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Edition 1.0 2013-05

TECHNICAL REPORT

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Fibre optic interconecting devices and passive components – Part 03-03: Reliability – Report on high-power reliability for metal-doped optical fibre plug-style optical attenuators

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Fibre optic interconecting devices and passive components – Part 03-03: Reliability – Report on high-power reliability for metal-doped optical fibre plug-style optical attenuators

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FOREWORD

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IEC 62627-03-03, 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/3458/DTR	86B/3506/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 in 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

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- withdrawn,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

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INTRODUCTION

Since 2000, the optical power in transmission systems has increased in conjunction with the increase in the number of channels for DWDM systems, with the help of deployment of RAMAN amplifiers and application of optical amplifiers. It is pointed out, however, that the transmission media of the optical transmission system such as the optical fibre, optical connector and optical passive components may sometimes be hazardous because of possible leakage of high-power light that results in personal injury, melting, or a damage possibly causing a fire.

IEC Japan National Committee (JPNC) and Optoelectronics Industry and Technology Development Association (OITDA) carried out the research on the high-power reliability and safety of optical passive components. The result was summarized in the OITDA Technical paper, TP04/SP-PD-2008 “Study on the High-Power Reliability of Optical Passive Parts for Communications.” IEC/TR 62627-03-02 was published based on the above report. According to that report, deterioration of optical passive components at high-power input is caused by temperature rise due to absorption of light as well as consequential thermal distortion. It was decided to undertake additional research whilst utilizing these findings, specifically on the plug style optical attenuator, whose resistance against high-power is relatively small. The study result was summarized in OITDA TP, TP09/SP-PD-2010.

This technical report was prepared on the basis of OITDA TP, TP09/SP-PD-2010,“*Technical paper of investigation of high-power reliability for plug-style fixed optical attenuators*”.

FIBRE OPTIC INTERCONECTING DEVICES AND PASSIVE COMPONENTS –

Part 03-03: Reliability – Report on high-power reliability for metal-doped optical fibre plug-style optical attenuators

1 Scope

IEC/TR 62627-03-03, which is a technical report, describes the investigation results of high-power reliability for metal-doped optical fibre plug-style attenuators.

This report contains the high-power test results for metal-doped optical fibre SC plug-style optical attenuators, the thermal simulation results and the analysis of degradation modes, long-term reliability test results under high-power conditions and the derivation of maximum limit of optical power for guaranteeing long-term operation.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC/TR 62627-03-02, *Fibre optic interconnecting devices and passive components – Part 03-02: Reliability – Report of high-power transmission test of specified passive optical components*

3 Outline of high-power test for optical attenuators in IEC/TR 62627-03-02

The test was carried out by inputting the high-power light into the SC plug style metal-doped fibre optical attenuators with an attenuation of 10 dB, 20 dB and 30 dB. The test ambient temperature was set at the assumed normal maximum operating temperature of 70 °C and the test method was the step stress test. The test result indicated failures in all the samples, i.e. the return loss decreased by 10 dB or more at 1,4 W to 2,3 W. Variation of the attenuation and the return loss before and after the test was within the range of measurement uncertainty. When the fibre end surface was checked after th test, it indicated either protrusion or withdrawal of the optical fibre.

On the other hand, thermal simulation was carried out and the result was that the maximum internal temperature reached 300 °C or more at the input power of 2 W for SC plug style metal-doped fibre optical attenuator of 10 dB attenuation.

In addition, the long-term reliability test of the optical attenuator was carried out for 500 h. The test conditions were 1 W for the input power and 70 °C for the ambient temperature. As a result of the test, it was found that the return loss did not decrease during the test, but withdrawal or protrusion of the optical fibre was found after the test.

Based on the result of the above tests, it was estimated that the mechanism of return loss decline consists of the softening of adhesive fixing the metal-doped optical fibre and ferrule, which in turn causes withdrawal of optical fibre and finally results in loss of physical contact (PC) between the fibre endfaces. Therefore, for the purpose of guaranteeing long-term reliability with high power, it is necessary to control the internal maximum temperature within the range in which the adhesive does not exceed the glass transition temperature. Thermal simulation results lead to the assumption that the input power of 500 mW is the limit at the ambient temperature of 50 °C for SC plug style optical metal-doped fibre optical attenuator of 10 dB attenuation.

After studying IEC/TR 62627-03-02, problems were found on the high power reliability for plug-style attenuators in the following areas:

– accuracy of internal temperature estimated by the thermal simulation;
– consideration of the variation of ferrule endface geometries for attenuators and optical connector plugs which affect the condition of PC (physical contact) detaching;
– identification of the mechanism of optical fibre withdrawal;
– confirmation of long-term reliability that considers temperature and humidity conditions.

4 Accuracy of the internal temperature estimated by the thermal simulation

In 2002, Yanagi et al. measured increasing temperature at high-power input for the MU plug-style optical attenuator [1][1]. Yamaguchi et al. used a similar test set-up when testing the SC plug style optical attenuator [2]. Figure 1 shows the test set-up of Yamaguchi et al. while Figure 2 shows their test results. Test samples were SC plug style optical attenuators without housing. The resistance temperature detector (RTD) was attached on the outer surface of the split sleeve to monitor the temperature. The ambient temperature was 23 °C. The test was carried out for the attenuation of 1 dB, 3 dB, 5 dB, 10 dB, 15 dB and 20 dB, respectively. Figure 2 shows the test result at the attenuation of 5 dB, 10 dB, 15 dB and 20 dB. It appeared that the temperature rose approximately linearly to the input power of 500 mW at maximum, then its rate of rise decreased. The temperature at the input power of 500 mW for 10 dB attenuator was 75 °C and the temperature rise from the ambient temperature of 23 °C was 52 °C.

