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# AN ADVANCED MULTI-UNIT COAXIAL CABLE FOR TOLL PCM SYSTEMS

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*ABSTRACT*

This paper reviews some of the physical and electrical problems encountered with multi-unit coaxial cables, particularly during installation, and the design, process development and material investigation associated with the development of a new laminated-corrugated coaxial unit for broadband application. The computer programme used in the evaluation of the unit and the production facilities are also described. The coaxial unit is shown to produce, in combination with a corrugated steel sheath, a physically rugged cable of toll quality, primarily for pulse code modulated systems, but also analogue systems of the higher frequency category.

*INTRODUCTION*

Prior to 1964, the use of multi-unit coaxial carrier cable in Canada was limited to wire line entrance links connecting the major urban centres with the microwave radio system.

During the early nineteen-sixties, it became evident that a coaxial cable system could compete with radio or paired carrier cable systems, if more competitive cable designs could be obtained. Furthermore, if mechanical, or more specifically, plowing methods of installation were also feasible, additional economic advantages could be realized in many areas.

In evaluating existing designs for this application, the use of solid dielectric coaxial units was considered, and rejected for economic reasons. The semi-air dielectric units available at that time were also considered and rejected, again primarily because of cost, but to some extent because of the relatively fragile nature of the product. Subsequently, an expanded (cellular foam) polyethylene insulated coaxial unit was selected and modified for carrier use. This expanded coaxial design proved very successful with a 240 channel carrier system operating in the 60 to 1,052 kHz range.

A proposal aimed at increasing the capacity of the system on this cable to 1200 or more channels highlighted the attenuation stability of chemically expanded dielectrics[1] and the critical nature of attenuation stability in a long distance analogue system. While the predicted attenuation variations could have been accommodated electronically, the economic penalty thus borne by the line equipment made such a proposal unattractive.

It was apparent therefore, that if a coaxial system was to be competitive, and the cable take advantage of mechanical methods of installation, a new semi-air dielectric coaxial unit would have to be developed.

This paper deals with the physical and electrical evaluation of various cable designs, the subsequent development of a physically rugged coaxial unit and its use with a sheath of similar characteristics.

*INITIAL EVALUATION*

One problem encountered when a coaxial cable is installed, is the change in impedance which can occur in the coaxial unit during the installation operation. An example of the cause of such a change is the compressive force which is exerted on the sheath between the guide chute and the soil when the plow changes direction. The extent of such an impedance change depends on the margin of safety between the forces which are encountered during installation, and the force on the cable which will result in an impedance change in the coaxial unit.

While some of the impedance changes of the type encountered can go undetected by conventional means of carrier cable evaluation, they can have a significant effect on the more sophisticated analogue and digital systems of the future. How such impedance changes are detected, and their significance evaluated, depends on a number of interrelated factors, ranging from test equipment, location and severity of the discontinuity, and the characteristics of the specific system This is in some respects beyond the scope of this paper.

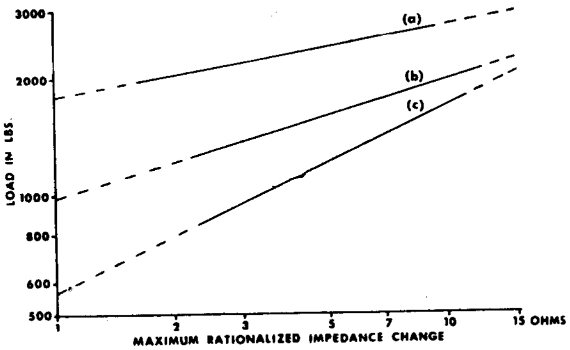
A laboratory and field evaluation was carried out to determine the magnitude of the forces involved and their effect on the impedance of the coaxial units.

In the laboratory stage of this program, discrete impedance variations were evaluated using Time Domain Reflectometer (TDR) techniques. In the field, TDR tests were supplemented by structural return loss (SRL) and standard pulse echo measurements.

*Laboratory Tests*

The laboratory study evaluated the effect on the coaxial units of a steady compressive stress and an impact force, when applied to various composite sheaths.

In the compressive stress tests, the ARPASP sheath was found to withstand a much greater force than a PASP sheath with a core of identical construction. A similar core, when protected by a corrugated steel sheath, had no electrical deterioration until the compressive force was at least double that applied to the PASP sheath. Fig. 1 demonstrates this effect on three 8-unit 375 designs.

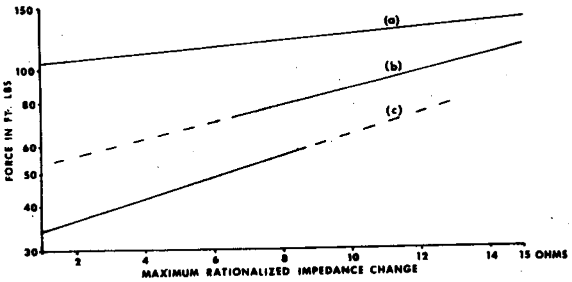



*(a) 8-Unit Corrugated Steel Sheath*
*(b) 8-Unit ARPASP Sheath*
*(c) 8-Unit PASP Sheath*

*FIG. 1 THE EFFECT OF A COMPRESSIVE FORCE OVER A 6" LENGTH OF 8-UNIT .375" SERRATED SEAM COAXIAL CABLE*

The effect of an impact force reflects an even greater relative difference between the various designs. See Fig. 2 for measurements on the same three 8-unit 375 designs.

The above impedance changes were detected using a 150 p. second step function. The manner in which the force could be distributed between the coaxials, under the applied load, was resolved[2] by assuming that each impedance change recorded was a VECTOR radiating from the centre of the cable through the coaxial unit in question. The vector sum of all impedance changes was calculated in each direction, omitting negative values from the calculation, and the maximum value used for comparative purposes. The summation of all impedances was named the rationalized impedance.

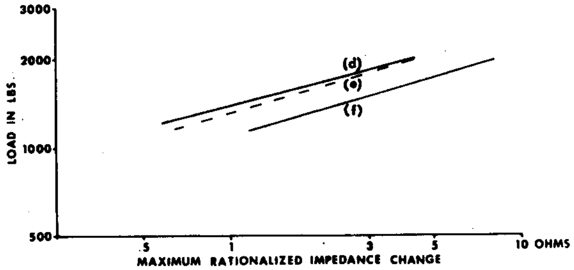



*(a), (b) and (c) as in FIG. 1*

*FIG. 2 THE EFFECT OF IMPACT ON 3" LENGTH OF 8-UNIT .375" SERRATED SEAM COAXIAL CABLE*

In addition to the different impeance changes which were produced by an identical force on cable sheaths with similar cores, the impedance changes were also found to be diameter dependent.

A comparison is made in Fig. 3 between an 8-unit and a 12-unit 174 coaxial with concentric coaxial unit lay-ups and an ARPASP sheath.




| | | |
|---|---|---|
| *(d) 8-Unit Design (Actual)* | *Diam.* | *1.3"* |
| *(e) 8-Unit Design (Theoretical)* | *"* | *1.3"* |
| *(f) 12-Unit Design Actual* | *"* | *1.6"* |

*FIG. 3 THE EFFECT OF A COMPRESSIVE FORCE OVER A 6" LENGTH OF .174" COAXIAL CABLE*

It can be seen from Fig. 3 that a decrease in diameter resulted in a relative improvement in the sheath crush resistance. The theoretical curve for the 8-unit design is shown relative to the 12-unit design, based on the following relationship:-

$$Z_2 = Z_1 \cdot \frac{t_1^3}{D_1^3} \cdot \frac{D_2^3}{t_2^3} \qquad (1)$$

This assumes that the numerical deflection in each sheath is proportional to the same rationalized impedance change. From the limited data available this appears to be a valid assumption.

