COPPER CLAD ALUMINUM FINE WIRE IN COAXIAL CABLE

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Two years ago at your annual convention in Boston, Texas Instruments
presented a paper suggesting that a materials system of copper clad
aluminum had significant application possibilities in the area of
CATV semi-rigid trunk or distribution cables. At that time your
industry had little experience, and no regular users, of this
material. For that reason the paper centered on an evaluation in
depth of those technical aspects of copper clad aluminum cable
relevant to its suitability for CATV. It might be well to review
the primary considerations of that presentation.

First, you may recall, we calculated the skin depth of copper
required to transmit the range of RF signals employed in CATV,
and compared it with the skin depth present on 15% copper clad
aluminum cable of three common gauges. Table I summarizes these
findings. Note that even at the lowest frequency, 15% copper clad
aluminum in the .412 cable provides approximately 3 times the skin
depth of copper needed to transmit this range of RF signals.

Next, we made a characteristic-by-characteristic comparison of
copper clad aluminum and solid copper conductors, as indicated
in Table II. Since this comparison would seem to indicate D.C.
electrical resistance as a possible drawback to copper clad
aluminum, we investigated this in considerable detail to determine
what this difference in resistivity could mean in CATV applications.
The conclusion, you may recall, was that use of copper clad aluminum
in an actual system approximating our theoretical analysis would
provide sufficient benefits in cost to more than offset the expense
of additional power supplies that might be required.

The paper also explored such factors as a comparison of thermal
expansion coefficients, especially as they might relate to the
common problem of conductor pullout; compared weights as they
might affect handling and safety; and discussed other significant
characteristics of copper clad aluminum.

Today, most of these points hardly require discussion with your
industry, because you have acquired considerable first-hand
experience with copper clad aluminum cable. It is, as you know,
receiving extensive use nationally, is readily available from
important suppliers to your industry, and has been chosen by major
installers for thousands of miles of CATV service.

We should, however, review briefly the experience to date on
conductor pullout. At the time of our first report we suggested
that the closely matched coefficients of linear expansion of a
copper clad aluminum center conductor and an aluminum outer

conductor should significantly reduce conductor pullout and cable buckling. As it turned out, the combination of matching coefficients of center and outer conductors only partially relieved this phenomenon. One factor remained unchanged: the coefficient of linear expansion of the dielectric material between the conductors. At least one major cable manufacturer has made significant progress recently in overcoming this final obstacle to pullout-free cable. Their solution is the application of optimum-adhesion bonding techniques between the conductors and dielectric. The field experience to date using this improved cable indicates that this approach goes a long way toward solving the pullout problem.

So much for background. Now let's examine what is happening with copper clad aluminum wire today, again as it relates to the CATV industry.

Early this year Texas Instruments announced to the cable industry the availability of copper clad aluminum in fine wire sizes as small as 40 gauge--finer than a human hair. The significance of this development to CATV is that you now can choose copper clad aluminum for drop cables, as well as for semi-rigid trunk or distribution cables.

It is particularly timely for us to re-examine drop cables today-- in light of increasing subscriber demand for high quality signals and the more rigid enforcement of government regulations on signal leakage and interference. The time has come, in short, for CATV to address itself to this, the weakest link in its transmission system. First let us consider the nature of the problem with drop cables as they generally exist today.

Since drop cable is installed or used only when a subscriber requests CATV service, it has not been considered a primary installation item, as with trunk or distribution cables. Perhaps for that reason drop cable design seldom has emphasized performance. RG-59B/U (Table III) flexible cable per MIL-C-17D is used extensively as a basic drop cable. But many variations and modifications have been made on this cable, primarily to reduce its cost. Performance, in fact, has been ignored to the point that some drop cables on the market have an incompatible characteristic impedance of 88 ohms, caused from substituting foam for solid dielectric without properly adjusting the diameter ratio of inner and outer conductors. Ironically, as drop cable performance has deteriorated, the acceptance of color TV has made the need for better drop cable designs increasingly important.

