

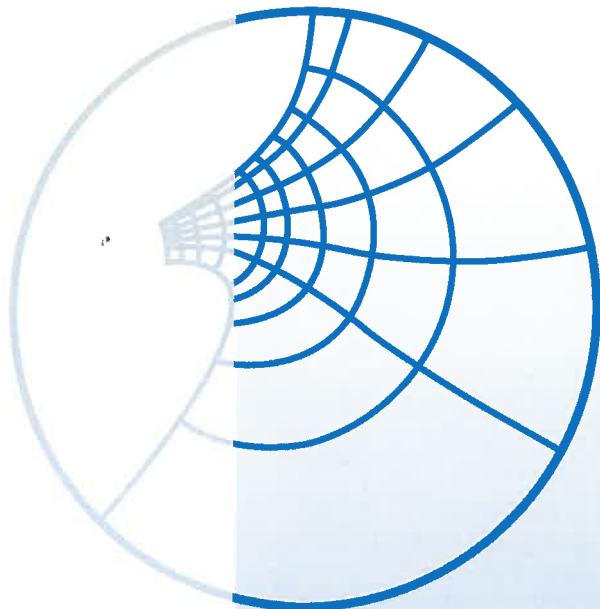
# EMMA - Club

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## **Phase-temperature characteristics of coaxial cables**

*Stan Evans*



# **The NPL Electromagnetic Materials Measurements and Applications Club**

**EMMA-Club Technical Note Number 3 September 1999**

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### **Introduction**

Making a choice of coaxial cable from a selection of manufacturers catalogues can be a time-consuming and perhaps bewildering experience because much of the data supplied may be irrelevant to one's own application. Manufacturers use their own type numbers most of which are related to military specifications. Current MIL specs begin with 'M17' but 'RG' numbers are in common use and though formally obsolete they usually appear in manufacturers tables of equivalents. One generally wants to know which cable is the cheapest, with adequate performance for the purpose, and compatible with the connector types already in use. This Technical Note will not provide a short-cut through that jungle; it is restricted to the question of phase stability and phase variations in cables subject to temperature cycling and, to a lesser extent, mechanical stress. It might enable the reader quickly to dismiss the problem of phase variations in his or her own application but, if not, to alert them to the danger and point to the cable types which are to be preferred. Those who want the answers without any explanation may now turn to figures 3 to 7.

The applications which we have in mind include all vector network analyser measurements, coherent detector systems in general, phased arrays of active or passive elements using dividers, combiner or couplers, indeed any phase-sensitive interconnections of elements or systems. The characteristics or coefficients to be given will be normalised (as a proportion in parts-per-million) to the total phase delay or the total time delay in any given cable, so that they are equally applicable in the frequency domain or in the time domain to baseband pulse and digital signaling or to binary keying of bandpass systems. In many of these applications the change of phase of the signal delivered by a single cable is not significant of itself; what is important is the difference between two or more cables, one of which provides the reference phase. Clearly the differences will be minimised if the cables can be of the same length, the same type, and kept at similar temperatures.

## Cable types

Coaxial lines and cables will be considered in broad groups: rigid, semi-rigid, and flexible, these characteristics are essentially determined by the outer conductor material and structure. Within each group there is a choice of dielectric materials and supporting structures for the inner conductor. The material and structure of the inner itself will not usually be a significant factor in the present considerations.

The principal solid dielectrics in use are polythene (polyethylene, PE) and PTFE (polytetrafluoroethylene, 'Teflon'). PE is retained for less demanding mechanical requirements, lower cost, narrower range of temperature, and generally for frequencies below about 1 GHz since dimensional stability is poor. PTFE is much more widely used for microwave applications and is so satisfactory from many points of view that it is the principal subject of this Technical Note, but it will be necessary to consider what its failings may be when temperature variations are to occur in service. After all, it is sometimes chosen because its maximum service temperature at 250 °C is one of the highest amongst polymers, and its minimum is -75 °C. Like most solid polymers, it has a significantly higher thermal expansion

Table 1. Representative thermal properties of some cable and connector materials at 25 °C.

