

# THE EFFECT OF TEMPERATURE ON INTERNAL CHARGING AND ITS POTENTIAL ROLE IN HAZARD MITIGATION

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## ABSTRACT

The conductivity of dielectrics is a major consideration when assessing their susceptibility to internal charging. This paper highlights the significant influence which temperature has upon the conductivity of polymers and discusses the implications for assessments of internal charging hazards on satellites. Methods for determination of thermally induced variation of conductivity are discussed and experimental results for selected polymers are reported. For hazard mitigation, the use of thermal control as an alternative (or as a supplement) to shielding is proposed.

## 1. INTRODUCTION

Engineering analysis of the internal charging problem requires good models of the energetic electron environment, the electron transport process and, finally, the flow of electrons once deposited. Key to the latter is the bulk conductivity of the dielectric. Materials which suffer internal charging in the natural space environment generally have dielectric conductivities below  $10^{-16} (\Omega\text{cm})^{-1}$ .

The conductivity of a dielectric is often quoted by manufacturers as a stand-alone figure with little or no additional information such as how it was derived. It is necessary to be cautious of such figures since, as will be seen, they may not always be suitable for application to the internal charging situation. Furthermore, conductivity is influenced by environmental conditions. For example, it is well known that radiation induces additional conductivity in materials according to the dose rate [1] and there are some reports of a total dose effect as well. However, from an internal charging perspective, ignoring radiation induced conductivity will yield a 'worst-case' conductivity and therefore a safe, if conservative, analysis.

High internal electric fields ( $>10^6$  V/m) are also a cause of additional conductivity within the dielectric. Again, ignoring field-enhanced conductivity leads to a safe but conservative analysis. In fact, if such high fields do exist within the dielectric then there is already a risk of breakdown, so generally other intervention measures should be used to ensure that these high fields are never reached

The most significant influence on dielectric conductivity is temperature. Since the standard

conductivity figures are strictly quoted for one temperature only, it is possible that in a given practical situation, the actual dielectric conductivity will be either higher or lower. Therefore ignoring the temperature effect can potentially lead to an unsafe analysis. It is clearly important to establish the magnitude of the temperature effect. With this aim in mind the standard methods of measuring dielectric conductivity were reviewed.

## 2. STANDARD MEASUREMENTS OF BULK CONDUCTIVITY

Methods for determining surface and bulk conductivity of materials are published in both Europe (IEC 93) [2] and the US (ASTM-D257) [3]. These two standards are, in essence, very similar. Each notes that repeatability of conductivity measurements is difficult to achieve even under apparently identical conditions – reproducibility is generally no better than 10%. The standards do not prescribe an exact method but offer guidance with various options which can be adopted. The results from a test should, ideally, include a full range of information on the conditions which applied at the time. Therefore it is difficult to be sure that any two conductivity figures quoted are ever directly comparable, unless the full set of conditions from the tests are available and found to be identical.

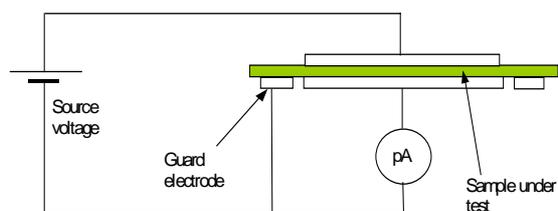


Fig. 1 Standard arrangement for measuring conductivity of dielectrics

The standard method requires electrodes to be applied on either side of a planar sample of dielectric. Since the effects of surface and bulk conductivity must be separated, a different electrode connection scheme is required for each type of measurement. Fig. 1 shows the arrangement described for measuring bulk conductivity: current flowing across the surface of the sample is intercepted by the guard electrode and does not pass through the current measuring equipment.

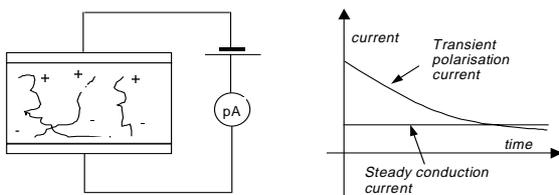


Fig. 2 Long-term polarisation of dielectrics

The standards define bulk conductance as ‘the ratio of the current in the volume of the specimen to the dc voltage applied to the two electrodes’ i.e. the application of external electrodes is inherent in the definition and the measurement standards. A potential difference is applied to the electrodes and the resulting (small) current flow is recorded. The conductivity is then derived from the conductance by taking account of the geometry of the apparatus and the sample.