What, then, are the characteristics of good drop cable design, and what are the alternatives in selecting cable for CATV systems? Table IV lists eight significant items for consideration when you are selecting drop cable. Using this as a guide, we can analyze the three types of drop cable available today, classified by the type of shielding employed: solid metallic, braid, or metallic tape.

SOLID METALLIC SHIELD

Drop cable with a solid metallic shield is similar in design to semi-rigid trunk and distribution cable, except of a smaller gauge. Without question it offers the most effective shielding, the greatest durability, and potential for long service life. On the other hand, installation is relatively difficult because it lacks flexibility and has greater weight than either braided or metallic tape cable. Principally for economic reasons, solid metallic shielded cable is used only in extreme cases of high signal density, where its exceptional shielding capability is of great value.

BRAIDED SHIELD

There are two types of drop cable employing braided shielding, one with a single braid and the other with a double braid. The principal difference between them is the significantly greater shielding provided by a double braid. A single braid cable design, RG-59, has been the standard drop cable for many years and has been specified for military applications. It received this wide acceptance because:

--It is readily available from all cable manufacturers

--Its 75 ohm impedance matches CATV system design

--Its flexibility makes it easy to handle and install

--It has good mechanical strength permitting unsupported aerial installation

--It has been performance-proven for over 30 years, including specification by the military

--Its copper clad steel center conductor can be used as a center pin for Type F connectors, thereby reducing connector costs

Its one drawback, in the single-braided form, is shielding effectiveness. On the other hand, no other design offers the flexibility and service reliability of braided cable. For that reason virtually all government-specified flexible cables are of braided design. Where required, double-braid cable can provide acceptable shielding of operating frequencies into the microwave region.

METALLIC TAPE SHIELD

The second type of drop cable in common use today is shielded by
a thin metallic tape of copper or aluminum foil, frequently bonded
adhesively inside a dielectric layer for mechanical strength.
Tape may be applied either longitudinally or in a helical wrap.
Longitudinal shielding is more effective but has poor flex-life.
Helical wrapping is flexible but offers relatively poor shielding.
Since the metallic tape cannot effectively conduct a power signal,
a drain wire or outer braid must be added to complete cable functions.
Tape-shielded cable provides excellent shielding until it is exposed
to repeated flexing and alternating thermal expansion and
contraction. If the elements cause even a small break at a
transverse plane, severe signal leakage can result, because a
signal radiator forms immediately. Cable flexing tests conducted
by Texas Instruments according to standard test methods MIL-C-915
resulted in drain wire failure at 300 flex cycles and metallic
tape failure after 800 cycles. (By way of comparison, braided
cable has maintained satisfactory performance after more than
2,000 cycles.)

As indicated in Table V, braided cable continues to offer the
best combination of drop wire characteristics. With copper
clad aluminum now available for braided cable application, the
question remains: can copper clad aluminum substitute for solid
copper braid without compromising performance? To answer this
we must examine the nature and properties of copper clad aluminum.

MAKING COPPER CLAD ALUMINUM FINE WIRE

From a material supplier's point of view, the standard copper
clad aluminum material is a 5/16" redraw rod. Its solid aluminum
core is covered completely and continuously with a layer of solid
copper. The ratio of cross-sectional area or volume is nominally
85% Al to 15% Cu. This rod is made by a continuous metallurgical
bonding process which joins these dissimilar metals at their atomic
level. There is no physical separation of the metals and no bonding
or adhesive elements are used in uniting the copper and aluminum
layers.

As a result of this kind of bonding, copper clad aluminum rod
performs and works exactly like a monometallic conductor. In
fact, 5/16" copper clad aluminum rod can be drawn and in-line
annealed down to 40 AWG fine wire on regular copper wire drawing
machines. For cable application, 36 AWG wire is the smallest in
common use today. In-line resistive annealing is essential in
copper clad aluminum fine wire manufacture to assure long flex-
life and more desirable spring-back qualities.