This expression was derived from the expression:-

$$\text{Load} = \text{Constant} \times \frac{t^3}{D^3} \times \text{Youngs Modulus} \times [\text{Deflection}$$

Hence comparing similar constructions we have, for the same load,

$$\text{Deflection}_1 \frac{t_1^3}{D_1^3} = \frac{t_2^3}{D_2^3} \text{Deflection}_2$$

$D_1$ = Outside diameter of the original sheath
$D_2$ = Outside diameter of the new sheath
$t_1$ = Proportional thickness of the original sheath wall
$t_2$ = Proportional thickness of the new sheath wall
$Z_1$ = Maximum rationalized impedance of the original design
$Z_2$ = Maximum rationalized impedance of a similar design

*Field Tests*

To obtain an appreciation of the forces exerted on a cable during installation, a cable plowing field trial was made to supplement the laboratory tests. This trial was conducted on ideal plowing terrain in an attempt to eliminate any random effects due to underground obstructions. The plow selected had a 5 ft. radius chute designed specifically for direct burial of 4" duct. Five cable designs were put through similar plow manoeuvres involving gradual and sharp turns (approx. minimum radius 8 ft.), raising and lowering the chute, etc., to simulate actual operating conditions.

Electrical measurements were taken before, during and after each cable installation, to evaluate the effect of the plow and its various guide components on the cable. Table I is a simplified summary of the results on three 8-unit .375" coaxial designs with similar core constructions but different sheaths. The core/unit design of the corrugated steel design differed slightly from the other two cables and probably accounted for the minor impedance changes detected at the lay frequency. No impedance change was detected in this latter cable due to an external force.

In addition to the 8-unit cables, a 4-unit .174" PASP sheathed cable was successfully installed, while an 18-unit .375" Stalpeth was found to be unsatisfactory.

Neglecting some problems with the plow/cable guide system, which were subsequently rectified by equipment modifications, all major points of trouble in the cable occurred where the plow changed direction.

While a direct correlation was not possible between the various cable designs after plowing, due to differences in the actual plow manoeuvres, there is little doubt from the readings taken that compressive forces of less than 1000 lbs. were developed across the ARPASP design, while forces in the order of 1500 lbs. were encountered by the PASP design. Since it is unlikely that the initial force impressed on any one cable was greater than that on the other, it is felt that the soil was softer than the ARPASP sheath, and thus gave slightly under the load. In the PASP case the sheath was the softer component and deformed under the load. If this is the case, the laboratory results should only be taken as an indication of the relative performance of the cables. In practice the differential will be greater than shown until the hardness of the soil

*TABLE I*

| Sheath | Worst Corrected Echo (Pulse Width 125 and 63 n sec.) | | Comment | Time Domain Reflectometer Impedance Change | S.R.L. Values Worst Value From 7-220 MHz | |
|---|---|---|---|---|---|---|
| | Original | Final | | | Original | Final |
| | dB | | dB | ohms | dB | |
| PASP | Avg. 66<br>Range 64-69 | 55<br>47-67 | Degraded<br>-11 | Average 1.9<br>Maximum 9.2 | 29 | 11.5 |
| ARPASP | Avg. 66<br>Range 59-72 | 68<br>62-74 | Similar<br>+2 | Average 0.12<br>Maximum 0.36 | 35 | 33 |
| Corrugated Steel | Avg. 66<br>Range 64-76 | 73<br>71-76 | Improved<br>+7 | Average 0.08<br>Maximum 0.1 | 27.5 | 25 |

exceeds the resistance to crush of the most resistant sheath being considered. At this point the laboratory results would be comparable with field performance.

It was concluded at the end of the laboratory/field evaluation that; (i) with some modification to plow equipment and installation procedures, an ARPASP design would have a reasonable margin of safety for the smaller diameter coaxial cables, and (ii) a more rugged cable construction was needed for the larger cables to improve the margin of safety. As a result of the preceding evaluation and related work on coaxial units, a two part program was approved to satisfy the immediate and future coaxial system needs.

The first part of the program was completed in 1970 with the successful installation of 34 miles of 12-unit .174" coaxial ARPASP cable in the vicinity of Calgary, Alberta. The majority of this cable was installed by a plow developed using the experience gained during the field trial. Fig. 4 is a photograph of the plow. In this installation the *worst* corrected echo per unit per repeater section in the plowed portion ranged from 52 to 69 dB. 228 readings were taken, the average worst value was 60 dB and the standard deviation 3.6 dB.

The second part of the program, which started in 1967, is the main subject of this paper and covers the development of a multi-unit coaxial cable for a high capacity PCM system. This cable is intended to meet, economically, the future long haul toll needs of the Bell Canada System, and have a reliability equivalent to that of existing high quality toll cables.

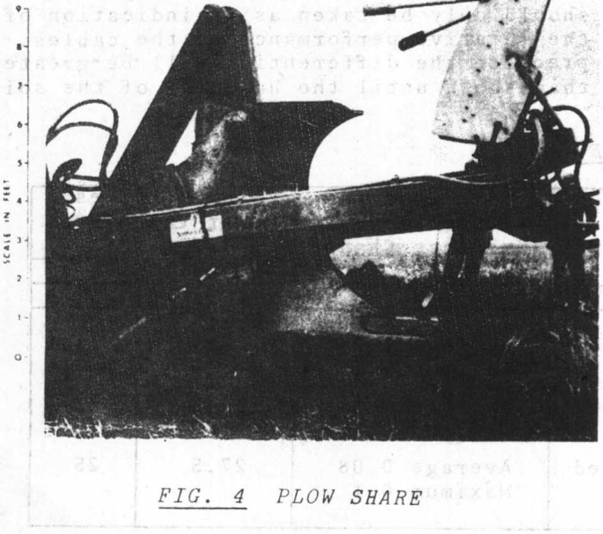



*FIG. 4 PLOW SHARE*

*THE PCM SYSTEM*

The PCM System, to which this coaxial cable will connect, will have a bit rate of 272 M bauds, will utilize a bipolar pair substitution code, and will be designated LD-4. The transmitted signal will have a rise time equivalent to a raised cosine pulse of amplitude 3.3 volts and a width of 1.7 nano-seconds at the half maximum height. The spectrum of the signal is significant in the frequency domain from 2 MHz to 490 MHz, See Fig. 5. By the time each bit of information traverses a complete repeater section, that signal will be acting upon and conversely it will be acted upon, by at least 100 other signals due to a combination of attenuation and phase delay effects. While amplitude and phase equalization prior to the regenerative section of the repeater will reduce such pulse dispersion, each bit of information will still cover slightly more than two time slots prior to entering the regenerator of the repeater.

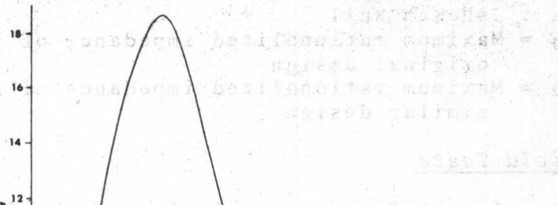



*FIG. 5 OUTPUT POWER SPECTRUM OF PULSE TRAIN*

The requirements for a coaxial unit to be used on a digital system are, in most respects, not as severe as those for an analogue system. The digital system does, however, have a few additional problems. Since its wide frequency spectrum includes some very high frequency components, which are reflected at impedance perturbations normally insignificant in the lower frequency analogue system, local changes in the characteristic impedance must be controlled to minimize error. Any impedance discontinuity will reduce the information-bearing signal by an amount proportional to the signal reflected. This reflection is subsequently rereflected from the sending repeater to interfere with subsequent pulses. These effects are both magnitude and phase sensitive and if not controlled can be a serious source of intersymbol interference. Initially this condition will be controlled by tight attenuation ripple requirements, T.D.R. measurements and wide frequency spectrum SRL requirements. Eventually high frequency techniques such as, high voltage reflectometry or frequency modulated continuous wave radar fault location will have to be developed.