Following the application of the constant voltage, the recorded current decays slowly over time. The standards attribute this effect to dielectric polarisation and the sweep of mobile ions to the electrodes (Fig. 2). For materials with conductivities greater than about  $10^{-12} (\Omega\text{cm})^{-1}$  a steady state should be reached within one minute of the application of the voltage [3]. Therefore the reading is taken after 1 minute. For materials with lower conductivities the decay may continue for hours, days or weeks, which is certainly the case for dielectrics of relevance to internal charging. In such cases the material is characterised by the ‘time dependence of the volume conductivity’ [2]. However, it seems that general industry practice is still to quote the value at 1 minute after commencement. While suitable for many purposes, the question of whether this measurement is appropriate for application to the internal charging problem is, of course, immediately raised.

It is noted that although the test results should state the temperature of the specimen at the time, determination of the influence of changes in temperature on the conductivity is not part of the test. Nevertheless the importance of temperature variations is recognised in [3] and briefly discussed. Fundamental temperature effects have been investigated in more detail by Adamec & Calderwood (A&C) [4].

### 3. RESULTS OF CONDUCTIVITY MEASUREMENTS AT DIFFERENT TEMPERATURES

Having reviewed the standard methods and the work of A&C, it was decided to measure the conductivity of selected polymers at a number of different temperatures. The results of one such set of measurements on PMMA (also known as Plexiglas or Perspex) are shown in Fig. 3. While PMMA is not used on spacecraft, it is often used as a reference material in

studies of dielectrics, partly because of its transparency. The test began with the sample stabilised at the highest temperature ( $112^{\circ}\text{C}$ ). Once a measurement set was completed the temperature was adjusted and the sample was allowed to reach equilibrium at the new temperature before proceeding. Time was allowed between each set of readings for full electrical relaxation of the sample.

It can be seen that as temperature is decreased, not only does the initial conductivity decrease but also the decay of the conductivity with time becomes progressively slower. At temperatures lower than  $50^{\circ}\text{C}$  the currents rapidly reached the measurement limits of the equipment and noise began to make a significant contribution. A similar form of result was also seen for FEP, but within the duration of the test, equilibrium was not seen to be achieved at any temperature employed. The results for PMMA compare well with those reported by Adamec & Calderwood.

A&C reported that processes which contribute to the time dependent current flow include slow types of dipole relaxation, trapping of charge carriers and complete or partial electrode blocking. It was noted that the current decay has sometimes been attributed to a reduction in the field strength in the bulk of the material due to the action of a counter-field produced by charges being accumulated at the electrodes. However A&C concluded that the charge accumulated by the small charging current during the relevant time would not be capable of reducing the field inside the specimen by any substantial amount. A&C noted that only at elevated temperatures ( $> 50^{\circ}\text{C}$ ) it is possible to

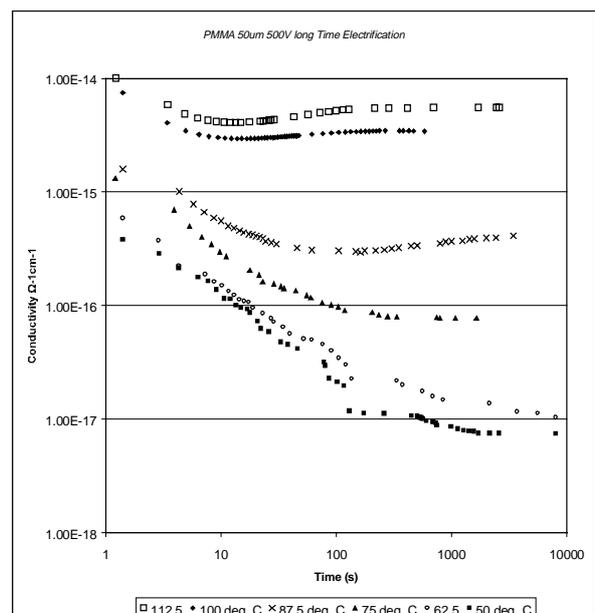


Fig. 3 Results from measurements of PMMA conductivity at different temperatures. A stable value is achieved more rapidly at higher temperatures.