Important to the manufacture of copper clad aluminum fine wire is the fact that rod can be drawn down to fine wire sizes without any change in cladding volume or area ratio. In Figure VI-A, showing magnified cross sections of a 5/16" rod and a #36 gauge fine wire, it is obvious that cladding area is maintained uniformly and concentrically. In fact, from a 1/4" length of rod we can create 71 feet of fine wire, as shown in Figure VI-B, with no ratio change.

PROPERTIES OF COPPER CLAD ALUMINUM FINE WIRE

Since copper clad aluminum fine wire is a metallic structure of both copper and aluminum, many of its properties--such as tensile strength, spring-back and DC resistivity--reflect the basic properties of the two monometals held in bond. But some important properties such as skin effect, RF resistivity, and braid contact resistance are different enough to require analysis.

Six important RF cable properties are listed in Table VII. According to these formulas for coaxial cable, it can be seen that characteristic impedance, capacitance, reflection coefficient and VSWR will not change when a copper conductor is replaced by an equal size copper clad aluminum conductor. This is because the function formulas are independent with respect to conductor resistivity. Attenuation and Q-factor formulas do depend on resistivity of the cable conductor and its skin depth.

A major reason for using copper clad aluminum wire for CATV transmission cable is its skin effect. As mentioned in our previous paper, there is ample copper to carry television signal frequencies in all three sizes of copper clad aluminum distribution cable. RF attenuation characteristics of the cable are exactly the same as with a solid copper center conductor.

Now, what will happen in a coaxial drop cable having copper clad aluminum fine wire with a copper skin depth only 0.000256" thick? The analysis given in Tables VIII and IX shows that even if the copper thickness of copper clad aluminum fine wire is less than one skin depth at the lowest television frequency, the effect on cable attenuation is still negligible. The reasons are:

--RF current density decreases logarithmically with respect to depth in conductor.

--Aluminum is also a good RF conductor.

--Braid resistivity contributes a much lower percentage of the loop resistance than center conductor resistivity.

As shown in Table IX, the theoretical attenuation increase due to AWG 34 copper clad aluminum braid shield in RG-59 B/U cable is only 2.7% at 50 MHz and 2.2% at 250 MHz. In laboratory tests, there are no significant differences in any RF property when copper clad aluminum braid shield cable is compared with solid copper braid, as shown in Table X.

BRAID CONTACT RESISTANCE

In braided cable design for better shielding, the current should be able to flow freely from one strand to another without meeting high resistance which causes current path alternation and increases cable attenuation. Therefore, braid contact resistance must be examined. An extensive test conducted in our laboratory indicates that copper clad aluminum wire braid has the lowest braid contact resistance of all cable tested, including copper, aluminum and copper clad aluminum.

--Compared to copper, annealed copper clad aluminum wire has low spring-back characteristics which produce a tighter braid with excellent electrical contact throughout the braided shield. This is an important factor why copper clad aluminum wire braided cable has shown a slightly lower attenuation and better shielding effectiveness in television frequency band during actual laboratory tests shown in Table X.

--On the other hand, when two aluminum conductors cross under low pressure a very high contact resistance results because aluminum's unavoidable oxide acts as an insulator. Aluminum also is more difficult to connect either to itself or to other materials.

SUMMARY

The cable television industry has acquired extensive experience during the past two years with copper clad aluminum semi-rigid trunk or distribution cables. It has proven itself a perfectly acceptable substitute for solid copper cable from a standpoint of performance and offers a number of desirable characteristics of its own, including the possibility of pullout-free cable. Now this metallurgically bonded materials system is available in fine wire sizes suitable for braided drop cable. Recent cable designs often ignore performance at the very time color television makes quality signals more important. A review of current designs indicates that single or double-braided cable still offers the best combination of drop wire characteristics. Detailed laboratory testing further indicates that copper clad aluminum fine wire can be substituted for solid copper in braided cable with no compromise in performance.