System studies of initial traffic density, growth, equipment and cable costs, operating costs, etc., indicated that system costs had a relatively flat optimum with respect to coaxial unit size. Consequently, the standard .375" size was selected, and standardized in a 12-unit cable makeup.

It remained therefore to reduce the cost of the coaxial unit consistent with its electrical characteristics. These were set, for the digital system, at ± 1% of the attenuation of the existing serrated seam .375" unit from 1 to 320 MHz, with a nominal characteristic impedance at 2 MHz of 75 ohms in the finished cable. For analogue carrier systems, the frequency spectrum over which the electrical characteristics were to be rigidly controlled was 500 kHz to 64 MHz. For CATV systems control was extended up to 300 MHz.

## *THE CABLE*

The cable for the LD-4 system will employ corrugated support members in both the coaxial unit and the sheath. By this means the effect of any change in dimension, that can occur during and after installation will be minimized, and the electrical characteristics of the installed cable improved.

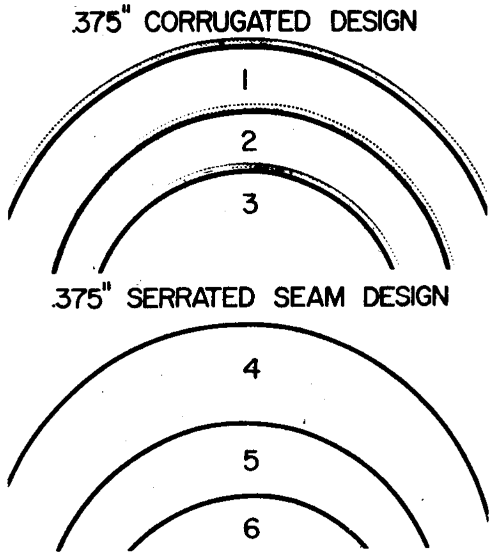
The cable was developed by adopting established techniques where this was economically advantageous. New developments were restricted to those areas where the effort expended would contribute to achievement of optimum results.

### *The Coaxial Unit*

*Physical*. Various .375" coaxial unit constructions were considered for this application and evaluated relative to the physical characteristics of the existing serrated seam design. The crush resistance, and the change in impedance which occurs when a semi-air dielectric coaxial unit is bent, were given particular attention. Both effects are considered more critical to higher frequency systems.

In addition to the normal installation forces that will be encountered by the new coaxial unit in regular service it will also be used in stub cable, where a unit radius of bend of less than 6" will be required. The same coaxial units were considered necessary in the stub cables to minimize any impedance mismatch between cables adjacent to the repeater.

Tests on various .375" units with flat outer conductors, indicated they had inferior handling characteristics relative to the corrugated designs. The X-ray photographs below (Fig. 6) show the effect of a typical bend on the internal dimensions of the serrated seam unit and a unit with a solid corrugated outer conductor.




| CORRUGATED SAMPLE | RADIUS | SERRATED SEAM SAMPLE | RADIUS |
|---|---|---|---|
| 1 | 5" | 4 | 5" |
| 2 | 4" | 5 | 4" |
| 3 | 3" | 6 | 3" |

*FIG. 6 EFFECT OF BEND ON INTERNAL DIMENSIONS*

The difference in crush resistance between flat and corrugated designs can be seen in Fig. 7.

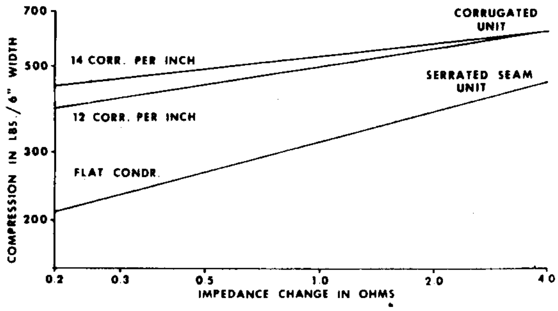



*FIG. 7 AVERAGE IMPEDANCE CHANGE UNDER COMPRESSIVE FORCE*

*TABLE II*

| MANDREL 6" RADIUS | SERRATED SEAM DESIGN BENT (OHMS) | SERRATED SEAM DESIGN STRAIGHT (OHMS) | CORRUGATED DESIGN BENT (OHMS) | CORRUGATED DESIGN STRAIGHT (OHMS) |
|---|---|---|---|---|
| After 1st Bend | .32 to .90 | 0 to .36 | 0 to .23 | 0 * |
| " 2nd " | .46 to 1.12 | .23 to .76 | .17 to .21 | 0 |
| " 3rd " | .52 to 2.28 | .30 to .79 | .23 to .38 | 0 |
| " 4th " | .88 to 2.59 | .28 to .93 | .23 to .34 | 0 |
| " 5th " | 1.91 to 3.95 | .52 to 1.12 | .30 to .52 | 0 to .23 |

* 0 *implies a value below level of detectability.*

Table II results are representative of the change in impedance which can occur in the .375" serrated seam and the corrugated designs, when the unit is bent and when the unit is subsequently straightened.

*Economics.* Of the four materials used in the .375" serrated seam design, the conductors account for approximately 80% of the material cost of the unit. Two approaches were investigated; (i) the use of a thinner outer copper conductor to take advantage of skin effect and (ii) the use of aluminum. It was recognized in (i) that a laminate of the conducting member and a supporting member, such as steel, would be required. This cost was included in the evaluation.

Various methods were investigated to achieve a suitable laminate. These included metallurgical bonding, soldering, thermoset, epoxy and thermoplastic bonding. The final selection was made on the bases of economics, consistency of bond, ease of processing, etc., and was essentially the method described by W.G. Nutt[3] et al at the Seventeenth Symposium, 1968. A square edged laminate was selected to take advantage of laminates in wider widths, and to permit a circular outer conductor configuration with a butting type joint.

Table III shows the effect of tape thickness on the attenuation of a 0.375" coaxial unit at various frequencies. Note that at 1 MHz and 600 kHz there is an optimum at .004" and .005" respectively.

Normal variations in tape thickness about the nominal were found to alter the attenuation at 500 kHz by approximately 2%, if 0.0035" material was used, and 1% if 0.0045" material was used. Above 1 MHz the effect was negligible and of little practical significance over the equalizing section of the analogue system considered.

Neither the characteristic impedance or the phase constant were found to alter significantly with normal tape thickness variations, on tapes with nominal dimensions between 0.003" and 0.005".

The temperature coefficient of attenuation varied with tape thickness as shown in Fig. 8.

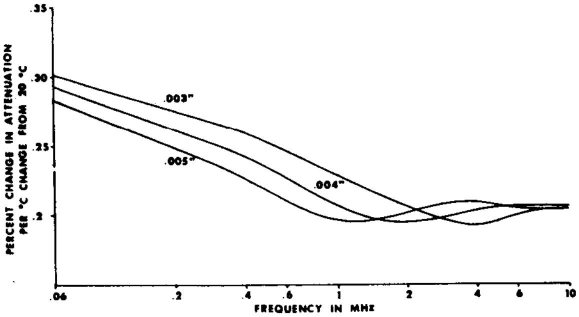



*FIG. 8 EFFECT OF TAPE THICKNESS ON TEMPERATURE COEFFICIENT OF ATTENUATION*

*TABLE III*

| OUTER CONDUCTOR THICKNESS IN INCHES | ATTENUATION dB/1000' AT 68°F kHz 60 | 200 | 400 | 600 | MHz 1 | 4 | 10 | 100 |
|---|---|---|---|---|---|---|---|---|
| .002 | .3529 | .4722 | .5795 | .6620 | .7947 | 1.445 | 2.320 | 7.380 |
| .003 | .2839 | .4018 | .5103 | .5956 | .7368 | 1.463 | 2.325 | 7.371 |
| .0035 | .2641 | .3820 | .4918 | .5793 | .7266 | 1.469 | 2.323 | 7.367 |
| .004 | .2493 | .3674 | .4790 | .5692 | .7231 | 1.470 | 2.322 | 7.363 |
| .0045 | .2378 | .3564 | .4701 | .5635 | .7236 | 1.469 | 2.320 | 7.358 |
| .005 | .2286 | .3479 | .4642 | .5609 | .7259 | 1.468 | 2.319 | 7.354 |
| .006 | .2149 | .3363 | .4586 | .5612 | .7311 | 1.466 | 2.316 | 7.346 |