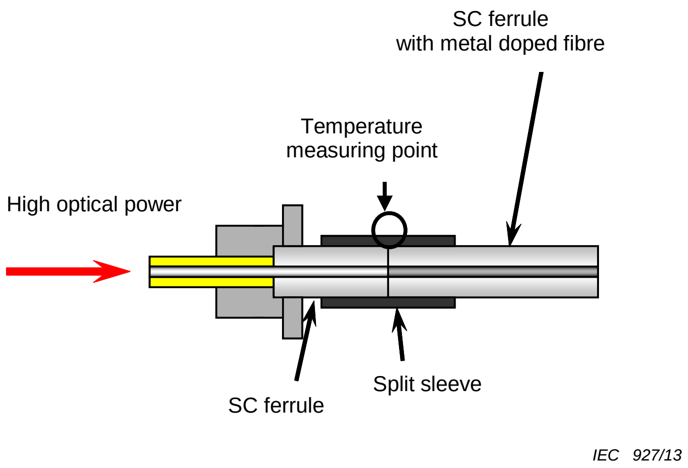


Figure 1 – Split-sleeve surface temperature measurement system on high-power input condition for the SC plug style attenuators by Yamaguchi et al.

1 Numbers in square brackets refer to the Bibliography.

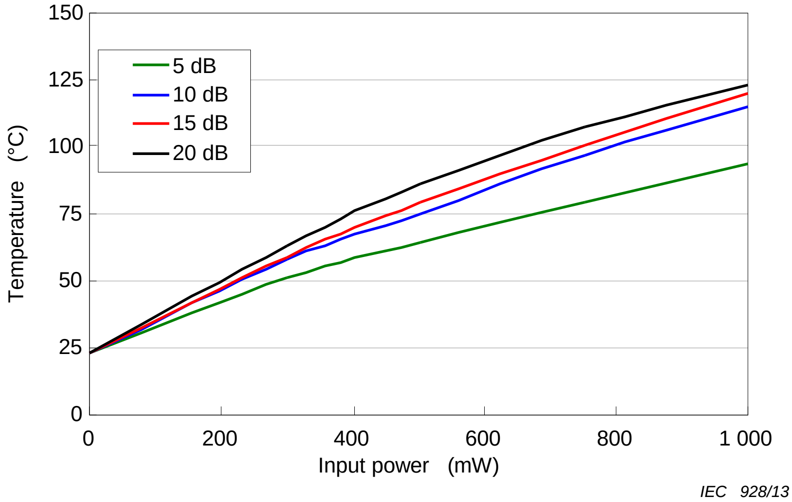


Figure 2 – Split sleeve out-surface temperature measurement results on high-power input condition for the SC plug style attenuators by Yamaguchi et al.

On the other hand, IEC/TR 62627-03-02 describes the thermal simulation results of the maximum internal temperature for SC plug style attenuators with and without housing. The thermal simulation of outer surface temperature of the split sleeve for SC plug-style optical attenuators without housing was calculated with the same method as that used in IEC/TR 62627-03-02. The simulation results are shown in Figure 3. For the SC plug style attenuator of 10 dB attenuation, the relation between the temperature rise ΔT (°C) and the input power P (mW) can be explained in the following equation:

$$\Delta T = 0{,}1169 \times P \tag{1}$$

As reported in IEC/TR 62627-03-02, the ambient temperature dependency of temperature rise was small. For SC plug style 10 dB attenuators, the temperature rise on the condition of input power of 1 000 mW could be calculated as 129,1 °C and 128,3 °C for the ambient temperature of 25 °C and 70 °C, respectively.

The test results of Yamaguchi et al. indicated that the input power of 500 mW optical powers into the 10 dB SC plug style attenuators made a temperature rise of 52 °C. According to the results of thermal simulation shown in Figure 3, the temperature rise is calculated as 0,116 9 × 500 = 58 °C. Accordingly, this thermal simulation could reproduce the demonstration results by Yamaguchi et al. under the condition of an input power of 500 mW or less. In Figure 2, the temperature rise rate tends to decrease at the input power of 500 mW or more. This is seemingly due to thermal conductivity between the RTD, split sleeve and the outside air. Note that the internal temperature rise of SC plug style attenuator with the attenuation of 10 dB is calculated by 0,133 7 × (input power (mW)).

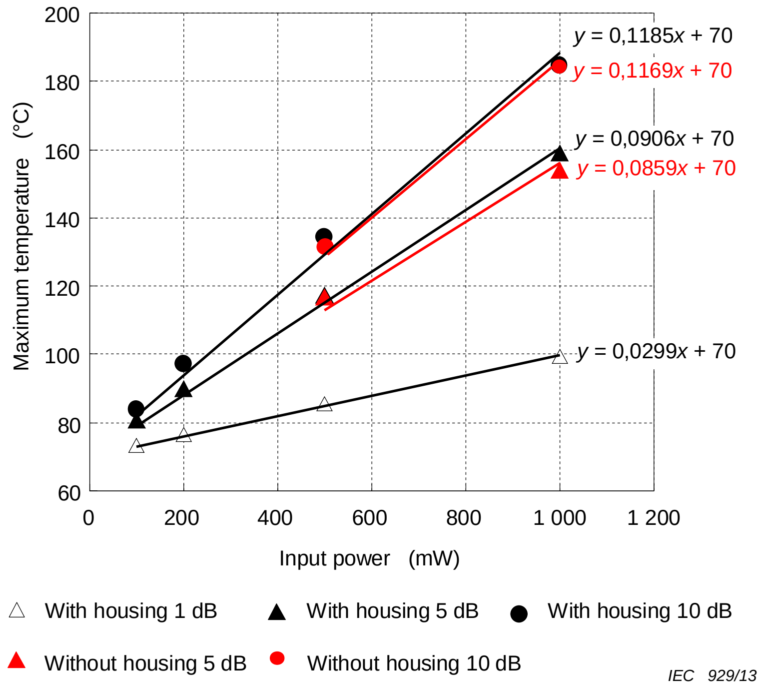


Figure 3 – Input-power dependency of split sleeve outer surface temperature of the SC plug style optical attenuator without housing

5 Return loss decreasing test for plug-style optical attenuators

5.1 Test samples

In order to minimize the deviation due to the manufacturing conditions of samples, the worst-case samples in which loss of PC occurred most easily in the test were used. Figure 4 shows the drawing of the worst-case samples. The worst-case samples have a ferrule endface geometry with an endface spherical radius r = 25 mm, an apex offset A = 50 µm and a fibre withdrawal W = 50 nm. Loss of PC occurs most easily when the apex offset directions of the optical attenuator ferrule is aligned in the same orientation as that of the optical plug ferrule to be connected. The worst-case samples were deployed for both the male side of optical attenuators and the optical connector plug to be connected.