detect the superposition of the transient component on the steady state component, which again compares well with our results. The primary conclusion from the work of A&C is to rule out the effects of electrode/dielectric interaction as being the cause of the slowly decreasing current. Rather, bulk processes in the dielectric are thought to be the cause, the most important being the very slow orientation of molecular dipoles in synthetic polymers after application of an electric field. At the same time a true conduction current will flow although this is be masked initially by the polarisation current, particularly at low temperatures when the relaxation is extremely slow. The polarisation process becomes more rapid at higher temperatures due to increased mobility of the charge carriers. Since the conduction current is higher, it becomes dominant that much sooner.

Under internal charging conditions the conduction current is the most critical parameter since this is the mechanism for removal of charge from the dielectric - polarisation current does not release charge from the bulk of the material. On the other hand polarisation must still occur within the charged dielectric under the influence of the internal field - this polarisation will tend to counteract the field which induces it.

It is clear that the measurements of conductivity most often quoted, i.e. taken at the 1 minute interval after application of an external field, must include a large element of polarisation current. Therefore it is concluded that these 'standard' values should not be relied upon for analysis of internal charging problems. Instead long-term measurements should be used in which polarisation processes are virtually complete. In general the resulting conductivity values will be lower than the '60s' values. At the same time it may also be necessary to increase the relative permittivity parameter of the material to take account of long term polarisation. However before taking such a step, the standard methods for determining permittivity should be reviewed.

It is clear from Fig. 3 that any plot of the variation of conductivity with temperature would be different according to the time-point (after start of the test) chosen to plot the conductivity readings. Shorter times lead to less steep variations in conductivity with temperature. Again, long-term measurements would appear to be needed in order to model the phenomenon properly [4].

The equation generally quoted in the literature to describe the behaviour of polymer conductivity with temperature is:

$$\sigma = \sigma_{\infty} \exp\left(-\frac{E_A}{kT}\right)$$

where  $E_A$  is the material-dependent 'activation energy'  
 $k$  is Boltzmann's constant  
 $T$  is temperature (K), and  
 $\sigma_{\infty}$  is the maximum conductivity as  $T$  approaches infinity.

The activation energy can be determined from plots of log conductivity against the reciprocal of temperature. The resulting plot for PMMA, using the late-time data from Fig. 3, is shown Fig. 4. The value of  $E_A$  is found to be 1.3 eV which compares with 1.7eV reported by A&C [3]. The difference may perhaps be attributable to differing specific formulation of the two products, despite having the same brand name. For FEP, equilibrium was not achieved so it is difficult to determine a reliable value of  $E_A$  at this stage.

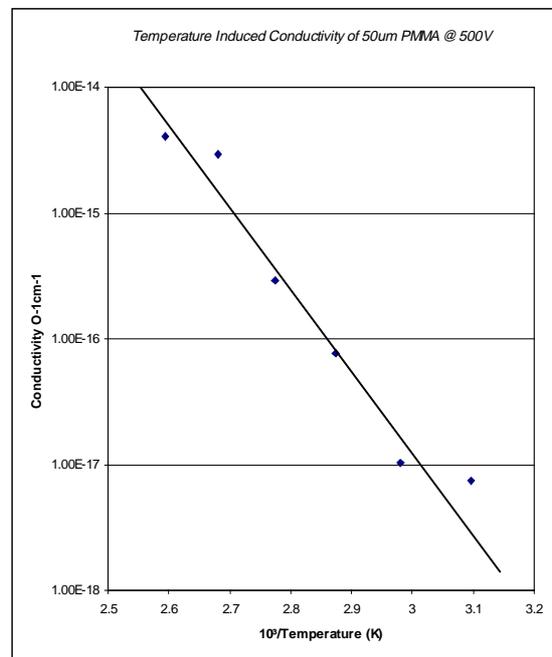


Fig. 4 Plot of late-time conductivity against reciprocal of temperature: the activation energy  $E_A$  is obtained from the slope of the line.

