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Fibre optic interconnecting devices and passive components

Part 05: Investigation on impact of contamination and scratches on optical performance of single-mode (SM) and multimode (MM) connectors

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Fibre optic interconnecting devices and passive components – Part 05: Investigation on impact of contamination and scratches on optical performance of single-mode (SM) and multimode (MM) connectors

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

FIBRE OPTIC INTERCONNECTING DEVICES AND PASSIVE COMPONENTS –

Part 05: Investigation on impact of contamination and scratches on optical performance of single-mode (SM) and multimode (MM) connectors

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

Enquiry draft	Report on voting
86B/3442/DTR	86B/3489A/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 the 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

- reconfirmed,
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INTRODUCTION

Contaminated optical connectors result in degradation of optical performance, which can be quantified by return loss (RL) and attenuation (A), functional failures and increased deployment costs. Fibre optic connector endface cleaning is recognized as a necessity for optimal signal performance. It is known that contamination impacts signal performance by blocking the core and impeding light transmission, as well as by preventing direct physical contact creating an air gap between the two connector enfaces [1, 2][1]. If an air gap exists, optical performance will be impacted due to the change in transmission medium. As contaminated connectors are mated and demated, contamination can be redistributed around the connectors' endface and block the fibre core. This presents a risk of signal performance degradation during the service life.

Since 2002, the iNEMI (International Electronics Manufacturing Initiative) working group has done substantial work, both theoretical and experimental, on impact of scratches and contamination on connector optical performance (A and RL). The following connector types have been used for this research: single-mode (SM) physical contact (PC) connectors, SM angle polished connectors (APC) and SM APC MPO connector. The impact of polishing scratches has been investigated for SM and multimode (MM) connectors. The work presented in this technical report was used as a base work for the development of IPC-8497-1 [3] and IEC 61300-3-35 [4].

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[1] Figures in square brackets refer to the Bibliography.

FIBRE OPTIC INTERCONNECTING DEVICES AND PASSIVE COMPONENTS –

Part 05: Investigation on impact of contamination and scratches on optical performance of single-mode (SM) and multimode (MM) connectors

1 Scope

This part of IEC 62627, which is a technical report, summarizes the extensive industry research on development of cleanliness specifications for single-mode (SM) and multimode (MM) connectors.

The summary of the result shows Table 1.

Table 1 – Summary of the result

Samples		**Scratch/Contamination/Defect**	**A/RL**	**Clause**	**Reference**
SM/MM	Single-fibre/ multi-fibre				
SM PC	Single-fibre	Scratch	RL	3	[1], [5], [6]
MM PC	Single-fibre	Scratch	RL	4	[7]
SM PC	Single-fibre	Contamination	A and RL	5	[2], [6]. [8]
SM APC	Single-fibre	Contamination	A	7	[11]
SM APC	Single-fibre	Scratch	RL	7.2	[11]
SM APC	Multi-fibre	Contamination	A and RL	8	[12]

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 61300-3-6, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 3-6: Examinations and measurements – Return loss*

IEC 61755-3-1, *Fibre optic connector optical interfaces – Part 3-1: Optical interface, 2,5 mm and 1,25 mm diameter cylindrical full zirconia PC ferrule, single mode fibre*

3 Abbreviations

A	attenuation
APC connector	angle polished connector
DUT	device under the test
GWPOA	gaussian weighted per cent occluded area
MFD	mode field diameter
MM connector	multimode connector

OTDR	optical time-domain reflectometer
OCWR	optical continuous-wave reflectometry
PC	physical contact
RL	return loss
SM connector	single-mode connector

4 Experimental methodology

In order to collect the data required to enable correlation between changes in optical performance (A and RL) with fibre optic images of the corresponding connectors, the experiment followed a multi-step process that involved

a) initially inspecting, cleaning and imaging connectors being tested (DUTs) and reference connectors; making multiple matings and dematings of each DUT with a reference connector, and recording A and RL data after each cycle,

b) manually applying dust to the cleaned endfaces of the DUTs, then

c) mating contaminated DUTs with clean reference connectors at least five times, taking A and RL measurements after each mating and saving fibre endface images for both connectors. The block diagram of the experiment is shown in Figure 1.