Fig. 9 shows relative cable attenuation-cost figures, in dollars per the reciprical of attenuation, or "dB·dollars", versus the coaxial unit tape thickness. From this figure it can be observed what the attenuation of the cable would be, relative to a specific tape thickness and a fixed dollar cost. Namely, with

| .005" | .004" | .003" | tape, the losses would be |
|---|---|---|---|
| 65dB | 65dB | 67dB | for $x at 400kHz |
| 78dB | 77dB | 78dB | for $x at 600kHz etc. or |

conversely, the cost of the cable for the same attenuation would be -
$65 $65 $67 at 400kHz etc.

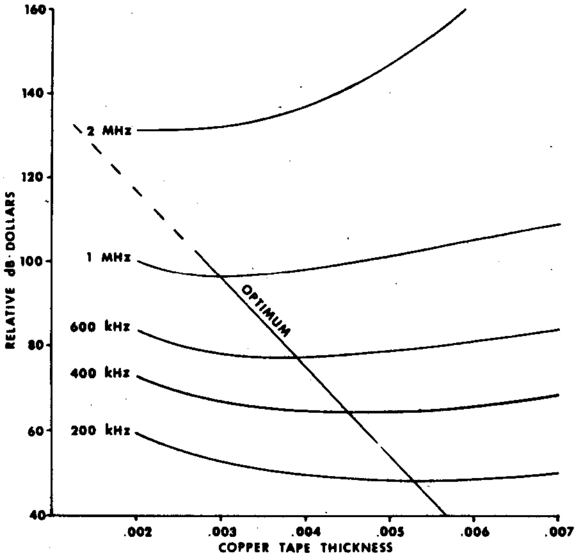



*FIG. 9 RELATIVE ATTENUATION-COST FACTOR AS RELATED TO OUTER CONDUCTOR TAPE THICKNESS IN INCHES*

The substitution of aluminum to replace copper as the outer conductor, was found to increase the attenuation of the unit by approximately 6%. This would have affected system optimization and reliability figures. To maintain the same attenuation in the unit, it was necessary to increase the diameter of the unit by 5%, with an overall cable saving of less than 4%. These savings would have been offset by possible splice problems and increased costs associated with the use of larger diameter cables, such as shorter lengths, increased testing and splicing, duct and manhole space allocation etc., and were not considered justified

The result of the economic analysis was that a .004" thick copper tape was selected on the basis of its effect on overall cable cost, attenuation and the anticipated minimum frequency of operation.

The substitution of aluminum for copper in the centre conductor was found to be uneconomical. The saving that could have been realized by the reduced cost of a copper-clad aluminum centre conductor was offset by the cost and difficulty of obtaining additional power feeding locations, particularly in remote areas. Copper centre conductors will continue to be used until a significant differential exists between these two costs.

*Electrical.* The use of a corrugated outer conductor of 0.004" copper, laminated to steel, brought into play a number of interrelated electrical, physical and economic factors which depended on the shape, depth and number of corrugations per inch selected. To simplify this work a computer program was developed to evaluate quickly their effect on the electrical characteristics of the unit.

## COMPUTER PROGRAMME

The computer programme was used to obtain, within certain dimensional restrictions, the best outer conductor shape consistent with attenuation and impedance requirements and physical deformation. More than fifty designs were evaluated from which the nominal twelve-per-inch corrugation design was chosen to provide the optimum combination of physical and electrical characteristics.

The programme calculated the primary parameters, and applied them to the long line equations shown below.

The attenuation constant $\alpha$, the phase constant $\beta$, and the characteristic impedance $|Zo|$, were obtained over a frequency spectrum ranging from 10 kHz to 500 MHz.

$$\alpha = \left[\frac{1}{2}\left\{\left[(R^2+\omega^2L^2)(G^2+\omega^2C^2)\right]^{\frac{1}{2}}+(RG-\omega^2LC)\right\}\right]^{\frac{1}{2}}$$

*NEPERS/UNIT LENGTH ......... (1)*

$$\beta = \left[\frac{1}{2}\left\{\left[(R^2+\omega^2L^2)(G^2+\omega^2C^2)\right]^{\frac{1}{2}}-(RG-\omega^2LC)\right\}\right]^{\frac{1}{2}}$$

*RADIANS/UNIT LENGTH ........ (2)*

$$|Zo| = \left[\frac{R^2+\omega^2L^2}{G^2+\omega^2C^2}\right]^{\frac{1}{4}} \Omega \quad \ldots\ldots\ldots\ldots\ldots (3)$$

The first step towards calculation of the primary parameters required that an effective inner diameter for the outer conductor be obtained, and the electrical requirement of a nominal 75 Ω characteristic impedance at 2 MHz was used as the criterion. Since the high frequency impedance may be regarded as mainly capacitance dependent, the effective diameter was based on an equivalence of capacitance between a straight coaxial unit and the corrugated design, as shown in appendix 1A. Calling this diameter $D_1$, the inner conductor $D_2$, and assuming a specific inductive capacitance of $\varepsilon$ for the unit, the primary admittance parameters could easily be defined as shown in equations 4 and 5.

$$C = \frac{2\pi\varepsilon}{\log_e\left(\frac{D_2}{D_1}\right)} \text{ farads/meter length} \ldots\ldots (4)$$

$$G = 2\pi . f . C . \tan\delta \text{ Siemens/unit length} \ldots (5)$$

*Where* $\tan\delta$ *is the dissipation factor, and is normally of the order of* $10^{-4}$ *for disk air type insulation.*

The series parameters resistance and inductance are subject to the skin effect phenomenon which produces a complex relationship between impedance and frequency. The solution to the Bessel equation (6), describing the change in current density across a tubular conductor carrying a sinusoidal current of angular frequency $\omega$, provides the relationship of the impedance with frequency (equation 7).

$$\frac{d^2I}{dR^2} + \frac{1}{R}.\frac{dI}{dR} - jm^2I = 0 \ldots\ldots\ldots\ldots\ldots (6)$$

*Where* $m^2 = 4\pi\omega/\rho$ *and* $I$ *is the current density at distance* $R$ *from the centre.*

$$Z=(R+j\omega L)=X(r)\left[\frac{I_o(X_2)+\frac{I_o'(X_1)}{K_o'(X_1)}K_o(X_2)}{I_o'(X_2)+\frac{I_o'(X_1)}{K_o'(X_1)}K_o'(X_2)}\right] (7)$$

*Where* $X(R) = \frac{jm\rho}{\pi D_2}$ ; $X_1=mD_2\sqrt{j}$ ; $X_2=m(D_2+t)\sqrt{j}$

$I_o(X\sqrt{j}) = BER_o(X)+jBEi_o(X)$ : *Kelvin functions of first kind*

$K_o(X\sqrt{j}) = KER_o(X)+jKEi_o(X)$ : *Kelvin functions of second kind*

Separating equation 7 into its real and imaginary components provides expressions for the resistance and inductance parameters in terms of Kelvin functions. Their evaluation may be carried out as accurately as the limitations on calculating the Kelvin functions will allow. These functions are not easily solved by conventional means and are best determined using computer methods. The basic set of power series defining the functions add complications to the method of programming because of the large value which each term may attain, therefore asymptotic approximations to the series were used for the larger arguments. A description of the modifications to these approximations and their subsequent evaluation is contained in Appendix 1.B.