#### 4. EXAMPLE: SPACECRAFT CABLE DIELECTRIC

Since cable looms are often situated in exposed locations on spacecraft, they are potentially subject to both significant fluences of energetic electrons and unusual thermal conditions. Cables can experience somewhat colder temperatures than active electronic units and they can be subject to wider daily or seasonal temperature variation. Hence the properties of cable dielectrics are of particular interest.

Raychem Type 44 cable, widely used in satellites, was selected for determination of the variation of its

dielectric conductivity with temperature. Due to the physical arrangement of a cable it is not directly

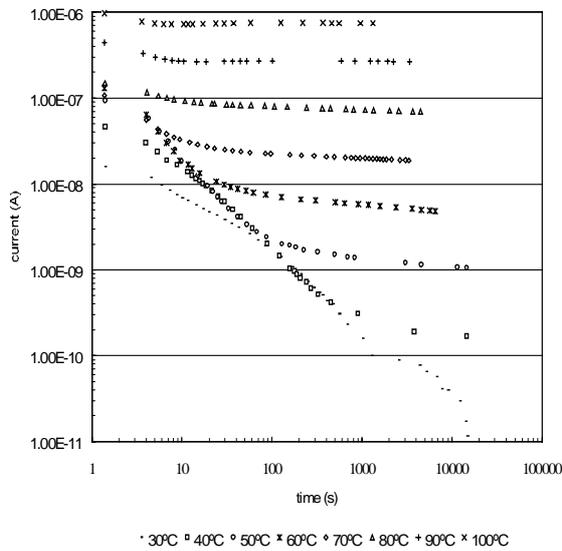


Fig. 5 Results of measurements of the conductivity of a cable dielectric (Raychem 44) at different temperatures

compatible with the standard methods described above. Instead a co-axial version of the cable was used in which the high voltage was applied to the core of the cable and the current flowing through the dielectric into the shield was measured. A long length of cable was used (>10m) in order to obtain currents in the region of nA. Otherwise the method was the essentially the same as required by the standards. The results (Fig. 5) show a very similar pattern to that found for PMMA. The variation of late-time conductivity (derived via the cable geometry) with temperature is plotted in Figure 6. Note that the curve becomes increasingly steep at the lower temperatures where it has a slope of around one

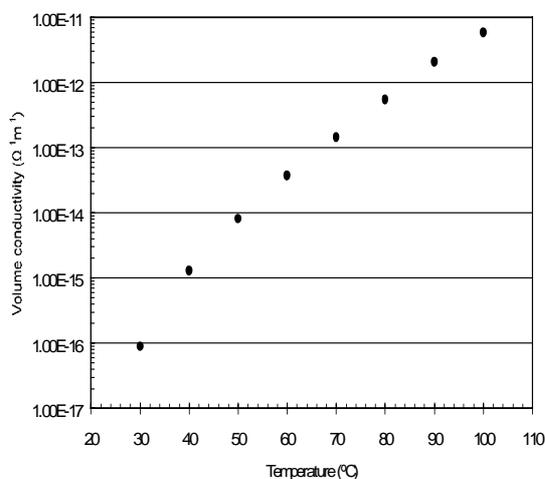


Fig. 6 Plot of the late-time conductivity of Raychem 44 dielectric against temperature

decade of conductivity for each 10°C change in temperature. By plotting a graph of log conductivity against the reciprocal of temperature the activation energy for the Raychem 44 dielectric is found to be approximately 1.5eV.

## 5. EXPERIMENTS TO VERIFY THE EFFECT OF TEMPERATURE ON INTERNAL CHARGING

In order to verify the predicted significance of temperature on internal charging, two simple experiments were conducted. Firstly, a block of PMMA was internally charged by irradiating it with MeV electrons and then removed from the beam. It is well known that if such a block is then struck with a sharp pointed electrode (assuming it was sufficiently well charged in the first place) a discharge will occur [5]. The discharge is observed as a bright blue flash and, in some cases, a number of subsequent smaller flashes. A 'Lichtenberg figure' is visible inside the block after the discharge which presents a permanent record of the event. It is found that the initiation of the discharge becomes difficult or even impossible if it is not done within several minutes of the block being removed from the beam. This is because of the leakage of charge due to the dielectric's bulk conductivity at room temperature (only very slight warming of the block occurs during irradiation). If, however, the block is cooled to around -20°C on being removed from the beam, it is found that the charge remains trapped inside for very long periods. Discharges have been readily obtained from such blocks even several months after the irradiation process (8 months is the maximum so far achieved at -20°C). However, the strength of the discharges obtained diminishes over time. Storage at -45°C is found to be significantly more effective, as would be expected. Since the time constant of the charge leakage appears to change from the region of minutes to months, it is deduced that the conductivity falls by around four orders of magnitude as a result of the ~40°C temperature reduction. It is notable that such long time constants greatly exceed the period of normal electron enhancements at geostationary orbit, which rarely exceed a few days.