All DUTs and reference connectors were initially inspected and cleaned using a cleaning cassette. Endface images were saved using fibrescope and image analysis software. This software was used to accurately measure the number of particles, their size and their location at the connector endfaces. More than 80 cables with SC simplex connectors (the DUTs) were used for the experiment. A small group of DUTs (five cables) with FC connectors, ten DUTs with LC connectors, and five DUTs with MU connectors were added.

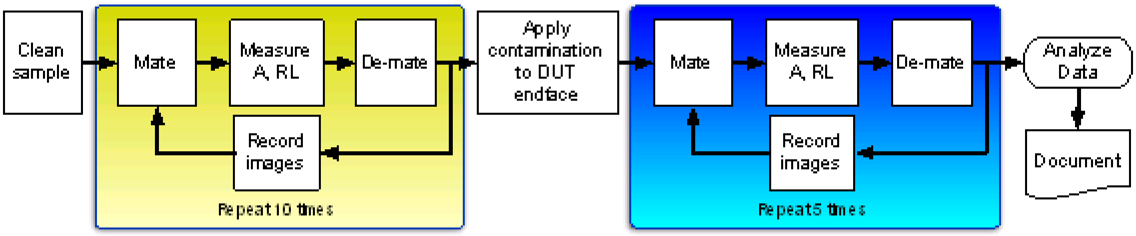


Figure 1 – Block diagram of design of experiment

After clean measurements and images were recorded, Airzona test dust was manually applied to the cleaned endface of the DUT. The two grades of Airzona test dust used for the experiment were ultra-fine (1-5 µm) and fine (6-25 µm). The contaminated DUT was mated with a clean reference connector. A and RL data were recorded. Each DUT and reference connector pair was mated and demated five times. After each mating, A and RL measurements were taken. After demating, the images of the DUT and reference connector endfaces were saved.

If the change in A or RL exceeded three times the standard deviation of A or RL for clean connector, the connector was judged a failure due to contamination. The pass criteria were achieved when both delta A and delta RL were within three standard deviations of A and RL.

The experimental methodology for SM APC connectors and for SM, APC MPO connectors was also based on design of the experiment shown in Figure 1. The details of the experimental procedure for these connector types are described in Clauses 8 and 9. The details of the experimental methodology for MM connectors are provided in Clause 6.

5 The impact of scratches on A and RL of single-mode connectors

A quantitative description of surface defects such as scratches and digs on optical performance was developed based on theory of surface scattering [5]. Further development led to a complete model for analysis of scratches impact on RL performance [6]. The model was based on the Gaussian distribution of incident power and included the effects from scratch location, size and number of the scratches. Based on the model it was predicted that the scratches through the fibre core cause some severe degradation, the scratches outside but near the core have some impact on RL, while scratches beyond 25 μm diameter centre area show little impact on RL performance [6]. These predictions were supported by experimental data [1]. To properly characterize the impact of scratches on performance parameters of mated optical connectors, first the optical performance parameters of pristine optical connectors were measured. Then, after applying scratches at different locations on the fibre endface, the optical performance parameters were measured again.