The effective fibre withdrawal Δ_1 can be expressed by the fibre withdrawal W, the endface spherical radius r and the apex offset A as follows:

$$\Delta_1 = W + ((r^2 + A^2)^{1/2} - r) \cong W + A^2 / 2r \quad (\text{when } A \ll r) \tag{2}$$

According to Equation (2), the effective fibre withdrawal with the worst-case endface conditions is calculated as 100 nm on one side and 200 nm on both sides.

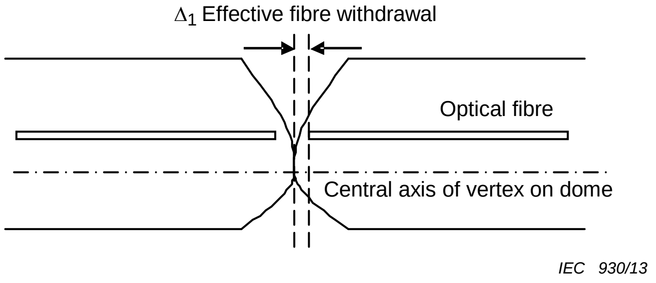
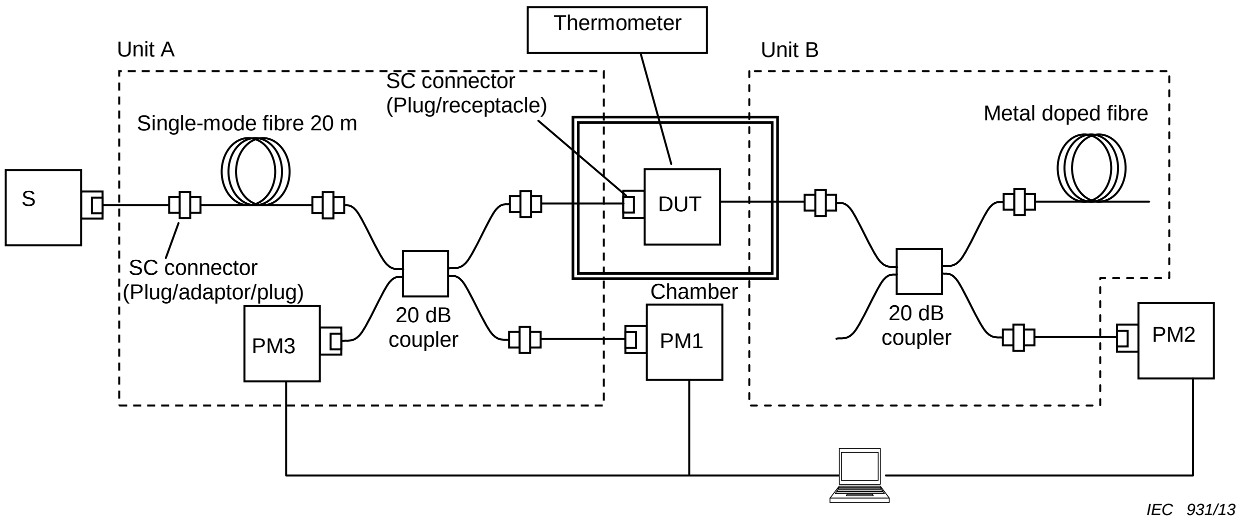


Figure 4 – Sample of design – Worst-case endface conditions

The male side of the optical attenuator and the optical connector plug of the optical jumper cord to be connected was manufactured for the purpose of achieving the worst-case endface conditions of an endface spherical radius r = 25 mm, an apex offset A = 50 μm and a fibre withdrawal W = 50 nm. Due to the lack of manufacturing uniformity, these values varied in individual samples. Therefore, the optical attenuators and the jumper cords were sorted, respectively, in terms of effective fibre withdrawal so that those with larger withdrawal amounts were grouped to enable testing the effects of their effective fibre withdrawal amount. Fourteen sets of samples were used for the test. The minimum and maximum values of the sum of the effective fibre withdrawals of both the optical attenuator and optical connector plug were 114 nm and 289 nm (the target being 200 nm).

5.2 Test set-up and test conditions

The test set-up of optical attenuators was the same as that for the test shown in IEC/TR 62627-03-02 (OITDA TP04). The test set-up is shown in Figure 5 while the test conditions are shown in Table 1.