The computer programme determined the resistance and inductance for the inner and outer conductors separately, and added them, with suitable modification to the outer conductor components to reflect the excess length due to the corrugation. The inductance due to the flux within the dielectric was also taken into consideration in equation 7, as was the component due to flux produced in the outer conductor by the inner conductor.

It is interesting to note that using an IBM Series 360 Model 67 computer, a complete output was obtained using approximately 20 C.P.U. seconds at a cost of $8.00.

To confirm the accuracy of the programme a series of tests were made on conventional coaxial designs before application to the present corrugated design. Given the configuration, it was found the electrical parameters could be predicted to a 99% accuracy (cf. the comparisons in the Results section).

Coaxial units with the desired electrical characteristics were then manufactured and evaluated with 14, 12 and 10 corrugations per inch and depths of corrugation of .034" and .037". The following observations were made.

Units with 14 corrugations per inch were found to form well and have good impedance control under compression and when bent, see Fig. 7 and 10. Their attenuation was higher than predicted by the computer programme at the lower frequencies. This was traced to deformation of the outer copper conductor in the valley of the corrugation, and resulted from the force necessary to corrugate the copper-steel laminate.

12 corrugations per inch, with corrugation depths between .034" and .037", were found to form well, and have good impedance control under compression and bend. They also met the predicted electrical characteristics.

10 corrugations per inch had similar characteristics to the 12 corrugation per inch design except that the impedance spread in the .034" design was greater when the unit was bent.

The unit selected has approximately 12 corrugations per inch to obtain the best compromise between electrical and physical characteristics, manufacturing convenience and cost. Fig. 11 is a photograph of the final unit design.

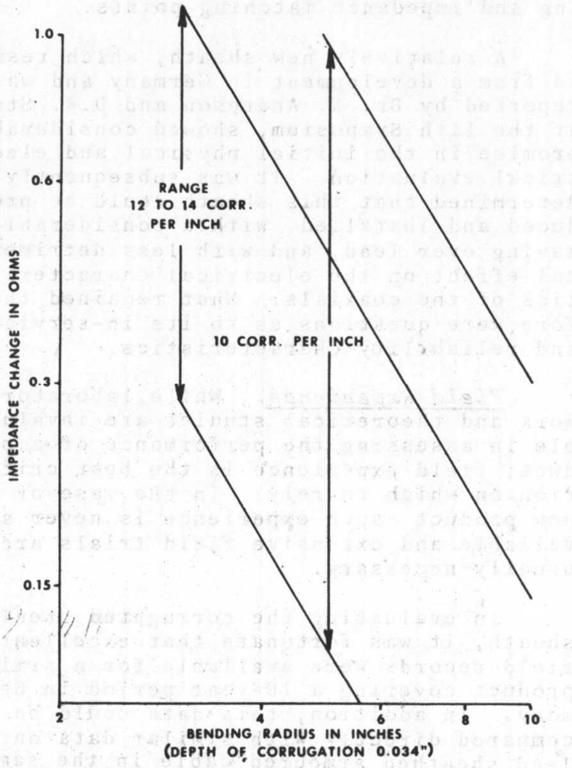



*FIG. 10 CHANGE IN IMPEDANCE VERSUS BENDING RADIUS*

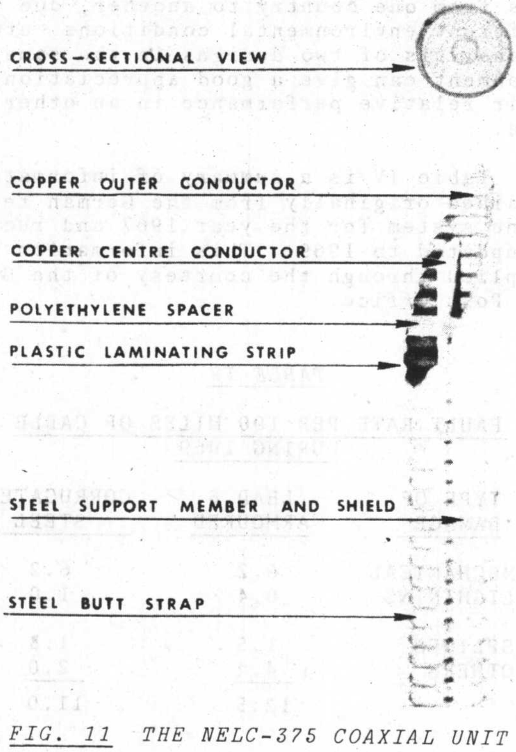



*FIG. 11 THE NELC-375 COAXIAL UNIT*

*Raw Material*. As with any new product comprising a number of individual components, the problem of raw material selection, procurement and control was a major factor in this development. Some of these problems which may be of general interest are presented here.

The material that was found to be the most critical in the control of impedance and structural return loss was the steel outer conductor support member. Using standard commercial material the nominal thickness on some tapes was found to vary from the nominal specification thickness by as much as 10%. Roll camber and end effects added to the problem, as did cyclical variations about the actual nominal.

An X-ray device was obtained to continually monitor thickness variations. This confirmed thickness variations predicted by S.R.L. measurements. Fig. 12 shows a theoretical relationship[4] between tape thickness and S.R.L. levels, assuming a pure cyclical variation in the tape thickness. The degree of correlation in the results varied with the degree of randomization in the cyclical pattern of the steel tape thickness variation. Also, since the tapes with the worst variations were obtained during early line development, other random effects were occurring. The effect of an automatic feedback controlling thickness in one supplier's plant was observed just above 10 MHz, while the effect of mill rolls in other suppliers' material was observed around 80 and 140 MHz.

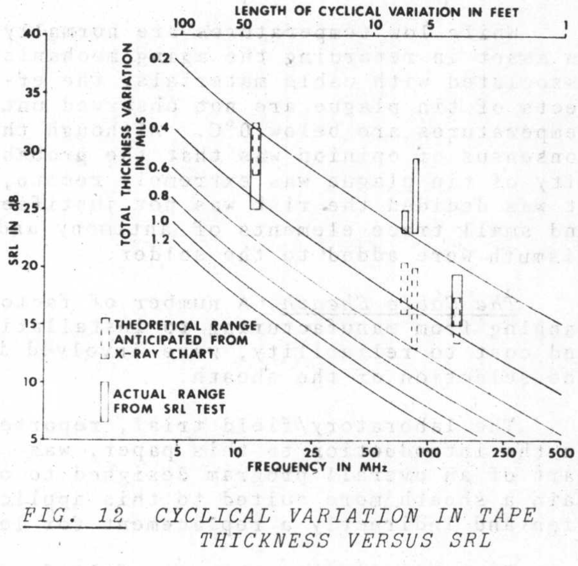



*FIG. 12 CYCLICAL VARIATION IN TAPE THICKNESS VERSUS SRL*

The steel tape supplier finally selected is now obliged to remove a specified percentage at each end and off each side of the tape roll. The tape is then processed further in the cable plant for selection and removal of any additional irregularities. This procedure permits the economic use of commercial material with a practical scrap allowance.

The selection and analysis of the best type of solder presented a number of problems, some of which are still under evaluation.

An "aging" phenomena was found to be critical to the rolling operation performed on the solder wire prior to soldering. This was finally related to the length of time which elapsed between the solder wire manufacturing and rolling operations, and was resolved by limiting this time period to 3 months.

Creep in the solder seam has to be limited to acceptable levels over the life of the cable by the use of a special solder and/or by the elimination of stress in the joint. The addition of certain elements to the solder reduces the rate of creep, but they also decrease the solders wetting properties and increase its plasticity range. These two factors can in turn make manufacture and impedance control more difficult.

