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TECHNICAL REPORT

colour inside

Fibre optic interconnecting devices and passive components – Part 03-01: Reliability – Design of an acceptance test for fibre pistoning failure of connectors during temperature and humidity cycling: demarcation analysis

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

FIBRE OPTIC INTERCONNECTING DEVICES AND PASSIVE COMPONENTS –

Part 03-01: Reliability – Design of an acceptance test for fibre pistoning failure of connectors during temperature and humidity cycling: demarcation analysis

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IEC 62627-03-01, which is a technical report, has been prepared by subcommittee 86B: Fibre optic interconnecting devices and passive components, of IEC technical committee 86: Fibre optics.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
86B/2996/DTR	86B/3038/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the IEC 62627 series, published under the general title *Fibre optic interconnecting devices and passive components,* can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

Fibre optic connectors rely on accurate positioning of the fibre with respect to an optical interface to achieve and maintain acceptable performance. Degradation of performance due to fibre motion (fibre pistoning) is a well known failure mode. It is activated by temperature and humidity exposure, especially cyclic. Clause 3 provides background on the pistoning failure mode.

An acceptance test is an accelerated test designed to detect degradation or failure modes if they would occur during life, and to show no change if no degradation or failure modes will occur. A perfect acceptance test is impossible [1][1] because (a) there can always be non-accelerable failure modes and (b) some failures may occur under acceleration that may not occur in service. However, a well-designed acceptance test provides for a supplier a reasonable check of the space of accelerable modes and is of great value in testing for reliability.

Demarcation mapping provides a method of viewing possible chemical and physical processes that can occur during a given stress exposure over a given time [1-4] and allows for selection of accelerating test conditions that will produce potential degradation or failure mechanisms during service. Clause 2 provides an overview of the demarcation approach and its application to developing acceptance tests.

Clause 3 provides a discussion of plausible physical processes accompanying degradation and fibre pistoning, based on an assumed service environment. It includes some models based on these processes, and mathematical tools necessary to develop the demarcation maps. Clause 4 summarizes the results of a numerical experiment, using demarcation maps for each of the processes developed in Clause 3, to compare 20-year life in an extreme tropical climate with accelerated tests.

1 Figures in square brackets refer to the Bibliography.

FIBRE OPTIC INTERCONNECTING DEVICES AND PASSIVE COMPONENTS –

Part 03-01: Reliability – Design of an acceptance test for fibre pistoning failure of connectors during temperature and humidity cycling: demarcation analysis

1 Scope

This part of IEC 62627 gives an example of the design of an acceptance test for ferrule style connectors when the dominant failure mode is fibre pistoning. The example applies to connectors which use epoxies or other adhesive polymers to bond the fibre into a ferrule. It combines existing evidence, mechanistic hypotheses and the demarcation approximation to develop an accelerated environmental exposure sequence that can be used on a pass-only basis to help ensure reliable service. This technical report was developed to serve only as an example of how accelerated acceptance tests can be designed. It is not intended as a normative standard for any specific application.

2 Optical fibre connectors and the pistoning failure mode

The most commonly used fibre optic connector designs are based on butt-joint fibre alignment. The fibre is generally adhesively-bonded inside a tightly toleranced ferrule capillary with a thermally cured epoxy. The ferrule is precision polished to ensure accurate positioning of the fibre endface for acceptable optical performance. Significant fibre motion during temperature-humidity exposure, especially cycling, will degrade the performance, causing both insertion loss and reflectance to increase and become unstable.

The stresses that drive fibre motion come from three sources: (i) residual stress from the connector termination process, (ii) externally applied contact stress from a mating ferrule, or (iii) and stress from differential thermal expansion of materials in the connector assembly. Mechanisms within the adhesive which allow the motion to take place include creep, adhesive failure and cohesive failure.

3 Demarcation map theory for thermally activated processes

3.1 Concept of demarcation energy

The demarcation approximation is derived from consideration of material systems where a macroscopically observable degradation process is driven by a set of parallel thermally activated (Arrhenius) processes. Assuming each process to consist of a single step, the rate for each local process has the form:

$$k_1 = \nu \exp\left(\frac{-E_a}{\mathrm{k}T}\right) \quad (1)$$

where

ν is a premultiplier,

k is Boltzmann’s constant,

T is absolute temperature, and

E_a is the activation energy (in the following, all activation energies are given in eV).

The relative amount (normalized to total amount which can react, also called the reaction *extent*) reacted over time for this local process then has the form:

$$\left(1-\exp\left(-\mathrm{k}_1 t\right)\right) \tag{2}$$

The value of Equation (2), for a given time, temperature and ν, is plotted across activation energies in Figure 1 and compared to the approximation:

$$\Delta(\mathrm{k}_1, t) = \begin{cases} 0, \mathrm{k}_1 t < 1 \\ 1, \mathrm{k}_1 t \geq 1 \end{cases} \tag{3}$$

The centre vertical line in Figure 1 is the approximation and the circles are the exponential function calculated at discrete activation energies. The two outer vertical lines corresponds to values of ν separated by two orders of magnitude, bounds which are important in the following discussions.