Key

S Light source (erbium-doped optical fibre amplifier (EDFA), λ=1 550 nm)

PM Power meter

Figure 5 – Test set-up of return loss monitor at high-power input into the optical attenuator

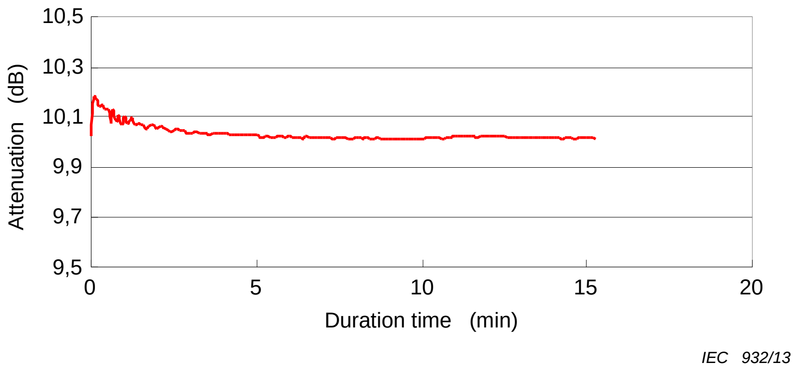
Table 1 – Test conditions of optical attenuators

Items	Conditions
Sample	SC plug style optical attenuator of 10 dB attenuation (worst-case endface conditions)
Test ambient temperature	50 °C ~ 90 °C
Light source	EDFA
Incident wavelength	1 550 nm
Input power	300 mW to 1 100 mW

5.3 Test results and the analysis

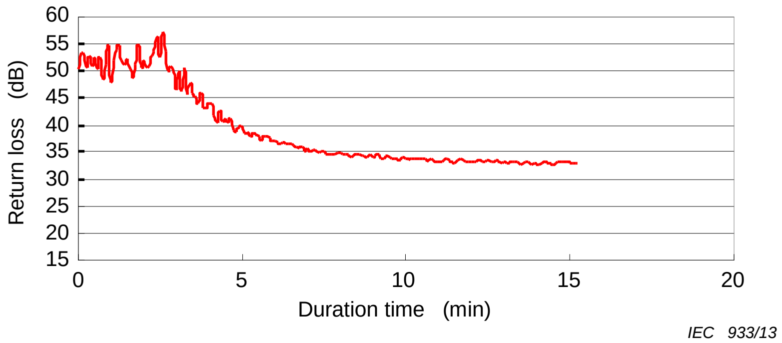
5.3.1 The degradation on high-power condition

Figures 6 and 7 show the typical monitoring results of the attenuation and return loss at the ambient temperature of 70 °C.



NOTE Attenuation change, 70 °C, at 1 000 mW input.

Figure 6 – High-power input test results of optical attenuator



NOTE Return loss change, 70 °C at 1 000 mW input.

Figure 7 – Result of high-power input test of the optical attenuator

The attenuation decreased by 0,2 dB, and then became stable in 10 min. The return loss started decreasing in 3 min and became stable at 33 dB in 15 min. It was estimated that decrease in the return loss is caused by withdrawal of optical fibre.

The reflectance *R* caused by interference of thin film can be expressed as follows in the case of the simplest condition of the single-layer structure and the incident angle of vertical:

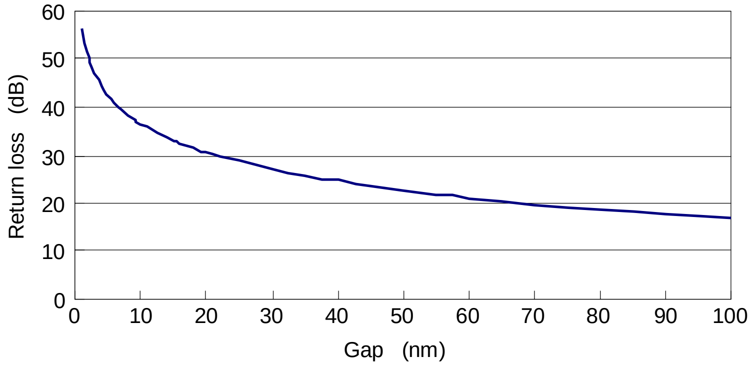
$$R \quad \frac{n^2(n_0 - n_s)^2 \cos^2 k\varDelta_2 \quad (n_0 n_s - n^2)^2 \sin^2 k\varDelta_2}{n^2(n_0 \quad n_s)^2 \cos^2 k\varDelta_2 \quad (n_0 n_s \quad n^2)^2 \sin^2 k\varDelta_2} \tag{3}$$

where n_s, n and n_0 are the refractive indexes of substrate, thin film and the top layer, respectively, k is the wave number and $\varDelta_2$ is the optical path length of thin film.

The following equation can be deviated for three layers of the silica (n_0), air (n=1), and silica ($n_s = n_0$):

$$R \quad \frac{(n_0{}^2 - 1)^2 \sin^2 k\varDelta_2}{4n_0{}^2 \cos^2 k\varDelta_2 \quad (n_0{}^2 \quad 1)^2 \sin^2 k\varDelta_2} \tag{4}$$

When the wavelength is 1,550 nm, the refractive index for the silica number is 1,44, in which the return loss (RL) and the air-layer thickness (gap (nm)) can be correlated as shown in Figure 8.



IEC 934/13

Figure 8 – Relationship between the gap and the return loss

Figure 7 shows that the return loss became stable at 33 dB, which indicates from Figure 8 that the gap between the optical attenuator and optical connector plug is estimated at 20 nm.

5.3.2 The result of permanent fibre withdrawals before and after the test

After the high-power test, the optical fibre withdrawal of tested optical attenuators and the optical connector plugs to be connected were checked, using a three-dimensional interferometer. Both the changes of the endface spherical radiuses and the apex offsets were within the range of measurement uncertainty. On the other hand, the optical fibre withdrawal actually altered. Figure 9 shows the relationship of the permanent fibre withdrawal between the optical attenuators and the optical connector plugs of jumper cords. The number of samples is 7 under ambient temperature conditions of 70 °C and input power of 1 000 mW. Deviations in the optical fibre withdrawal of optical attenuator are plotted along the horizontal axis, while deviations in the optical fibre withdrawal of the optical connector plug are plotted along the vertical axis.