Stresses imparted to the seam prior to and after forming of the outer conductor have to be controlled. Long term studies are continuing on creep and until these are completed it is recommended that very short radius bends, in the order of 3", be encapsulated in a rigid epoxy as a precautionary measure.

While low temperatures are normally an asset in retarding the aging mechanisms associated with cable materials, the effects of tin plague are not observed until temperatures are below 0°C. Although the consensus of opinion was that the probability of tin plague was extremely remote, it was decided the risk was not justified and small trace elements of antimony and bismuth were added to the solder.

*The Cable Sheath*. A number of factors ranging from manufacturing to installation, and cost to reliability, were involved in the selection of the sheath.

The laboratory/field trial, reported in the introduction to this paper, was part of an overall program designed to obtain a sheath more suited to this application and indirectly a replacement for lead.

Our objection to the use of lead was its high cost and weight, and the limited mechanical protection it afforded the underlying coaxial core. There was also a desire to supply longer lengths of cable, and to reduce the number of splices, testing and impedance matching points.

A relatively new sheath, which resulted from a development in Germany and was reported[5] by Dr. K. Andreson and D.R. Stein at the 11th Symposium, showed considerable promise in the initial physical and electrical evaluation. It was subsequently determined that this sheath could be produced and installed with a considerable saving over lead, and with less detrimental effect on the electrical characteristics of the coaxials. What remained therefore were questions as to its in-service and reliability characteristics.

*Field Experience*. While laboratory work and theoretical studies are invaluable in assessing the performance of a product, field experience is the best criterion on which to rely. In the case of a new product such experience is never available and extensive field trials are usually necessary.

In evaluating the corrugated steel sheath, it was fortunate that excellent field records were available for a similar product covering a 10-year period in Germany. In addition, this data could be compared directly with similar data on a lead sheathed armoured cable in the same environment.

Although it is difficult and in some cases impossible to compare fault statistics from one country to another, due to different environmental conditions etc., an analysis of two designs in the same environment can give a good appreciation of their relative performance in an other area.

Table IV is a summary of information obtained originally from the German telephone system for the year 1967 and recently updated to 1969. This information was supplied through the courtesy of the German Post Office.

*TABLE IV*

FAULT RATE PER 100 MILES OF CABLE DURING 1969

| TYPE OF DAMAGE | LEAD & ARMOURED | CORRUGATED STEEL |
|---|---|---|
| MECHANICAL | 6.2 | 6.2 |
| LIGHTNING | 0.4 | 1.0 |
| SPLICES | 1.5 | 1.8 |
| OTHERS | 4.4 | 2.0 |
| | 12.5 | 11.0 |

*Note 1:* *This covers 60,000 miles of medium and long distance toll cable, 90% of which is directly buried at a depth of 30 to 40 inches and protected by tiles.*

*Note 2:* *By 1969 22.3% of the installed system was corrugated steel against 17.9% in 1965. 80 to 85% of newly installed long distance toll cables will be of this design in 1971 and 95% in 1972.*

Two significant points to observe in the above comparison is the higher incidence of lightning trouble in the steel sheath and the lower "other" problems. The former has resulted in the German Post Office deciding, as of 1971, to install a shield wire directly over the corrugated steel sheathed cable. This will reduce the incidence and magnitude of strikes entering the cable and significantly reduce the fault rate due to lightning. The "other" category covers earth displacement, vibration, rock movement, electrolytic and chemical corrosion.

Unfortunately, comparable data was not available within the Bell Canada System. The best estimate obtained was that the incidence of trouble was in the order of 3 per 100 miles, with approximately 60 percent of the damage reported being mechanical.

A value of 0.4 service interruptions per 100 miles per year has been suggested for the PCM system, however, a value of 1 appears more practical without going to the full extent of a "hardened" system.

*Sheath Design.* In view of the high reliability that is desired from the cable, and the length of time which may elapse between an alarm and repair crews taking corrective action, a modification has been made to the basic corrugated steel sheath.

An aluminum tape has been bonded to the inner surface of a polyethylene jacket containing longitudinal flutes to increase the dimensions of the outer envelope and reduce its pneumatic resistance.

In the field the cable will have two independent gas pressurization systems. The inner system being static at approximately 12 psi and the outer dynamic from 11 to 6 psi.

The aluminum tape will be electrically bonded to the outer steel envelope at all repeater locations, to assist in reducing the sheath potential during a lightning strike and improve the reduction or shielding factor of the steel sheath. Fig. 14 compares the reduction factor of the proposed design to a Lepeth PJ construction with an identical core.

Fig. 13 is a photograph of the complete cable.

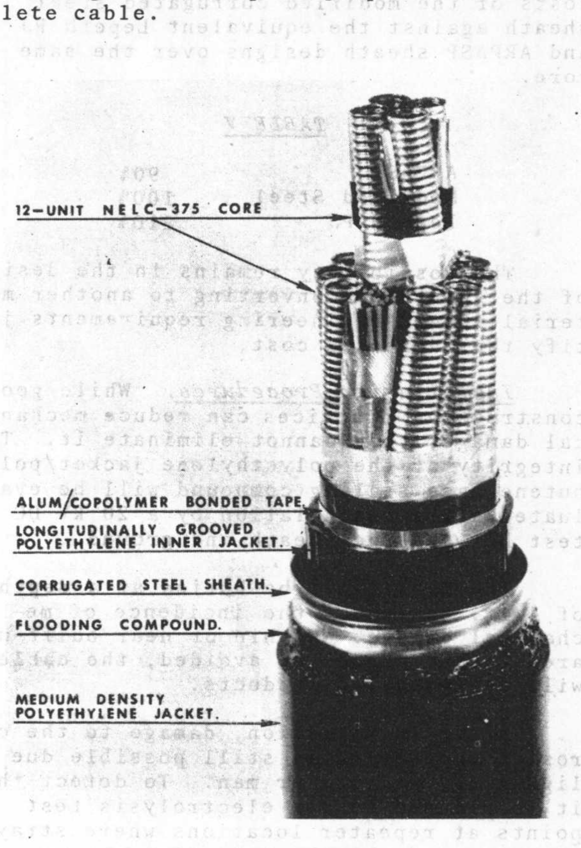
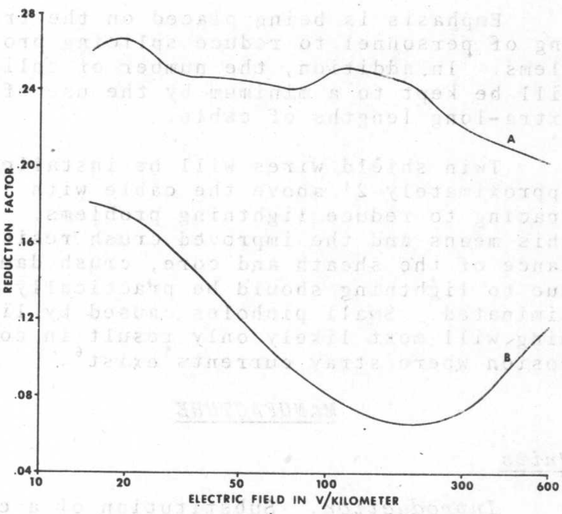



*FIG. 13 COMPOSITE LD-4 CABLE*




*(A) LD-4 Cable with Lepeth PJ Sheath.*
*(B) LD-4 Cable with Aluminum & Corrugated Steel Sheath.*

*FIG. 14 REDUCTION FACTOR TO THE CENTRE CONDUCTOR OF A COAXIAL UNIT*

Table V shows the relative material costs of the modified corrugated steel sheath against the equivalent Lepeth PJ and ARPASP sheath designs over the same core.

*TABLE V*

| | |
|---|---|
| ARPASP | 90% |
| Modified Steel | 100% |
| Lepeth PJ | 210% |

The possibility remains in the design of the sheath of converting to another material should engineering requirements justify the increased cost.