| Materials            | Linear expansion<br>coefficient, $\alpha \times 10^6 \text{ K}^{-1}$ | Thermal conductivity<br>$\lambda / \text{W m}^{-1} \text{K}^{-1}$ |
|----------------------|----------------------------------------------------------------------|-------------------------------------------------------------------|
| Copper               | 17                                                                   | 400                                                               |
| Brass                | 17 - 20                                                              | 110 - 120                                                         |
| Al and alloys        | 20 - 24                                                              | 200 - 240                                                         |
| Stainless steel 304  | 16                                                                   | 15 - 20                                                           |
| Kovar® FeNiCo        | 5                                                                    | 14                                                                |
| Polythene            | 150 - 250                                                            | 0.3 - 0.5                                                         |
| PTFE                 | 100                                                                  | 0.2 - 0.3                                                         |
| Polystyrene          | 80 - 120                                                             | 0.1 - 0.25                                                        |
| Borosilicate glass   | 3 - 6                                                                | 1.0 - 1.5                                                         |
| Fused silica         | 0.5                                                                  | 1.0 - 1.5                                                         |
| Mica                 | 10 - 40                                                              | 5                                                                 |
| Alumina              | 6 - 8                                                                | 24                                                                |
| Steatite             | 8 - 10                                                               | 5                                                                 |
| Macor® glass-ceramic | 10                                                                   | 1.5                                                               |

coefficient than metals so this will cause radial stresses, or leave annular airgaps, in rigid and semi-rigid lines with rise or fall of temperature and longitudinal differential expansion will likewise be troublesome at the connectors. However these particular problems are minimal in flexible cables with outer conductors of copper braid, or braid and foil.

### Behaviour of PTFE

There are two complications, specific to PTFE, upsetting the simple picture of uniform thermal expansion. The first is a change of molecular structure at about 19 °C with a consequent non-linear change in density of about 7 parts per thousand, seen in the volumetric expansion curve in figure 1. It is doubly unfortunate that this should occur within the regular ambient range of temperature.