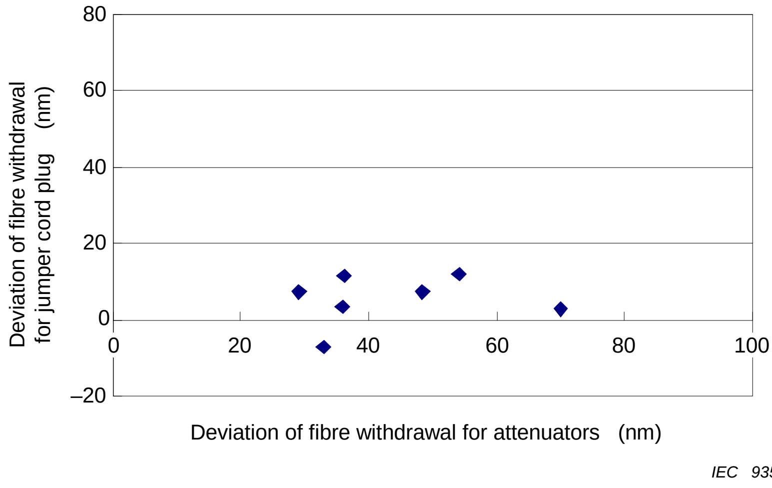


Figure 9 – Distribution diagram of the optical fibre withdrawal of both the optical attenuator and the optical connector

When compared to the deviations of optical fibre withdrawal of optical attenuators ranging from 30 nm to 70 nm, the deviations of the optical connector plugs were 12 nm at maximum, which is within the measuring uncertainty. Figure 10 shows the temperature distribution along the centre axis that is calculated by the thermal simulation with different input power. The horizontal axis shows the distance from the contact surface in two fibres. The left side shows the optical connector plug and the right side shows the optical attenuator.

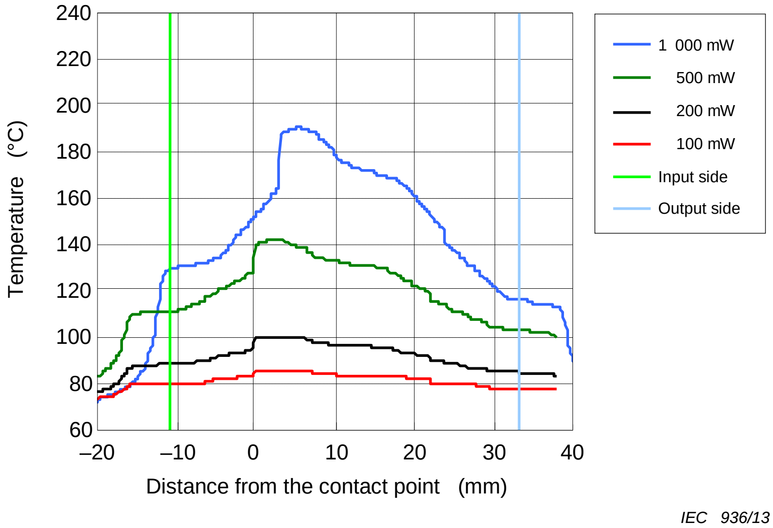


Figure 10 – Temperature distribution along the central axis derived from thermal simulation (10 dB optical attenuator)

With input power at 1 000 mW, the maximum internal temperature of optical attenuator reaches almost 200 °C. In contrast the temperature of optical connector plug ranges is down to 140 °C ~170 °C. It is lower approximately 40 °C than the temperature of optical attenuator. It is estimated that this temperature difference is due to the effect of thermal conduction as the diameter of contact area between two ferrules is about 200 μm which is much smaller than the diameter of ferrule of 2,5 mm. This temperature difference may be a factor causing the withdrawal of the optical fibre on the optical attenuator side only.

With input power at 1 000 mW, the maximum internal temperature of optical attenuator reaches almost 200 °C. In contrast the temperature of optical connector plug ranges is down to 140 °C ~170 °C. It is approximately 40 °C lower.

5.3.3 Stabilization time of return loss decreasing

As shown in Figure 7, the return loss became stable at a given value in about 15 min after inputting the optical power. The time spent for such stabilization, that is, about 15 min or less, is the period during which the thermal capacity and thermal conductivity of the optical attenuator are balanced with the thermal conduction to the outside (air). Thermal simulation as reported in IEC/TR 62627-03-02 (OITDA TP04) indicates that the increase of maximum internal temperature has stabilized within approximately 20 min (1 200 s). The results of thermal simulation are shown in Figure 11.

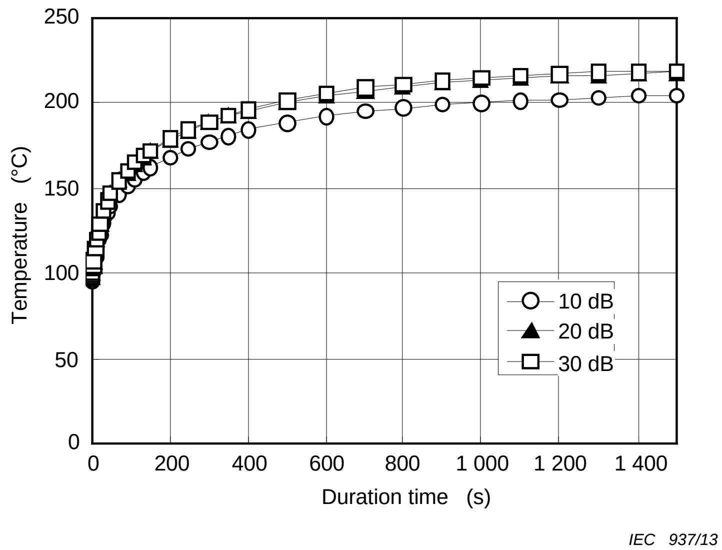


Figure 11 – Time dependence of the maximum temperature in thermal simulation of the optical attenuator

5.3.4 Relation of optical input power, test temperature and stabilized return loss

When checking more details of the relationship between the stabilized return loss and the input power, it was found that the decrease of return loss was seen at a different input power and/or under different temperature conditions. The example of the test results (sample no. ATT44/JC35) is shown in Figure 12. This test was carried out at a test temperature of 70 °C ~ 90 °C and at an input power of 500 mW to 1 100 mW. As is shown in Figure 12, the stabilized return losses vary, depending on the test temperature and input power.