TABLE I

CATV FREQUENCY RANGE	USEFUL "SKIN"	CATV SIZE	"SKIN" AVAILABLE 15% CU/AL
50	.00108	.750	.00570
		.500	.00380
250	.00048	.412	.00300

TABLE II

PROPERTY	CU/AL	CU
DENSITY ($\#/in^3$)	.132	.323
RESISTIVITY ($\frac{ohms}{CMF}$)	15.60	10.27
WEIGHT, COPPER (%)	36.8	100
T.S. Kpsi ANNEALED	17.0	35.0
Y.S. Kpsi ANNEALED	13.0	20.0
COEFF. OF THERMAL EXPANS. in/in/° C x 10^{-6}	22.0	16.8

TABLE III

RG-59 B/U COAXIAL CABLE

INNER CONDUCTOR: 0.0230" COPPER COVERED STEEL

INSULATION: SOLID TYPE A (POLYETHYLENE)
           DIAMETER: 0.146" ± .004"

OUTER CONDUCTOR: SINGLE BRAID
               TYPE: BARE COPPER
               WIRE SIZE: 34 AWG
               CARRIERS: 16
               ENDS: 7
               PICKS/INCH: 8.2 ± 10%

JACKET: TYPE II a (NON-CONTAMINATING PVC)
       DIAMETER: 0.242" ± .004"

ENGINEERING DATA:

       NOMINAL IMPEDANCE: 75 ± 3 OHMS
       NOMINAL CAPACITANCE: 21.1 pf/ft
       ATTENUATION: 55 mc - 2.6 db/100 ft.
                      83 mc - 3.2 db/100 ft.
                     175 mc - 4.9 db/100 ft.
                     211 mc - 5.4 db/100 ft.