*Installation Procedures*. While good construction practices can reduce mechanical damage, they cannot eliminate it. The integrity of the polyethylene jacket/polybutene base sealing compound will be evaluated after installation by a 20 kV DC test between the sheath and ground.

The cable will be buried at a depth of 4 ft. to reduce the incidence of mechanical damage. Within or near built-up areas, that cannot be avoided, the cable will be installed in ducts.

After installation, damage to the corrosion protection is still possible due to lightning, rodents or man. To detect this it is planned to use electrolysis test points at repeater locations where stray currents and sheath protection change. The outer envelope gas alarm system will give secondary protection.

Emphasis is being placed on the training of personnel to reduce splicing problems. In addition, the number of splices will be kept to a minimum by the use of extra-long lengths of cable.

Twin shield wires will be installed approximately 2' above the cable with 18" spacing to reduce lightning problems. By this means and the improved crush resistance of the sheath and core, crush damage due to lightning should be practically eliminated. Small pinholes caused by lightning will most likely only result in corrosion where stray currents exist[6].

## *MANUFACTURE*

### *Units*

*Introduction*. Substitution of a corrugated copper-steel laminated outer conductor for flat copper resulted in a more economic design. A metallurgically bonded seam was indicated desirable in order to obtain superior mechanical properties from the coaxial unit. A structurally self-sufficient construction, by which is meant a construction which would provide better resistance to flexing, crushing and torsional stresses on the units, without the use of other supporting components such as binders, wrappings, extruded jackets etc., could be obtained only by mechanically or metallurgically bonding the edges of the outer conductor seam. Soldering was selected because of the problems imposed by the corrugated profile, speed of manufacture and possible heat damage to the insulating discs.

To obtain a soldered seam and at the same time a smooth circular inside profile was a challenging problem which was solved by the "Butt Strap" construction. This design has many manufacturing conveniences: 1) the tooling for the corrugators is simple, 2) introduction of the solder to the joint is relatively easy, 3) the tooling for roll-forming the outer conductor is straightforward and 4) the butted construction permits the laminating of copper and steel tapes in wide widths. The "Butt Strap" did, however, introduce some new problems, such as precorrugating two separate strips, putting them together so that the two profiles nest properly, and holding them together during heating and cooling cycles of soldering. Much of the development effort was devoted to solving these problems.

Considerable work was also put into the development of the laminating equipment, the Disc Applicator for fast and efficient application of discs on the centre wire, forming the outer conductor into a circular tube, rolling the solder wire into a ribbon and soldering the seam. A brief description of some of the problems we faced and the present equipment is given in the following paragraphs.

Simplicity and reliability of operation were always the guiding principles in the design and development of this facility. It was found convenient to separate the laminating and coaxial manufacturing operations. This provides some versatility in production. The volume of production foreseen, and the advantages of low initial cost, made a coil to coil type of manufacturing schedule the most attractive system, instead of a continuous running mill.

*Laminating*. Laminating copper to steel using an adhesive copolymer film is an apparently simple process, but practical utilization of this process introduces many manufacturing problems[7]. These are 1) cleanliness of the bonding surfaces, 2) providing adequate heat transfer to obtain laminating temperatures, 3) registering the edges of the three components, 4) contacting the bonding faces and 5) thickness control.

The copper and steel tapes are scrubbed, degreased, rinsed and dried in a specially designed degreaser which uses trichloroethylene as the solvent.

The principle of electrical resistance heating has been used in the Laminator illustrated in Photograph A. Transferring an adequate quantity of heat into the tapes by contact type heaters proved to be slow and inefficient. Excessive surface temperatures in the copper could give rise to tarnishing and oxidizing. The resistance heating arrangement has worked very well.

Tracking and alignment of the edges of the tapes are serious problems, especially on thin and delicate materials such as the 0.004 in. thick copper tape. We have overcome many of these problems by employing floating type guides.

When hot, the copolymer ribbon becomes sticky and adheres to any hot object it contacts. Further, when a small quantity of this substance is deposited on a roller, over which the hot laminated tape passes, the resulting hot copolymer lump picks up more of the same, thus accumulating large quantities in a short time. Consequently, we have avoided contacting any hot rolling surfaces with the laminated tape.

The final thickness is obtained by squeezing the semi-bonded tapes between a pair of cool rollers.

The Laminating line has operated satisfactorily at speeds up to 120 feet per minute. Peel strengths usually obtained are in the neighborhood of 16 to 18 lbs/in.

*Insulating*. Application of Polyethylene discs on the center wire at high speeds has undergone much development. On conventional machines there are two distinct problems: 1) orienting and feeding the discs at the required rate and 2) slitting and applying discs on the centre wire. The equipment available for orienting and feeding were found to be too slow for the line speeds contemplated for this unit.

Considerable effort was spent in developing a fast feeder for loose discs which could deliver the discs in excess of 2000 per minute. However, the oriented discs still had to negotiate the feeding tracks on their way to the disc applicator and many small, but significant, factors contributed to the frequent stoppage of disc flow, such as static electricity, foreign particles and plastic dust, to name only a few.

After numerous trials mechanical force feeding of the discs was found to be the answer and the idea of a disc chain evolved. Instead of punching loose discs from a plastic strip, a chain of discs is stamped. This chain is synchronously fed into the disc applicator by a pair of squeeze rollers. The disc applicator wheel has cutting knife elements mounted on it which sever the disc from the chain The rest of the disc application mechanism is similar to that on the serrated seam machines; namely, the slitting of the discs radially, opening the slit by passing the slit disc over a gradually expanding guide member and depositing it on the centre wire. Photographs B and C illustrate this machine.

This system has performed very well. Speeds up to 120 fpm can be obtained and the frequency of missing discs has been reduced by a couple of orders of magnitude from the existing design.

*Corrugating and Tube Forming*. The butt strap construction requires two corrugators, one for the laminated tape and the other for the butt strap. The profile of corrugation of the butt strap is designed so that proper nesting is obtained when the butt strap is laid over the corrugations of the laminated tape. The drive for the two corrugators is arranged so that an identical number of corrugations are produced on each tape per each revolution of the corrugator drive shaft.

The Tube Former is a simple roll forming machine with eight roll stands. All the eight sets of rolls are driven and the tooling is designed so that the insulated centre conductor passes right through the tooling.

Photographs D and E illustrate the Corrugator and Tube Former respectively.

*Solder Flattening and Fluxing*. This equipment required considerable development. The starting material is a solid solder wire. When a soft solder wire is rolled into a ribbon, the width obtained is dependent upon many variables such as the surface roughness of the rolls, the temperature of the rolls, the lubrication of the rolls, the front tension of the ribbon, the back tension of the incoming wire, etc. All these variables have to be held within very narrow limits in order to obtain accuracy of dimensions of the ribbon. Solid solder wire is rolled and the solder ribbon thus produced is then passed through a Flux Applicator to produce a thin covering of flux on the ribbon. In this manner the flux remains on the outside of the ribbon where it is most effective.

*Soldering Apparatus*. The combination of the tube formed by the laminated corrugated tape, the fluxed solder and the butt strap are heated to soldering temperature by means of a radio frequency induction coil. The power generation equipment is simple and conventional.

The joining elements are held together by a fixture during their heating and cooling cycle[8].

A drum capstan and a traversing take-up form the rest of the apparatus.

*Performance*. The insulating and soldering line can run at line speeds up to 120 fpm. The present operating speed of the line is 80 fpm. The drive arrangement and the control of the line are quite simple.

*Cable*

*General*. Special equipment, atmosphere control equipment and a complete reorganization of the production facilities were necessary to manufacture the LD-4 cable. The entire unit manufacturing area will be temperature, humidity and dust controlled.. The cabling, jacketing, sheath welding and stripper-locate areas will be completely air conditioned. The jacketing line, the stripper-locate equipment and the inspection facilities have also been specially modified to suit the needs of manufacturing. A brief description of some of the new facilities is presented in the following paragraphs.