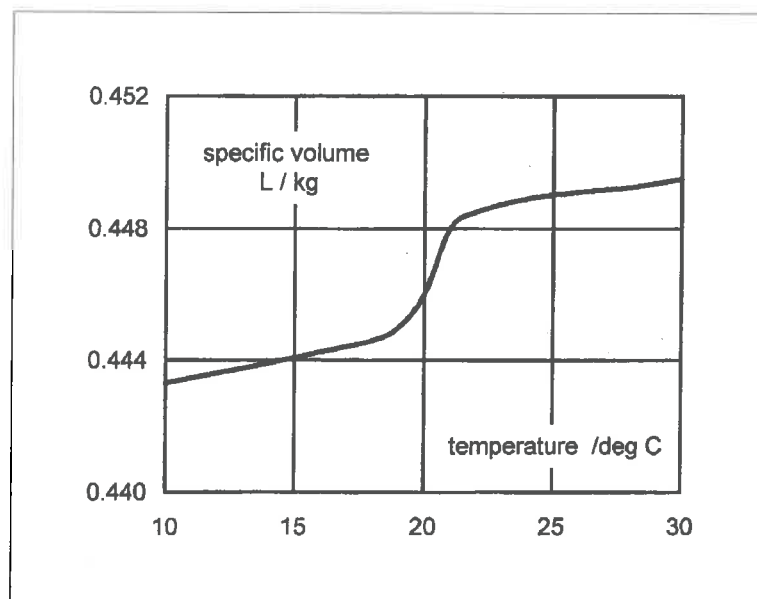


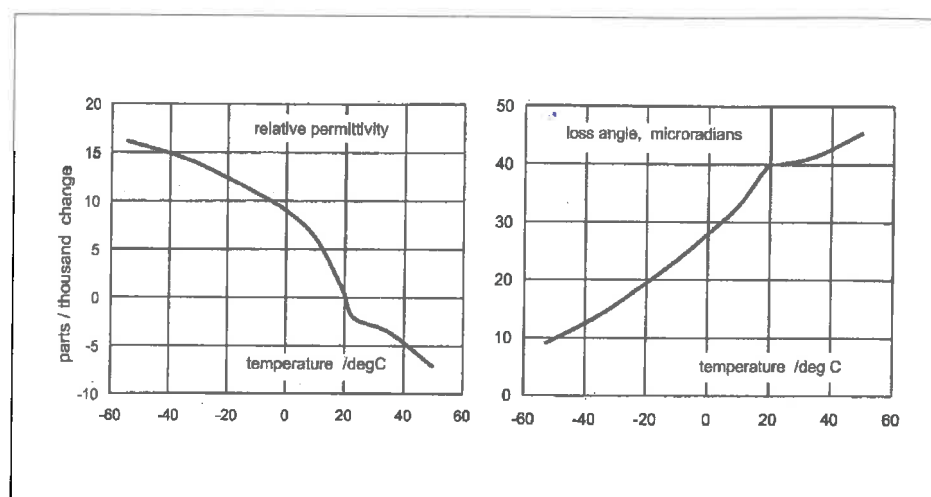
Figure 1 Volumetric expansion of PTFE, after Rigby & Bunn [1]. For a wider temperature range see Kirby [2].

From X-ray diffraction studies it is found that, below 19 °C, the

chain of carbon atoms in the polymer carry the fluorine atoms on branches in a helical configuration making one 180° twist every 13 carbons. The helices in adjacent chains are packed and linked side-by-side to form a regular lattice; i.e. the structure is crystalline. The crystallinity is never total but varies from about 50% to 95% depending on the manufacturing process and the subsequent thermal history. Above 19° but below 30°, the chains untwist to 15 carbons per 180° rotation and a less compact but regular packing is still possible. There is a further smaller discontinuity in density at 30°C where the links between the chains begin to become disordered and the distance between the chains then increases steadily with further increase of temperature. However the chains are much stiffer than in most polymers and are not entangled, which accounts for the 'leathery' (as distinct from 'rubbery') behaviour, and the high melting point.

The changes in density associated with the regular thermal expansion and the discontinuity due to the structural transition, both have their effect on permittivity and loss as shown in figure 2, based on measurements made at NPL. A decreasing density leads to a decreasing permittivity and non-polar solids with low loss tangent follow the Clausius-Mosotti relation (Reitz et al [3] and ICI [4]) which we apply in the analysis in the following section. The effect with the change of structure seen in figure 2 around 19 °C, is in the sense expected but the magnitude is difficult to assess; from the density change the predicted discontinuity in permittivity would be 4.5 parts /thousand. It can be noted as an aside, that in materials with

**Figure 2**  
*Temperature coefficient of relative permittivity and loss tangent for PTFE at 9 GHz, as measured at NPL. This sample is unsintered and highly crystalline whereas the sintered polymer typically 60% crystalline, has loss angle 200 to 250 microrad at 25 °C.*



polar molecules ( $H_2O$  for example) the molecular polarizability decreases as  $1/T$ , so the low-frequency permittivity of such materials decreases more steeply than would be expected from volumetric expansion alone.

A second complication intruding on uniform thermal expansion is that, with temperature cycling, PTFE exhibits hysteresis and a 'permanent set' in the phase delay after a recommended annealing routine. The magnitude of these effects depends on constraints imposed on the dielectric by the cable construction and examples are therefore given later with the relevant cable types.

In recent years both PE and PTFE have been employed in cable manufacture in low-density forms described as microporous or foamed, and (for PTFE) in wound tape form. The lower density inherently reduces dielectric loss and at the same time it reduces any variations in velocity or attenuation due to thermal effects. Velocity factors from 0.78 to 0.88 are normal. The density can, to some extent, be tailored so as to cause cancellation of competing influences in the thermal variations as we shall show.

As an alternative to foam, the inner conductor may be supported by dielectric splines, or by a helical fibre or blade, the primary aim of which is to reduce losses by the use of the greatest possible proportion of air. Velocity factors reach 0.93 but hermetic sealing is required if the loss performance is to be sustained.

### Analysis of cable delay

Consider a cable of length  $L$  at ambient temperature between defined reference planes. With temperature change  $\theta$  from ambient there may be two different thermal expansion coefficients:

$\alpha_1$  the effective longitudinal coefficient for the cable as a whole. This coefficient will be determined by the outer conductor if that is rigid or semi-rigid. In flexible cables with braided outer conductor the inner may impose some constraint on longitudinal expansion.