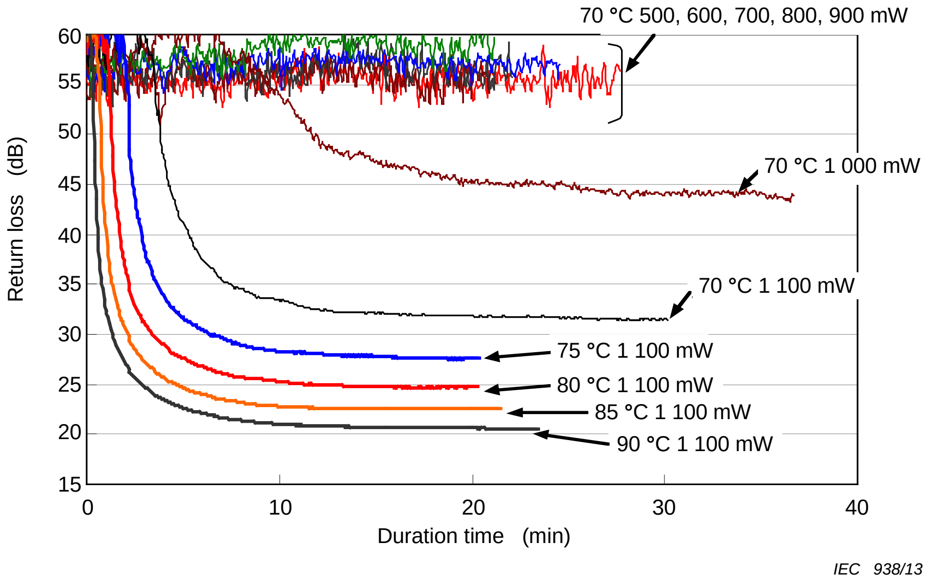


Figure 12 – Return loss decreasing curve in the tests with various test temperatures and input powers (sample no. ATT44/JC35)

The maximum internal temperature can be estimated from the test temperature and input power through thermal simulation. Figure 13 is a correlation diagram between the maximum internal temperature and the stabilized return losses in the same sample as the one in Figure 12. It appears that there is a distinct relationship between the stabilized return loss and the maximum internal temperature.

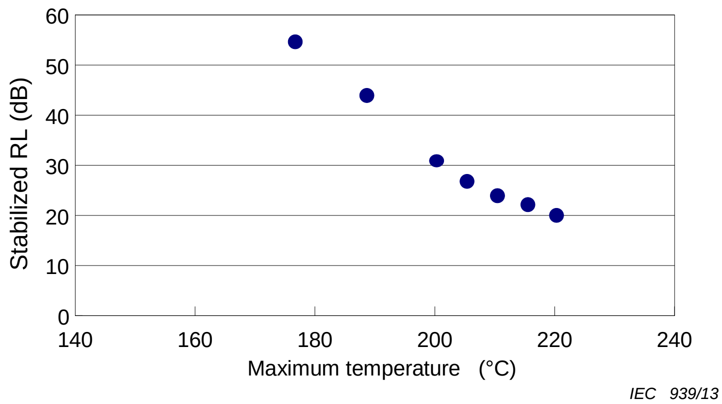


Figure 13 – Relationship between the maximum internal temperature and return loss stabilization point of the sample tested with various test temperatures and input powers (sample no. ATT44/JC35)

Moreover, as shown in Figure 8, the stabilized return losses can be converted to the gap between both fibres. Figure 14 shows the relationship between the maximum internal temperature and the gap at the stabilization of the same sample, as shown in Figure 13. Since the total effective fibre withdrawal of this sample before the test was –256 nm which corresponds to –94 nm margin to PC detachment, it was plotted at the point where 25 °C and –94 nm are crossed in Figure 14.

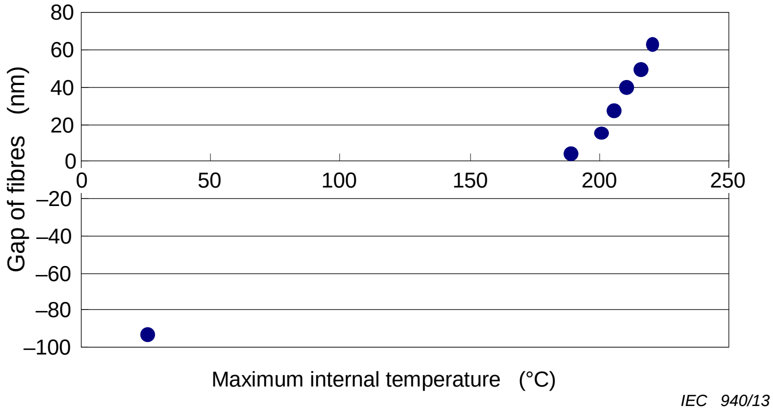


Figure 14 – Relationship between the maximum internal temperature and the gap at stabilization of return loss of the sample tested with various test temperature and input powers (sample no. ATT44/JC35)

6 Mechanism of fibre withdrawal on high-power condition

6.1 Estimate of the mechanism of fibre withdrawal

Based on Figures 13 and 14, it can be found that there is a definite relationship between the maximum internal temperature and the gap between optical fibres, i.e. the withdrawal of optical fibres in the optical attenuator.

It may be assumed that temperature rise in a structure of three layers consisting of optical fibre (silica), ferrule (zirconia), and adhesive (epoxy), triggers the internal distortion due to the difference in the coefficient of expansion of these layers, Young's modulus, and Poison's ratio, all of which resulted in withdrawal of optical fibre. The calculation model of thermal stress is shown in Figure 15 [5].