The comparison of Equations (2) and (3) shows that $\mathrm{k}_1 t$ = 1 is a reasonable demarcation between reactions which are complete and those which are not. Substitution from Equation (1) gives the demarcation approximation of Equation (4).

$$E_a = \mathrm{k}T\ln(\nu t) \tag{4}$$

For fixed values of time and temperature, Equation (4) gives the relationship between E_a and ν, where E_a is the activation energy below which reaction processes are complete and above which they are not. This provides a tool for comparing reactions at potential test times and (accelerating) temperatures with those of actual service conditions. Note that the approximation in this figure does not depend on there being a distribution of activation energies.

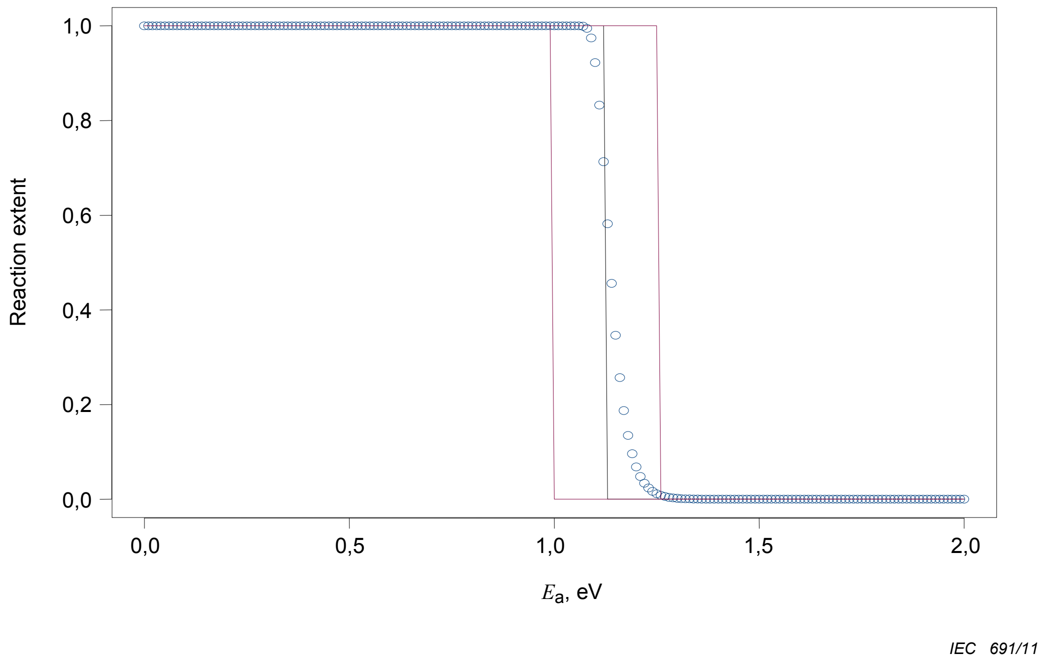

Figure 1 – Reaction extent as a function of activation energy compared to the $\Delta k_1 t$ function

3.2 Demarcation maps

With the demarcation approximation of Equation (4), it is possible to map the boundaries of completed reactions under given conditions of time and temperature in the two-dimensional space of E_a and $\ln\nu$ and compare service life and accelerated tests conditions. For the simple case of time at a fixed temperature, the boundaries are straight lines. For the more general case where service or test temperatures are not constant, the demarcation boundaries take a different form. For each value of ν time at one temperature can be transformed to an equivalent time at a different temperature corresponding to the same value of E_a as follows:

$$\mathrm{k}T_1 \ln(\nu t_1) = E_a = \mathrm{k}T_2 \ln(\nu t_2) \tag{5}$$

or

$$t_1 = \frac{(\nu t_2)^{T_2/T_1}}{\nu} \tag{6}$$

which implies that after a step in temperature, Equation (4) can be re-expressed:

$$E_a = \mathrm{k}T_2 \ln\left(\nu\left(t_2 + \frac{(\nu t_1)^{T_1/T_2}}{\nu}\right)\right) \tag{7}$$

A transformation such as Equation (7) can be applied to situations such as the example of a product which is first baked at 180 °C for 4 h, followed by 25 years service at 50 °C. Such a product might be a device requiring metallization [11] of the fibre, or a fibre Bragg grating [3], either of which might require a stabilization anneal. The demarcation map for this product is shown in Figure 2. Clearly these temperatures are not appropriate for epoxy based connectors, however the visual illustration is clearer for these more extreme temperatures. The area above and left of line 1 corresponds to those reactions completed by the bake and those within the shaded area correspond to those reactions subsequently completed by the 25 years service. This can be compared to an accelerated test consisting of the same bake followed by 5 h exposure at 260 °C. The region between curves 1 and 2 corresponds to those reactions completed during the 260 exposure °C after the bake. This accelerated test region includes all reactions occurring during life for values of ν greater than 10^3.