$\alpha_2$  the radial expansion coefficient for the dielectric. If the dielectric is unstressed at

ambient temperature then a solid outer conductor will constrain it for increased temperatures, possibly not for reduced temperatures. Braided outer conductors are unlikely to cause significant constraint on dielectric expansion or contraction.

Then 
$$\frac{dL}{d\theta} = \alpha_1 L \quad 1.$$

and the volumetric expansion is

$$\frac{dV}{d\theta} = (\alpha_1 + 2\alpha_2)V \quad 2.$$

Rewritten in terms of density

$$-\frac{1}{\rho} \frac{d\rho}{d\theta} = -(\alpha_1 + 2\alpha_2) \quad 3.$$

With reduction in density the velocity of EM wave propagation is increased and this factor can more than compensate for the increase in cable length. From the Clausius-Mosotti relation we have [4]

$$\frac{\epsilon' - 1}{\epsilon' + 2} = k\rho \quad 4.$$

where k is a constant for the material. We need to derive the proportional change in  $\epsilon'$  due to change in  $\rho$ . The neatest way is to take the natural log of both sides and then differentiate each term with respect to  $\theta$ , the temperature change. The result is

$$\frac{1}{\epsilon'} \frac{d\epsilon'}{d\theta} = \frac{(\epsilon' - 1)(\epsilon' + 2)}{3\epsilon'} \frac{1}{\rho} \frac{d\rho}{d\theta} \quad 5.$$

Writing  $n = \sqrt{\epsilon'}$  the total travel time is  $t = n L/c$  and the fractional increase in time, with temperature is therefore

$$\frac{1}{t} \frac{dt}{d\theta} = \frac{1}{L} \frac{dL}{d\theta} + \frac{1}{n} \frac{dn}{d\theta} \quad 6.$$

$$= \alpha_1 - (\alpha_1 + 2\alpha_2) \frac{(\epsilon' - 1)(\epsilon' + 2)}{6\epsilon'}$$

The first term in equation 6 represents increased delay due to the increase in length, the second term a reduction in delay due to the increase in velocity, and the effects of these two terms can now be considered for various cable types. There is a possibility of confusion in the sign convention adopted by different manufacturers. In this Technical Note, since we represent all changes as a proportion of total time delay  $t$ , or total phase delay  $\phi$ , of a given cable, then an increase in delay is positive, and the gradient  $d\phi/d\theta$  is positive. (The alternative point of view is that the phase at the receiving end is retarded so the phasor has a negative argument.)

## Measured properties of different cable types

### 1. Rigid air-line.

Solid conductors of plated brass, 7 mm or 14 mm outside diameter, with the inner supported by precisely-designed dielectric beads in GPC connectors. In straight lengths and usually reserved for minimum possible loss and accuracy of characteristic impedance with precision laboratory instruments. The second term in eq 6 is zero since  $\epsilon' = 1$  and a representative phase measurement is shown in figure 3 where the average positive slope of 19 ppm/K is within the  $\alpha$ -values for brass in Table 1. There is no hysteresis between cooling and warming cycles.

### 2. Semi-rigid air-articulated.

Using outer conductors which can be pre-formed by hand, means to support the inner conductor with a minimum of solid dielectric have been introduced by several manufacturers. The Precision Tube Company produce sizes from 3.6 to 12.7 millimetres o.d. in aluminium or copper with longitudinal splines of extruded PTFE, a minimum bend radius

6 x o.d. and velocity factor 88.4%. Figure 3 shows the phase changes in two temperature cycles for a cable with 6.3 mm copper outer. The expansion overall will be determined by the conductors due to the small proportion of dielectric but the effect on the velocity factor as analysed above is clearly not entirely appropriate for this geometry of cross-section. However it can be seen by comparison with pure air-line that the presence of