*Cabling Facilities*. Cabling of the coaxial units may introduce Structural Return Loss particularly at lay frequencies. Experience with this problem has been applied to the development of a new Cabler designed especially for coaxial cables. This equipment will be installed in 1972. It will have twelve coaxial give-ups in the beginning with features that could extend this number to eighteen at a later time. The give-ups are located symmetrically in one plane with special consideration given to small angles of deflection at guides and lay plates. Centrifugal tensions and the cyclical variations of these will be kept to a minimum by employing a rotating capstan and a rotating take-up. This cabler incorporates good tension control systems for the give-ups and a random lay variation feature should this be necessary.

*Welded and Corrugated Sheath Line*. The steel sheath welding and corrugating line utilizes the inert gas electric arc welding process. This line has been well proven in many countries particularly in Europe. The corrugator is of the eccentric ring travelling carriage type. Photograph F shows the Tube Forming and Welding sections of this line and Photograph G shows a close-up view of the corrugator. Following the manufacture of the welded sheath a gas pressure test is carried out to ensure the integrity of the weld. Over the welded sheath a moisture barrier of a specially formulated flooding compound is applied. This completely fills the corrugations of the sheath, thereby providing a reservoir of compound to seal any defects in the outer jacket which may arise in service.

## *PRODUCT EVALUATION*

### *Electrical Characteristics*

The following results are from product made during a period of 12 months on prototype equipment. Since both the equipment and the product had been under development during this period, some anomalies have had to be allowed for in the results.

*Impedance*. The stability of the mean characteristic impedance during processing has been impressive. For example, to allow for an anticipated decrease in impedance during the various manufacturing stages, the unit was designed to have, at the initial manufacturing stage, an impedance of 75.2 ohms at 2 MHz using a 125 nano-second pulse. Due to the excellent handling characteristics of the unit no significant decrease in impedance occurred.

The new unit's average impedance is approximately .2 ohm above the existing serrated seam design at 2 MHz, and .2 ohm below 75 ohms at "infinite" frequency. No further changes are contemplated in the impedance level.

The control of the mean characteristic impedance has been very precise with this equipment. The standard deviation of the last batch of 21 reels was within .08 ohms with an average of 75.26 ohms.

Relative to the mean characteristic impedance, the deviation of the effective characteristic impedance, when measured using a radio frequency source, was poor. The main cause of this was traced to steel raw material variations, and the same corrective action was taken as in the case of SRL problems. These deviations are critical for the analogue systems.

Fig. 15 shows the variation of the characteristic impedance with frequency based on the computer predictions. Actual measured mean values using the r.f. technique were .4 to .1% higher than predicted between .5 and 10 MHz. The present range of deviations (.8%) are shown in this figure relative to the theoretical mean for graphical purposes only. Deviations as great as 1.5% have been detected.

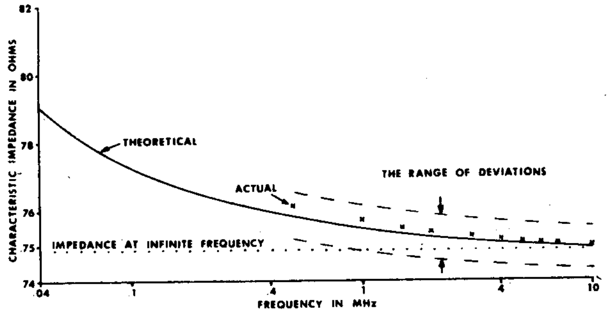



*FIG. 15* CHARACTERISTIC IMPEDANCE VARIATION WITH FREQUENCY FOR CORRUGATED .375" DESIGN

*Attenuation*. The average attenuation of the coaxial unit has been found to conform to the expression $\alpha=a+b\sqrt{f}+cf$ above 3 MHz, where a=.0096, b=.729, c=.00107 and f is in MHz, for dB/1000 ft. of unit at 68°F.

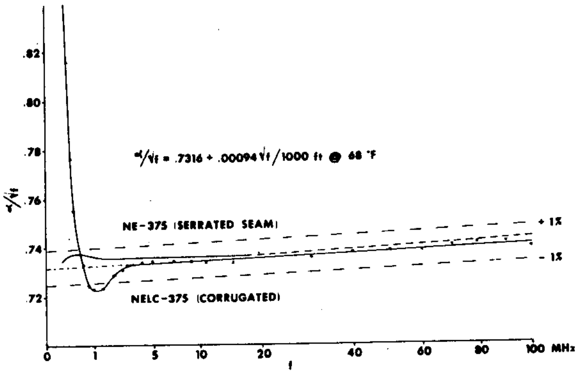



*FIG. 16* ATTENUATION DIVIDED BY SQUARE ROOT OF FREQUENCY FOR CORRUGATED AND SERRATED SEAM .375" DESIGNS

To permit an enlarged scale for Fig. 16 the attenuation has been divided by the square root of frequency. A comparison is made with the serrated seam design, and between computed and actual measurements on the corrugated design.

The amount of ripple on the attenuation curve is very critical to the digital system and has to be controlled precisely. The maximum R.M.S. deviation desired from the mean is specified at 0.08%. Present indications are that this value is under .17% with some portion due to measurement error. More precise methods of attenuation measurement are being developed.

*Phase*. Fig. 17 shows the theoretical phase change predicted by the computer programme and the actual measurements made up to 12 MHz. A good correlation was obtained.

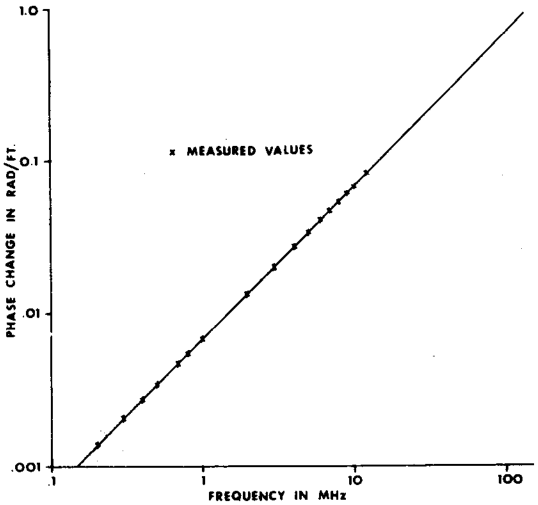



*FIG. 17* PHASE CHANGE VERSUS FREQUENCY FOR CORRUGATED .375" DESIGN

*Structural Return Loss*. All units manufactured to date have been "swept", in the laboratory, from 5 to 500 MHz. Although a very high value of SRL is, in itself, unnecessary for the digital system,

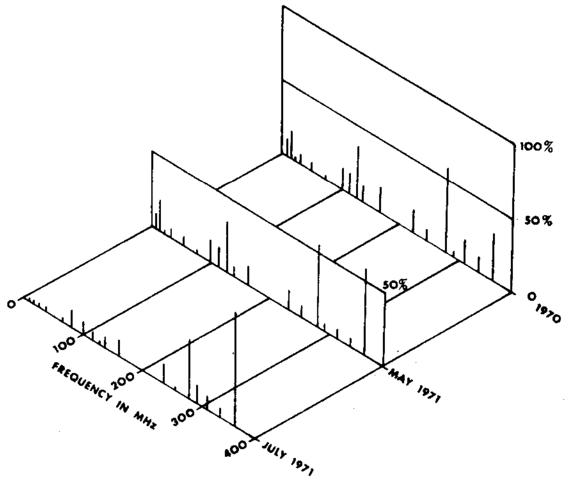



*FIG. 18* PERCENTAGE OF SRL READINGS BELOW 32 dB