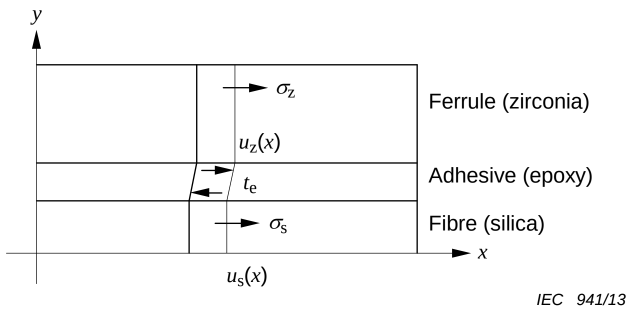


Figure 15 – Thermal stress simulation model for three layers of zirconia, epoxy and silica

As a result of the calculation, the optical fibre withdrawal δ can be expressed as follows against the temperature increase ΔT:

$$\delta = 4{,}3 \times 10^{-4} \Delta T \left[\times \mathrm{m} \right] \qquad (5)$$

From this equation, it can be determined that 20 nm withdrawal of optical fibre occurred at the temperature change of 50 °C.

Figure 16 shows how thermal distortion simulation overlaps relationship between sample maximum internal temperature and gap between optical fibres of the sample tested with various test temperatures and input powers.

In Figure 16, the added curve (blue broken line) was obtained by interpolating each point of Figure 14, and the added straight line (red broken line) was derived at 20 nm/50 °C. The gap of fibres started exceeding the calculated value when the maximum internal temperature reached 120 °C. This may be due to the softening of adhesive, as it exceeded the glass transition temperature of 120 °C, with declining Young's modulus and rising Poisson's ratio.

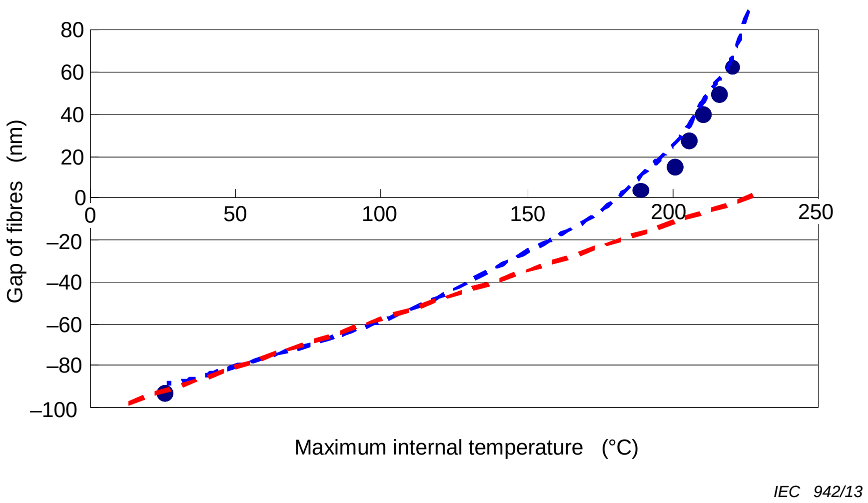


Figure 16 – Result of thermal distortion simulation and relationship between the sample maximum internal temperature and the gap

Based on the above results, it can be estimated that decrease in the return loss under the condition of high-power input is attributable to the withdrawal of optical fibre that causes loss of PC and is subsequently followed by a gap forming. The mechanism of optical fibre withdrawal was as follows: internal temperature rises as the attenuation fibre absorbs the incident optical power which, in turn, causes distortion between the optical fibre, epoxy and ferrule under thermal stress.

6.2 Fibre withdrawal after application of high-power test three times

At 70 °C and 1 000 mW, the return loss decreased and became stable at about 30 dB in about 15 min. Following this test, high-power input was repeated three times at 70 °C and 1 000 mW for 30 min for the purpose of confirming the withdrawal of optical fibre.

Figure 17 shows the alteration of fibre withdrawal. In the test, in two samples, it can be seen that there was greater optical fibre withdrawal on both samples of about 60 nm after the first high-power input, while there was only a small increase in withdrawal after second and third inputs. As described in 6.1, the optical fibre withdrawal occurs due to the thermal stress caused by the difference in the coefficient of expansion among silica (optical fibre), epoxy (adhesive) and zirconia (ferrule). The internal distortion by thermal stress is generally reversible. This can be the reason why the fibre withdrawals become stable in the second and third inputs. It can be said that the small alteration of fibre withdrawals in the second and third inputs is due to the softening of epoxy, as the maximum internal temperature of 200 °C at the test temperature of 70 °C, and the input power of 1 000 mW exceeds the glass transition temperature of epoxy.

After this test, it can be roughly confirmed that, within the range not exceeding the glass transition temperature of the adhesive, optical fibre withdrawal can alter reversibly under the thermal stress.

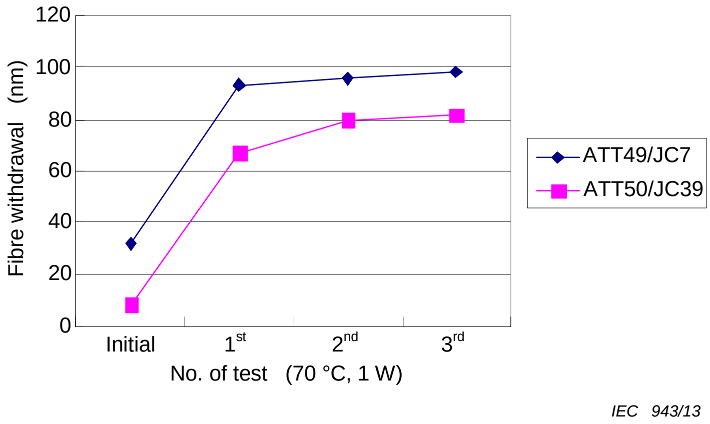


Figure 17 – Optical fibre withdrawal alternation under repeated power input to the optical fixed attenuation (70 °C, 1 W, 30 min, repeated inputs)

7 Long-term reliability test

7.1 Test conditions

Optical attenuators are used for fibre optic communication systems; this means that high reliability is required. Since it is usually used for 7 years to 15 years or longer, on a continuous basis, the high-power test with due consideration of long-term reliability is indispensable.