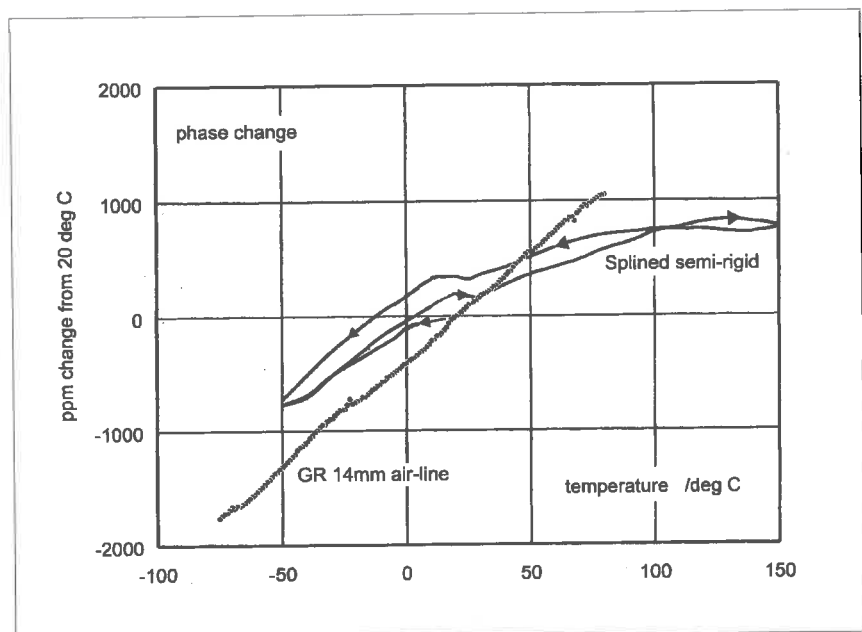


Figure 3 Comparison of rigid air-line (author's measurements) and air-articulated semi-rigid line with dielectric splines (after [15]).

some dielectric has achieved a useful measure of compensation above 20 °C and a residual hysteresis ~100 ppm. The irregularity in the region of 20 °C is readily visible; below this there is apparently no effective compensation since the gradient is the same as the air-line.

Diameters of air-articulated cables from 12.7 to 127 mm o.d. with a single helical blade inner support are produced by Andrew Corp. for high power antenna feeds. Velocity factors reach 92% with rather less phase-temperature compensation than the example above.

### 3. Semi-rigid, solid PTFE dielectric.

This popular cable type generally with copper outer conductor and velocity factor 70% is available from 0.5 to 8.3 mm o.d. Nevertheless it introduces the twin problems of hysteresis in temperature cycling and non-linearity of expansion from 10 to 25 °C. The following preconditioning or annealing procedure should be followed preferably after cable lengths have been formed to the shape required in service and before final trimming for connector assembly.

1. Heat the cable to the maximum temperature which may be encountered in service.  
Maintain for one hour
2. Cool to -50 °C and maintain for one hour. The low temperature will cause the dielectric to contract away from the outer conductor.
3. Repeat steps 1 & 2 two or more times.

Anyone who doubts the necessity for this should now refer to figure 4 which shows the changes in phase delay in a 3.6 mm cable; in this example the cycle starts with the low temperature which disengages the dielectric from the outer and possibly increases crystallinity, which factors cause the first excursion at high temperature to be exaggerated. In fact

