the shield. This strap is then brought to the outside grounding points. The shields for the cables entering the cable vault normally continue up to the main frame where they are left unterminated. Therefore the field conditions are simulated in the laboratory as accurately as possible with this setup.

This test produced very different results than did the first test of C2. The basic difference is that in this test the current has a very small path to travel in leaving the shield and this allows more of the current to go into the conductors. This greatly reduces the shielding efficiency of the cable, particularly at high frequencies; this can be seen in figure 11, in which the original test of cable C2 is repeated for clarity.

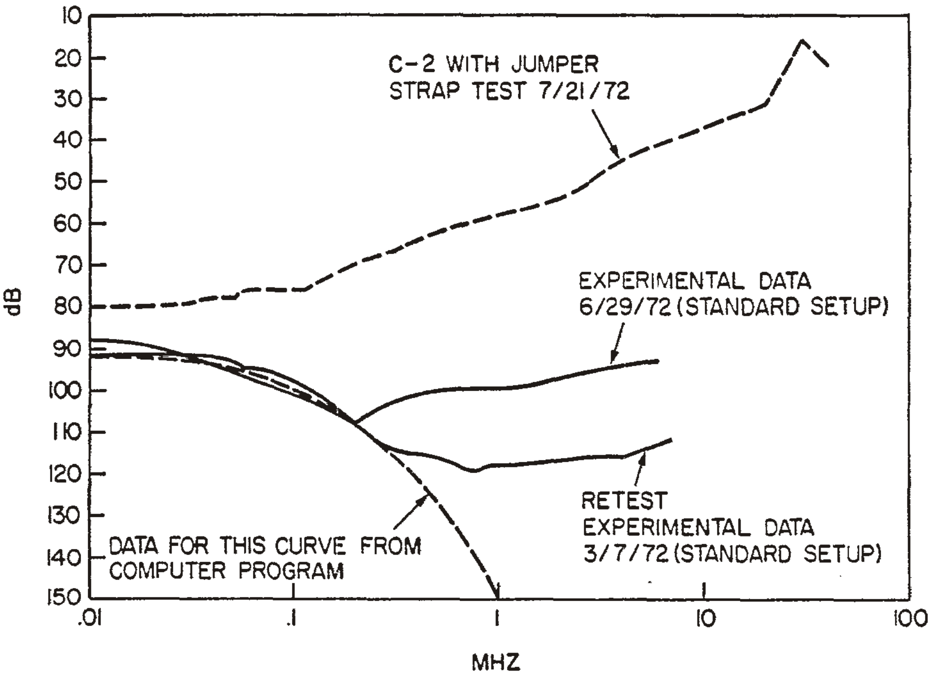

Figure 11. Comparison of cable C2 responses for various test configurations

A calculation of the inductance of the ground strap yields 25 nH. Using the experimental results to calculate the magnitude of the reactive component of the shield-transfer impedance gives an equivalent inductance of 12 nH.

7. CONCLUSIONS

Shielding effectiveness transfer functions have been obtained and verified for the six telephone cables considered. Correlation was made between experimental and predicted transfer functions for the solid-lead sheathed cables. The analysis was not as valid for the steel- and aluminum-sheathed cables. The problem of treating multiple shields will have to be analyzed more extensively. However, the experimental data for these cables are valid and interpolations for other cables may be possible.

The analytical model developed here can be used to predict the transfer function for any lead-sheathed cable knowing only its length, outside diameter, and the thickness of the shield. There is, however, a frequency versus cable length limitation for the model. The lumped parameter model is only valid for frequencies below one tenth the fundamental frequency of the cable which is equal to the velocity of propagation V_p, divided by the cable length, ℓ, ($f \leq .1 V_p/\ell$).

Therefore, to make accurate predictions for very long cables, transmission-line theory must be applied using the transfer impedances described here. It should also be pointed out that the internal response of a cable is highly dependent on the distribution of the external sheath current and the termination of the cable shield.

This fact leads to the importance of proper termination of the shields as demonstrated, both in the leakage problem of the test-fixture joints and in the ground-strap-termination test. Serious alterations in the cable transfer function were noted by using a termination strap similar although much shorter in length to the standard termination strap used in access facilities. In an actual access facility, the longer termination strap would have a proportionately higher impedance and therefore would greatly increase the coupling of an external transient current to the interior bundle, making proper protection of equipment more difficult. The actual performance of the protective carbon blocks on the main distribution frame would most likely have to be determined experimentally.

However, by applying some engineering intuition, it is possible to visualize at least two undesirable effects created by the standard procedure of grounding both the cable shields and the main distribution frame through the same long ground lead. First, since all of the internal equipment uses the same gounding system as the shields of the external cables, it is possible that the energy flowing on the shields could be coupled into the internal equipment. At the frequencies being considered, long ground runs will appear nonexistent and the entire installation may be driven to some high potential above ground.

A second phenomenon that could occur at the main frame under the above conditions would be the operation of the protective carbon blocks in reverse. Since the cable shield is at a much higher potential than that of the internal bundle, the carbon blocks could conduct in a reverse direction (from the main frame to the internal wires) if the main frame ground floats with the sheath current. The current on the shield will seek the closest lower potential, which could be the inner bundle and not the ground rods.

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