The apparatus for the second experiment is shown in Fig. 7. The dielectric sample (PMMA of 3mm thickness) was heated and stabilised at a given temperature. Then the 1.1 MeV electron beam, with a current density of approximately 2pA/cm<sup>2</sup>, was switched on. The increase in potential of the sample was monitored periodically using a non-contacting potential monitor. This potential is the integral of the electric field within the dielectric with respect to  $x$  (in Fig. 7). The temperature was set initially at 120°C and allowed to stabilise; this high temperature was chosen in order to enable the charging equilibrium state to be reached more quickly (time constant  $\tau = \epsilon/\sigma$ , so higher

conductivity leads to a shorter time constant). Nevertheless, equilibrium was not quite reached even after 75 minutes of irradiation. The temperature was then *reduced* by 10°C as rapidly as thermal inertia would allow, keeping the electron beam constant (save for a brief unintended interruption of a few minutes). The effect of the temperature change was immediate

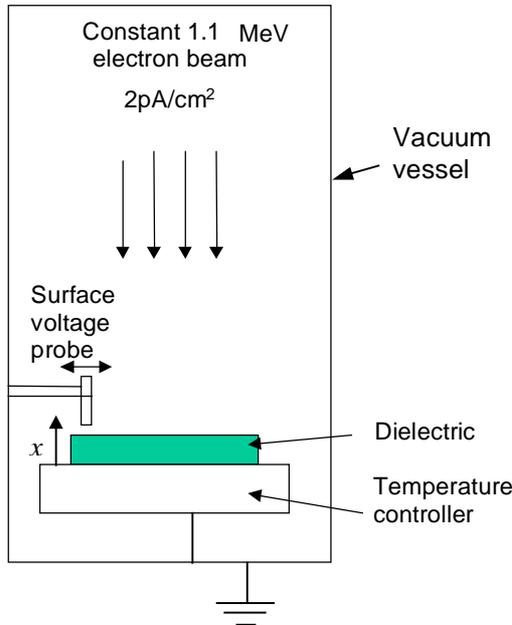


Fig. 7 Experimental arrangement to verify temperature effect on charging

and, as clearly shown in Fig. 8, resulted in a rapid rise in potential, towards a new final value. It was not possible to continue the test until the new equilibrium level was reached due to time constraints, but by

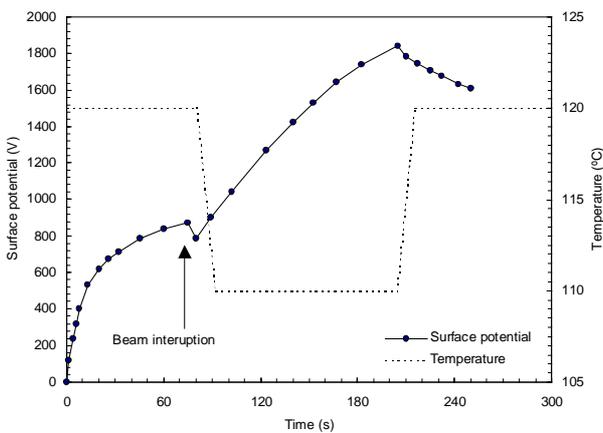


Fig. 8 Effect of temperature variation on dielectric (PMMA) potential while under constant MeV electron irradiation

inspection of Fig. 8 the new equilibrium potential would be reasonably expected to be a number of times higher than the previous one. The temperature was then

*increased* by 10°C in order to return to the starting temperature. The result was a rapid reduction in potential; again it was not possible to continue until the new equilibrium was reached. Overall, the qualitative effect of temperature was found to be consistent with the theoretical and empirical models mentioned earlier.