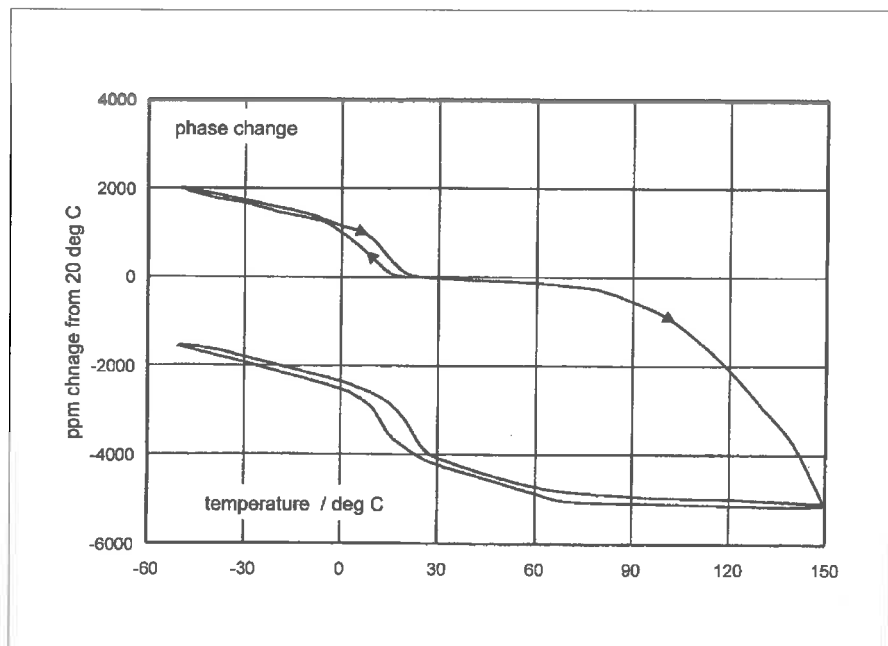


Figure 4 Preconditioning of semi-rigid cable with solid PTFE dielectric (after [5]).

most of the permanent set is due to taking the first cycle above 100 °C; subsequent cycles lie within the boundaries shown in the lower part of the plot.

An example of a single temperature sweep (with a different sample of the same cable) appears on expanded scale in figure 5 and it is instructive to relate this

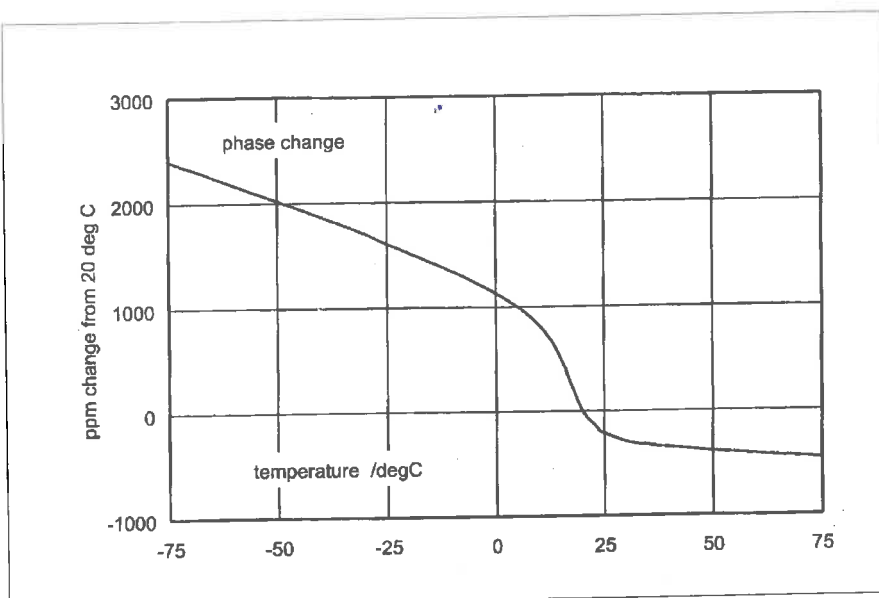


Figure 5 Variation of phase in RG 402 semi-rigid cable (author's measurements).

to the terms in eq. 6. It might be supposed that  $\alpha_1 = \alpha_2$  as determined by the inner and outer conductors constraining the radial expansion. If that is assumed to be the case, and putting  $\epsilon' = 2.1$ , the compensation as calculated from equation 6 is almost perfect, the overall coefficient being -1 ppm /K. The measured gradient above 20 °C on the plot is -3 ppm /K.

The discontinuity in figure 5 with change of structure between 10 and 25 °C is about 1250 ppm. Although this is very significant in relation to other changes in phase delay likely to be encountered in service, it is less than would be calculated from a volume change of 7 parts per thousand and the Clausius Mosotti relation. Furthermore, for all lower temperatures in figure 5, if the value of  $a_2$  were to increase to that for unconstrained PTFE, the overall coefficient would be -60 ppm/K whereas the observed gradient below 0 °C is -17 ppm/K. We must suppose that the dielectric is never entirely free.