PER MIL-C-17D

TABLE IV

BASIC DROP CABLE DESIGN REQUIREMENTS

1. ELECTRICAL TRANSMISSION QUALITY

2. LOW COST

3. SHIELDING EFFECTIVENESS

4. FLEXIBILITY

5. MECHANICAL DURABILITY

6. LONG SERVICE LIFE

7. LIGHT WEIGHT

8. AVAILABILITY
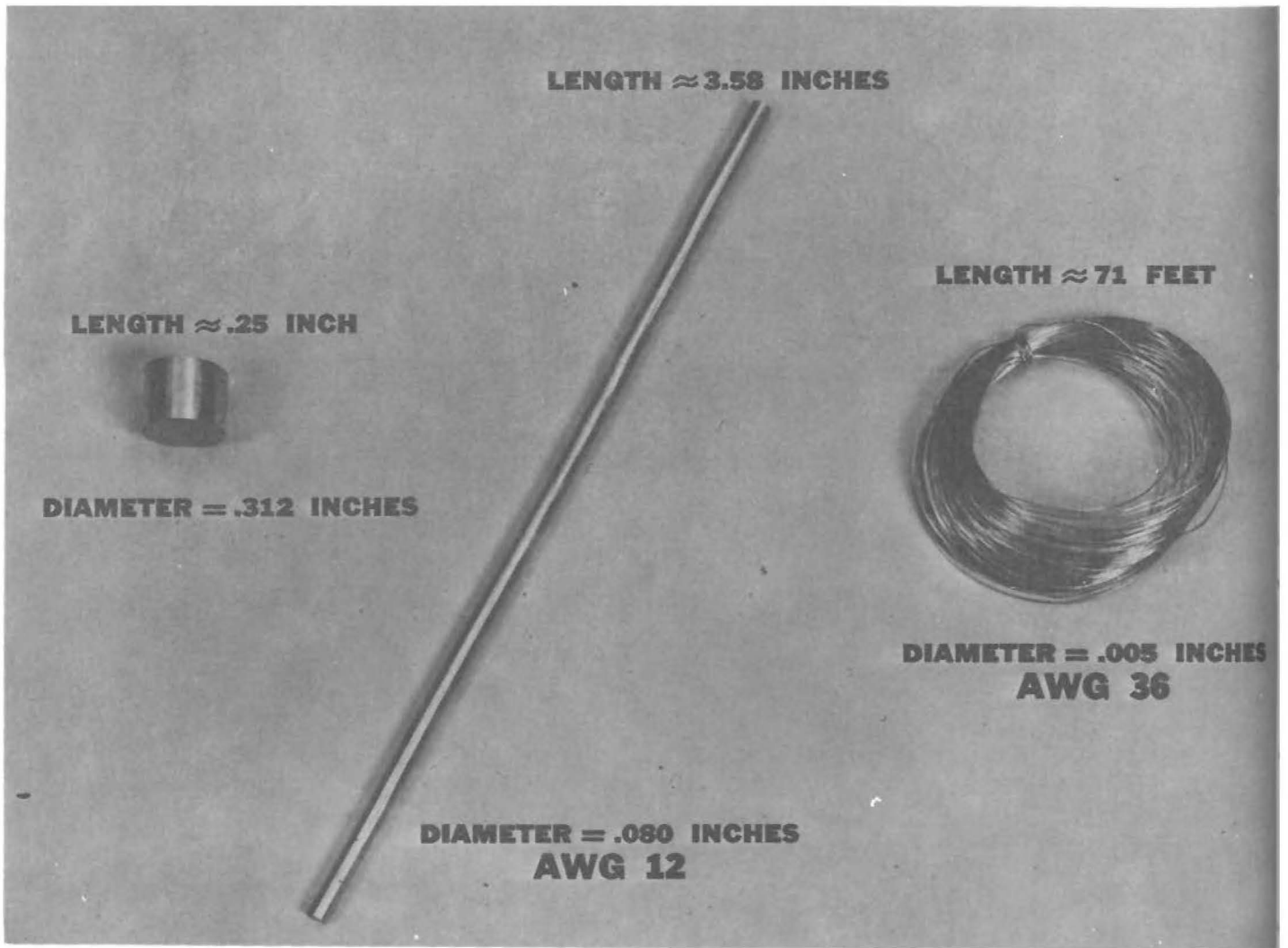
TABLE V

COMPARISON OF DROP CABLE CONSTRUCTIONS

DESIGN CHARACTERISTIC	SOLID METALLIC SHIELD	TAPE SHIELD HELICAL	TAPE SHIELD LONGITUDINAL	BRAIDED WIRE CONSTRUCTION SINGLE	BRAIDED WIRE CONSTRUCTION DOUBLE
ELECTRICAL TRANSMISSION	A	A	A	B	A
LOW COST	D	A	A	A	B
SHIELD EFFECTIVENESS	A	C	A	B	A
FLEXIBILITY	D	A	C	A	A
DURABILITY	A	B	C	A	A
LONG SERVICE LIFE	A	B	D	A	A
LIGHT WEIGHT	D	A	A	A	B
AVAILABILITY	D	C	A	A	C