From the test results and thermal simulation results, it can be estimated that the limit of input power is such that the temperature of the adhesive (epoxy) fixing the optical fibre with ferrule does not exceed the glass transition temperature. When the environment of 70 °C, which is the normal maximum operating temperature, is assumed, the limit of power for the optical attenuator is expected to be 300 mW, based on the fact that, with this power input, the maximum internal temperature reaches 110 °C.

On the other hand, the effects of humidity cannot be ignored if we consider the long-term reliability. In this context, the long-term test was conducted at the maximum operating condition, i.e. at a temperature of 70 °C and humidity of 85 % RH. Table 2 shows the test conditions. The test set-up was similar to that used in the short-term test (see Figure 5).

Table 2 – Conditions for high-power, long-term test of the optical attenuator

Parameters	Test conditions
Samples	SC plug style optical attenuator with attenuation of 10 dB Worst-case endface conditions (effective optical-fibre withdrawal: 200 nm)
No. of samples	8 sets
Incident light source	1 550 nm (external cavity LD and EDFA), 300 mW
Test environment	70 °C, 85 % RH
Test period	5 000 h
Monitoring characteristics	Return loss

7.2 Test results

7.2.1 Return loss changing during the test

Figure 18 shows an example of high-power, long-term test results of optical attenuators. None of the eight sets of samples showed any decrease in the return loss. It can be seen that the return loss fluctuated within a range of 52 dB ~ 65 dB. It can be considered that such fluctuation is attributable to the interference by high coherency of the light source which is the external cavity LD, and multiple reflections from the optical couplers, optical power meters, etc. included in the test set-up.

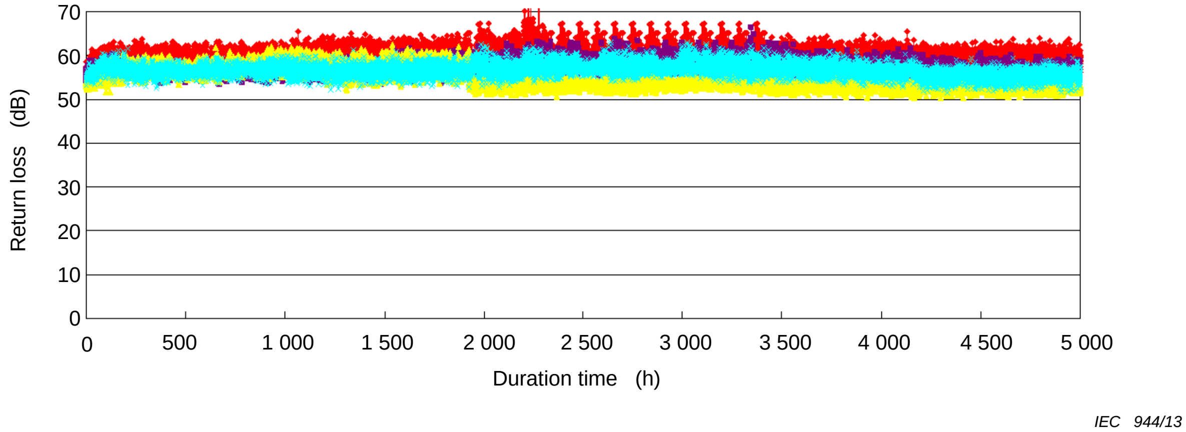


Figure 18 – High-power, long-term test results of the optical attenuator

7.2.2 The performance deviation after the test

The attenuations and return losses were measured over 5 000 h of testing. For the measurement mating to the reference optical connector plug, no deterioration was found on either the attenuations or the return losses.

7.3 Analysis of long-term, high-power reliability test

In the case of the long-term reliability test, there was no decrease in the return loss at 70 °C and 85 % RH for 5 000 h. Eight sets of samples were tested, and worst-case samples were used for the test. Since there is an extremely low probability that the plug of an optical attenuator with the worst-case endface conditions for spherical radius, apex offset and fibre withdrawal connects an optical connector plug with the similar worst-case conditions, it is believed that the number of samples tested was adequate. The test results confirmed that the long-term reliability is guaranteed at maximum input power if the SC plug-style, metal-doped fibre optical attenuator of 10 dB attenuation is 300 mW.

For an optical attenuator with a different attenuation, the maximum input power can be derived by calculating the maximum internal temperature of the attenuator based on the result of thermal simulation reported in IEC/TR 62627-03-02. For example, the upper limit of input power is 380 mW for an attenuation of 5 dB, and 280 mW for an attenuation of 20 dB.

8 Conclusion

An SC plug-style optical attenuator with full zirconia ferrule, in which metal-doped silica fibre was mounted using epoxy, was tested, injecting high optical power light, and obtained the following results. Test results can be extrapolated to high temperature test analysis of other passive components using full zirconia ferrule in which metal-doped silica fibre was assembled using epoxy material.

The mechanism of return loss decrease at high-power input of the optical attenuator was as follows: the metal-doped, optical fibre in the optical attenuator absorbs light and generates heat which causes temperature rise. This, in turn, produces thermal stress, due to the difference in material characteristics in the three-layer structure comprising the optical fibre (silica), adhesive (epoxy) and ferrule (zirconia) which finally resulted in the withdrawal of optical fibre and finally loss PC,

It was confirmed from the test results at 70 °C and 85 % RH for 5 000 h that the input power that can guarantee long-term reliability of an SC plug-style, optical attenuator is 300 mW.

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