#### 4 Low-density PTFE semi-rigid cable

Available in the same sizes as for solid PTFE but with a velocity factor of 83% and much lower loss, figure 6 shows characteristics of an air-articulated tape-wrap design 3.6 mm diameter with annealing cycle going from -20 °C to +150 °C as in figure 4 for the solid dielectric. The permanent set is now in the opposite sense to figure 4 and about one quarter the magnitude, and the gradient in the positive temperature range is also in the opposite sense at about +12 ppm K above 90 °C which implies that it is mainly due to increasing length of cable with very little compensation by increased velocity. At lower temperatures the compensation is excellent but the irregularity in the vicinity of 20 °C remains, somewhat reduced in magnitude.

Table 2. Summary values

Typical values of total phase-change in ppm for different temperature ranges. 'PreCon' is the permanent set at 25 °C, after cycling from -50° to +150 °C; most of the change is due to the range above 100 °C.

| Cable                               | PreCon | -60 to 0 °C | 0 to 30 °C | 30 to 90 °C |
|-------------------------------------|--------|-------------|------------|-------------|
| 1. Rigid air-line                   | 0      | +1100       | +550       | +1100       |
| 2. Semi-rigid<br>splined dielectric | +250   | +1000       | +200       | +450        |
| 3. Semi-rigid,<br>solid PTFE        | -4000  | -1100       | -1400      | -200        |
| 4. Semi-rigid,<br>LD PTFE           | +1100  | -170        | -800       | < 50        |
| 5. Braided flexible,<br>solid PTFE  | na.    | -2700       | -2900      | -3400       |
| 6. Braided flexible,<br>LD PTFE     | na.    | -240        | -1050      | +400        |

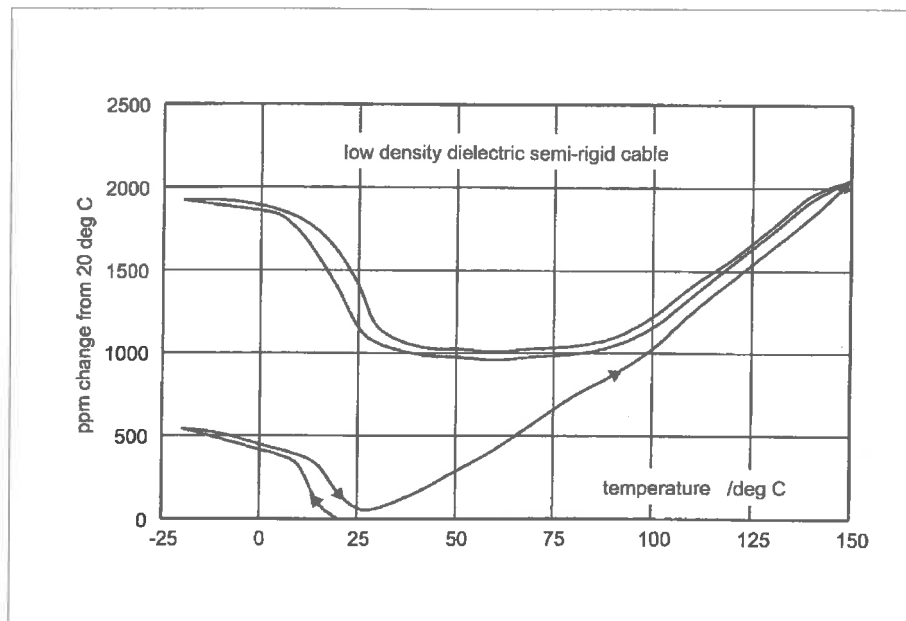
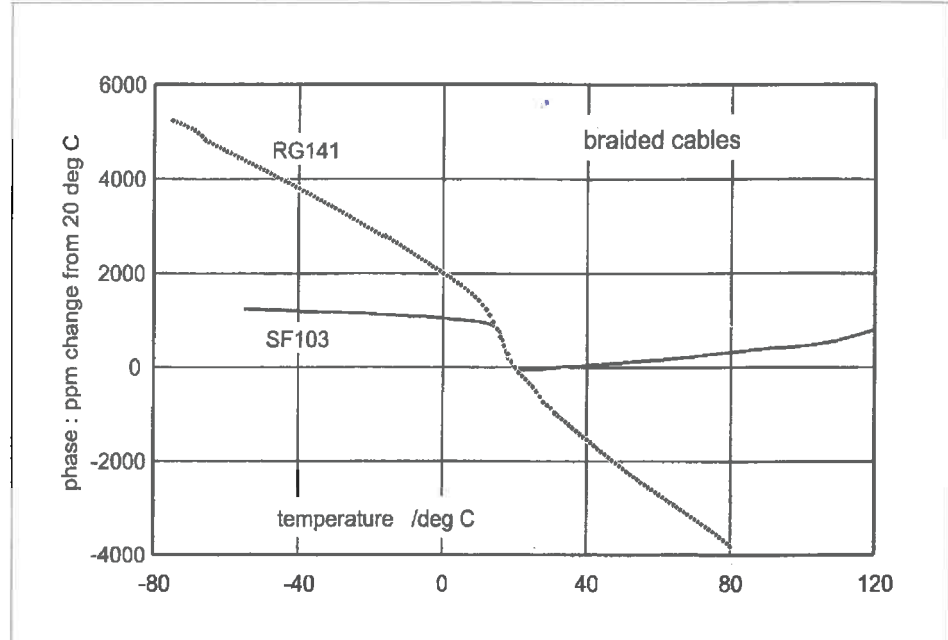