KEY

    A - EXCELLENT
    B - GOOD
    C - FAIR
    D - POOR

FIGURE VI-B

ONE GRAM OF
COPPER CLAD ALUMINUM WIRE

LENGTH ≈ 3.58 INCHES

LENGTH ≈ 71 FEET

LENGTH ≈ .25 INCH

DIAMETER = .312 INCHES

DIAMETER = .005 INCHES
AWG 36

DIAMETER = .080 INCHES
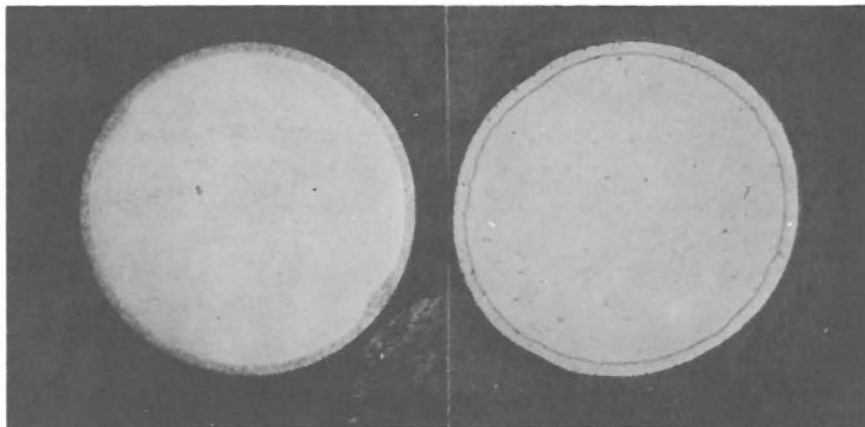AWG 12

CROSS SECTION OF METALLOGRAPHIC PHOTO

COMPARING COPPER CLAD ALUMINUM ROD (.312″) & COPPER CLAD ALUMINUM FINE WIRE (.005″)

ROD   **FINE WIRE**

DIA. .312 inches   DIA. .005 inches
AREA 0.07666 SQ. IN.   AREA 0.0000196 SQ. IN.

AREA RATIO = 3900

TABLE VII

COAXIAL CABLE FORMULAS

Listed here are some of the more important formulas for CATV coaxial cable.

(1) Characteristic Impedance

$$Zo = \frac{138}{\sqrt{\epsilon}} \quad \log_{10} \frac{D}{d}$$

(2) Capacitance

$$C = \frac{7.36}{\log_{10} \frac{D}{d}}$$

(3) Reflection Coefficient

$$r = \frac{Z - Zo}{Z + Zo}$$

(4) VSWR

$$VSWR = \frac{1 + r}{1 - r}$$

(5) Attenuation

$$= \frac{2.387 \times 10^3 \sqrt{\epsilon} \ f}{\log_{10} \frac{D}{d}} \left(\frac{\sqrt{R_1}}{d} + \frac{\sqrt{R_2}}{D} \right)$$

(6) Q - factor

$$Q = \frac{\pi \ fcZ_o}{\alpha}$$

where:

Z_o = Characteristic Impedance in Ohms
C = Capacitance in Micro-Micro farads per foot
r = Reflection coefficient in Percent
α = Attenuation in decibel (DB) per 100 feet
ϵ = Dielectric constant
D = Inner diameter of outer conductor
d = Outer diameter of inner conductor
f = Frequency in cycles per second
R = Resistivity of conductor
c = Velocity of electromagnetic wave

TABLE VIII

SKIN DEPTH

$$I_z = I_0 \, e^{-\frac{x}{d}} \, e^{-j\left(\frac{x}{d}\right)}$$

where I_z = current function

I_0 = current at surface

x = depth function

d = skin depth

If only the magnitude of current is considered, then the equation can be written as

$$I_z = I_0 \, e^{-\frac{x}{d}}$$

$$\frac{I_z}{I_0} = e^{-\frac{x}{d}}$$

$$J_t = \text{Total Current} = \int_0^\infty I_0 \, e^{-\frac{x}{d}} \, dx = I_0 \, d$$

Current in outer metallic layer

$$J_1 = \int_0^y I_0 \, e^{-\frac{y}{d}} \, dx$$

$$= - I_0 \, d \, e^{-\frac{y}{d}} \, \Big|_0^y$$

$$= I_0 \, d \, (1 - e^{-\frac{y}{d}})$$

THEREFORE, THE TOTAL CURRENT IN THE OUTER LAYER FOR

$$J_1 = I_0 \, d \, (1 - e^{-\frac{y}{d}})$$

$y = \frac{1}{10} d \qquad J_1 = I_0 \qquad (1 - e^{-0.1}) = I_0 \, d \, (0.10)$

$y = 1/2 \, d \qquad J_1 = I_0 \qquad (1 - e^{-0.5}) = I_0 \, d \, (0.40)$

$y = d \qquad J_1 = I_0 \qquad (1 - e^{-1}) = I_0 \, d \, (.633)$

$y = 2d \qquad J_1 = I_0 \qquad (1 - e^{-2}) = I_0 \, d \, (.865)$

$y = 3d \qquad J_1 = I_0 \qquad (1 - e^{-3}) = I_0 \, d \, (.951)$

$y = 4d \qquad J_1 = I_0 \qquad (1 - e^{-4}) = I_0 \, d \, (.982)$

TABLE IX

FREQUENCY (MHz)	CURRENT IN COPPER (%)	CURRENT IN ALUMINUM (%)	RF RESISTIVITY (RATIO TO COPPER)	RESISTIVE LOSS (BRAIDED CABLE*)
50	23	77	1.21	2.7%
250	40	60	1.17	2.2%