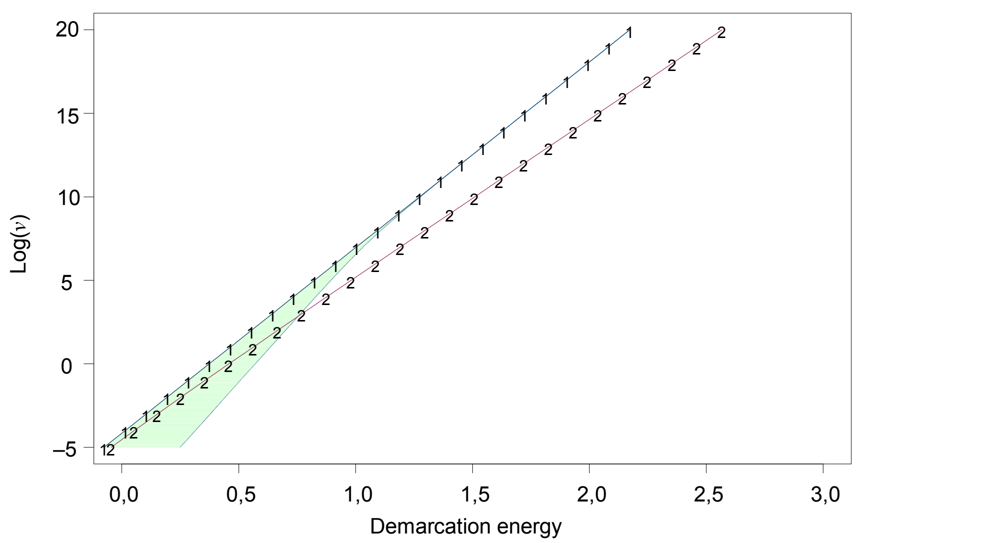

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Figure 2 – Demarcation maps for service life and accelerated test of example in 4.2

If the goal is to design an acceptance test, it is important for the test to provide coverage for all the processes which might occur during life, while minimizing the chances of rejecting a good material system, with the minimum cost and time expenditure. The plot and discussion above suggest a single number that can be extracted from the demarcation maps which provides a simple characterization of the degree of conservativeness of the accelerated test with respect to accelerable failure modes. That number is the minimum value of ν where the accelerated test contains all the processes occurring during life. This is the simplest use of demarcation mapping to design accelerated tests which will arguably reach end of life. A conservative value of ν for the purpose both of including processes running totally to completion, and some more complex processes is a value 3-orders of magnitude lower than what one would estimate is the lowest value for a simple single step chemical process in the materials under consideration. The minimum value of ν as described above is the index of coverage of the accelerated test for life stress. For every value of ν above that value, all reaction occurring during life will be reached.

4 Plausible physical effects in a model of the degradation process associated with fibre pistoning

4.1 General

The objective in this subclause is to list a series of plausible physical effects of degradation associated with fibre pistoning that can be used for demarcation approximation, and to illustrate the demarcation calculations for the simplest of these. The calculations will be done for an assumed service life of 20 years of a diurnal cycle between 20 °C, 70 % RH and 50 °C, 90 % RH, and compared with an accelerated cycle going between 25 °C, 85 % RH and 85 °C, 85 % RH. The diurnal cycle is approximated as four steps, 6 h each at the conditions: 20 °C and 70 % RH, 35 °C and 80 % RH, 50 °C, 90 % RH, and 35 °C, 80 % RH. The accelerated cycle has a 1 h dwell at 25 °C, 85 % RH and a 3 h dwell at 85 °C, 85 % RH, with a 2 h ramp between. The accelerated cycle is approximated as six steps with 1 h at 25 °C, 85 % RH, 1 h at 45 °C, 85 % RH, 1 h at 65 °C, 85 % RH, 3 h at 85 °C, 85 %, 1 h at 65 °C, 85 % RH, and 1 h at 45 °C, 85 % RH.

The possible physical effects associated with the above exposures include:

a) thermal degradation process;
b) direct action of moisture in terms of relative humidity, absolute humidity, or the effect of water accumulation at an interface;
c) diffusion of water into the actively degrading regions;
d) thermally induced mechanical stresses at interfaces;
e) thermally induced mechanical stresses within polymer adhesive;
f) the effect of cyclic fatigue on interfaces, and within the polymer.

In No.1 of Table 2, effects a) and b) were combined and in No.2 of Table 2, a) and b) (looking at absolute humidity only) were combined with c). In 3.1, delamination at the edge of the epoxy Equation (4) driven in part by thermal expansion mismatch is examined. Diffusion (Equation (3)) is not considered important, but temperature and humidity are considered as a function of a plausible model of an isotherm at an interface[12]. In No.4 of Table 2, the model used in No.3 of Table 2 is adapted to stress relaxation of the epoxy, assuming diffusion, temperature, and humidity as absolute humidity are important. In No.5 of Table 2, two approaches are considered to bound the effect of cyclic fatigue. One slightly more primitive, where some elements of the model of 4.4 are combined with a conservative approximate calculation of an acceleration factor based on a Coffin-Manson [15] model for hysteresis, and the other where a connection between the Coffin-Manson [15] model, and diffusion of defects in the polymer is proposed.