## 6. IMPLICATIONS AND USES OF THE TEMPERATURE EFFECT

It is clear that dielectric temperature is a very important parameter in the analysis of internal charging problems. Consequently the temperature effect was incorporated into the ESA 'DICTAT' engineering tool for internal charging assessments [6,7]. However, the correct material activation energy is still required as an input parameter and reliable measurements are difficult to find. Using a default parameter may give misleading results. It should also be noted that the applicability of any particular activation energy is limited to the temperature range over which the measurements were actually taken. This is because in other temperature ranges different energy absorption processes may govern the conductivity mechanism and therefore significantly different activation energies may apply [3].

It is evident that while low temperatures can increase the internal charging hazard; by the same token increasing temperature can reduce the risk. This approach may, in some circumstances, be an alternative to increasing shielding and may on occasion be more mass efficient. A combination of both methods may also be considered. Increasing temperature is, in effect, a method of producing a 'leaky' dielectric. A simple rule of thumb for spacecraft engineers would be to try to keep dielectrics warm where feasible e.g. avoid routing cables via cold regions of the vehicle where a ready alternative exists.

A graphical representation of the effect of both temperature and shielding is provided in Fig. 9. It has been produced using the DICTAT tool, assuming, for the present, that only one activation energy is applicable over the temperature range from -20°C to +60°C (this has not been verified). The chart shows contours of the peak electric field seen around the geostationary orbit (in a specified dielectric) according to the shielding and temperature. A polymer with the same conductivity characteristics as the Raychem 44, but used in a planar geometry (i.e. slab of material 5mm thick with slab shield in front) was assumed. The shielding is aluminium.

From Fig. 9 it is easy to see how, starting from a point situated in the danger area ( $E > 10^7$  V/m, red), it is possible to reach the safe region ( $E < 10^6$  V/m, green) by use of either shielding or temperature, or a combination of the two. Note that a margin of hardly more than

20°C separates the danger area from the safe area over most of the chart.

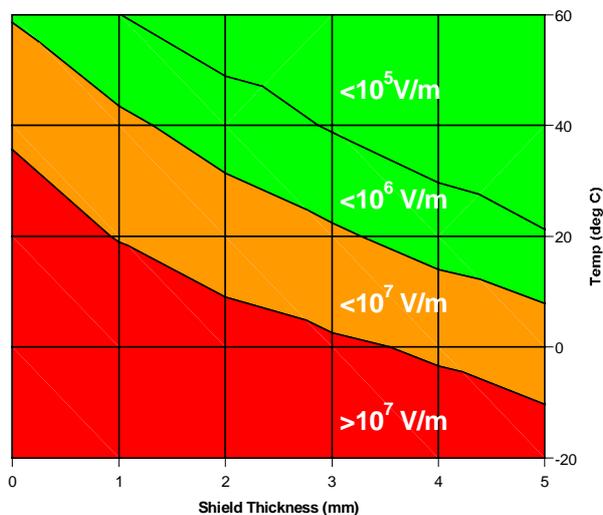


Fig. 9 Contours of peak internal electric field around GEO plotted against temperature and (aluminium) shielding depth (DICTAT simulation of a Raychem 44-type polymer). The safe region is top right and the danger area bottom left.

## 7. CONCLUSIONS

Spacecraft design engineers need to be aware of the importance of thermal environments when analysing the internal charging hazard and, in particular, the significantly increased risks at low temperatures. At the same time the possibilities of using thermal control as a tool for mitigating internal charging should also be more widely appreciated. As a rule, dielectrics should be kept warm to minimise the charging hazard.

Standard 'quoted' values of dielectric conductivity must be treated with some caution when analysing internal charging since they are not derived with an issue of this nature in mind. It is recommended that a database of material conductivities specifically applicable to the spacecraft internal charging process should be developed. In particular bulk conductivity over the ranges of temperatures likely to be encountered in space should be determined. The DICTAT materials file should then be updated accordingly. Such measurements should be performed for both planar samples and cables.

Finally, satellite anomaly data sets currently linked to internal charging could usefully be reviewed for evidence of thermal sensitivity (e.g. seasonal effects).

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