*NOTE: RG-59 B/U cable attenuation increases by a factor

$$A = R \frac{d}{d + D}$$

where R = Percent increase of Resistivity

d = Outer diameter of inner conductor

D = Inner diameter of outer conductor

A = .21 (.13) = 2.7% at 50 MHz

A = .17 (.13) = 2.2% at 250 MHz

For the 34 AWG copper clad aluminum braid wire, the copper

skin layer has a nominal thickness of 0.000256 in. which is

equivalent to approximately 0.258 at 50 MHz and 0.508 at

250 MHz. According to the above analysis the RF current was

carried by the two metals in their proportions.

TABLE X

COMPARISON CHART

RG 59/U MODIFIED

	CU/AL BRAID CABLE	COPPER BRAID CABLE
Impedance	71.8 ohms	70.8 ohms
Capacitance	21.2 pf/ft	21.5 pf/ft
Velocity of Propagation	66.8%	66.7%
Conductor DCR	52.3 ohms/Kft	52.1 ohms/Kft
Shield DCR	6.25 ohms/Kft	3.98 ohms/Kft
Loop DCR	59.3 ohms/Kft	56.7 ohms/Kft
Reflection coefficient	0.178	0.170
Attenuation		
1 MHz (db/100')	.7	.5
10 MHz (db/100')	1.4	1.5
50 MHz (db/100')	2.6	3.3
100 MHz (db/100')	4.0	4.3
400 MHz (db/100')	7.9	8.6
1000 MHz (db/100')	15.6	16.0
Cable Weight Lbs/100 ft.	2.703	3.417

DISCUSSION

Mr. Frank Spexarth: Thank you.   Are there questions?

Question: Not audible

Mr. Spexarth: You're referring to the trunk and distribution cables, primarily?   I think on that particular question, I'd have to ask John Fan, technically, to back me up on that.   You went beyond me as soon as you got into that.

Mr. John Fan: First of all, the skin depths even down to the video frequencies of 10 megacycles we test still have sufficient to carry even down to video frequency.   Another thing is we use the fine wire here.   Even aluminum, itself, is also a damm good RF conductor.   So, basically, we really don't have to worry anything about it.   We test, actually, down to 1 megacycle always.

Question: Not audible.

Mr. Fan: That is correct.   It depends on the size.   We cannot really describe the quality of video transmission at that range, but in the trunk end distribution cable like 412, the real sync difference we can see in the attentuating measurement is actually down to 150 KC range.

Question: Not audible.

Mr. Fan: We really get it down to a half dB or .2 dB difference of accuracy.   We really didn't say that copper clad aluminum is one and half better than copper, but actually it showed a trend that it did have a slight better than copper.

Question: Not audible.

Mr. Fan: Yes.   We braid this thing, actually.   This was made by one of the cable manufacturers and on a standup production and they put 34 guage copper braid on and also put another roll of thin cable with 34 guage copper clad aluminum on.

Question: Not audible.

Mr. Fan: The point we tried to point out is the attentuation consists of three factors---one is resistive loss which is dissapative loss and second is leakage loss due to the braid

leakage and third is reflective loss due to the cable VSWR.
So if you have these three components to consider, the resistive
loss seems like it starts to disappear by contribution from
two other factors into the cables.

Question: Not audible.

Mr. Fan: That is correct. However, the leakage hiding the
braid for the leakage loss it does show up a little bit
better. Any other questions? Thank you.