Figure 6  
Preconditioning of  
low-density semi-rigid  
cable (after Precision  
Tube [5]). Cycles after  
the first remain within  
the upper envelope  
between 1000 and  
2000 ppm.

Figure 7 Phase change in braided cables, 4.4 mm od. RG141 (author's measurements) is a solid PTFE dielectric cable with a velocity factor of 0.70. SF103 has low-density PTFE dielectric with velocity factor 0.78 (after Huber+Suhner [6] ).



## 5. Flexible braided cables

Flexible cables are available in diameters from 1.8 mm upwards, with solid or stranded inner conductor, solid or low-density dielectric, various qualities of wire-braiding with or without foil wrap, and a variety of jacket materials. It is to be expected that the dielectric will expand and contract fairly freely within braid, making both terms in eq. 6 much larger than for types considered so far. Typical solid dielectric and low-density types are compared in figure 7. For the RG141, the steep negative gradient implies that the velocity term is dominant, over-correcting for the expansion in length, and the magnitude requires that the longitudinal coefficient  $\alpha_1$  is about half the unconstrained value. The huge improvement achieved by the use of low-density PTFE is illustrated by the curve for Suhner type SF103 though some irregularity near 20 °C is unavoidable. These cable types also have superior phase stability with mechanical strain in bending and twisting. There is a useful discussion of attainable standards in phase matching and phase tracking in the Sucoflex, catalogue [6].

### Practical consequences: a numerical example

Suppose an open-ended coaxial probe is to be used for assessing the state-of-cure of a concrete mix, which decreases in permittivity as the material hydrates. The probe is used at 300 MHz on a flexible cable of length 1 m and velocity factor 0.7. The total out-and-return phase delay is therefore  $2 \times 360^\circ / 0.7 = 1028^\circ$ . The probe has been calibrated in the laboratory with the cable at 25 °C and it is now used out-of-doors at 5 °C introducing a phase advance of  $2400 \text{ ppm} = 2.47^\circ$ .

The probe is modelled by a lumped capacitance  $C = 0.16\epsilon \text{ pF}$  where  $\epsilon$  refers to the material sampled. For the purpose of this example let  $\epsilon = 8.0$  (an imaginary component could be included but for ease of calculation we shall omit it.)

The probe impedance,  $Z_1 = 1/j\omega C = -j 414 \Omega$

The true voltage reflection coefficient is

$$\rho_1 = \frac{Z_1 - Z_0}{Z_1 + Z_0} = 0.971 - j 0.238 = 1.0 \angle -13.76^\circ$$

(note unit magnitude since we postulated a lossless load )

Due to the phase advance calculated above, the instrument records

$$\rho_2 = 1.0 \angle -112.9^\circ = 0.981 - j 0.196$$

Transformed to an apparent load impedance

$$Z_2 = \frac{1 + \rho_2}{1 - \rho_2} Z_0 = -j 505 \Omega$$

and the apparent permittivity is,  $\epsilon_2 = 8.0 \times 414/505 = 6.5$

Thus there is an error of 18 % in  $\epsilon$  due to the change in temperature of the cable.

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