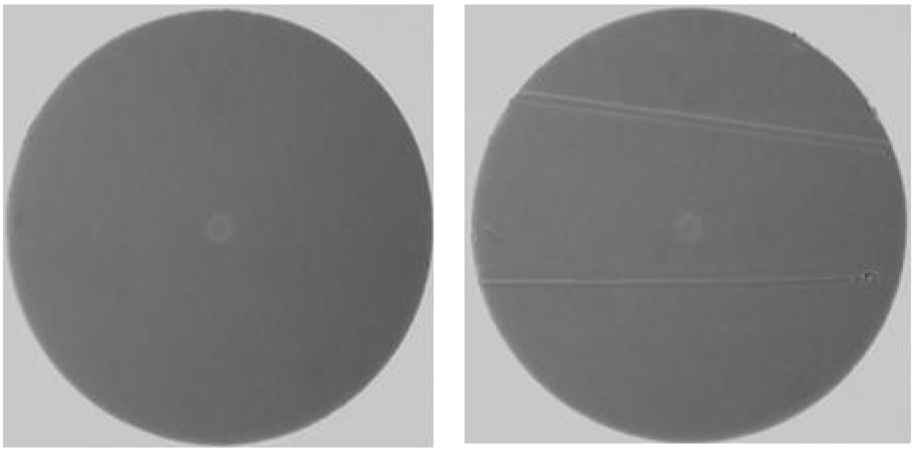
A sample set of 24 optical cable assemblies and launch cables were polished to PC performance using standard polishing process. The samples were divided into two groups. Scratches were induced only within the cladding region of the first group of connector endfaces, while for second group of optical cable assemblies the scratches were applied to the fibre mode field diameter (MFD).

The results of this study indicated that

a) polishing scratches and scratches made during connector cleaning, outside the fibre MFD, have no impact on A and RL of the mated optical connectors,

b) scratches 2 μm wide or less within the mode field diameter have no impact on A; the A change observed is within the measurement uncertainty of the test equipment,

c) scratches, within the fibre MFD, can degrade the RL of the mated connectors. The level of degradation depends on the size (width and depth), and the number of scratches crossing the fibre MFD. Figure 2 and Figure 3 provide the images of the connector endface with the scratches outside the MFD area and scratches through the fibre core correspondingly.



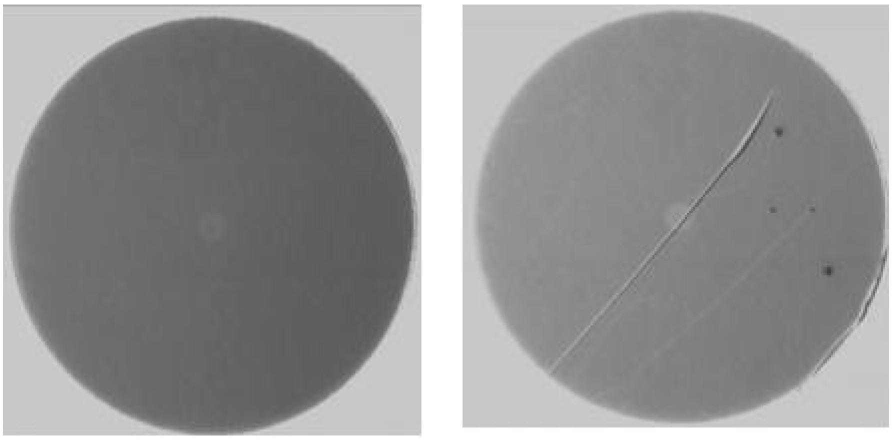
Key A = 0,14 dB; RL = 54,7 dB

Figure 2a – Pristine connector

Key A = 0,11 dB; RL = 54,8 dB

Figure 2b – Scratched connector

Figure 2 – Connector endface with the scratches outside the MFD area



Key A = 0,10 dB: RL = 52,7 dB

Figure 3a – Pristine connector

Key A = 0,10 dB; RL = 40,7 dB

Figure 3b – Scratched connector

Figure 3 – Connector endface with scratches passing through the core

6 Effects of scratches on RL of MM connectors

The effects of scratches on return loss of 50 µm core diameter MM connectors have been experimentally investigated. The results were presented at IEC SC86B, WG4 and WG6 meetings, Charlotte, in 2005. All samples had initial endface geometry according to IEC 61755-3-1. The samples were polished using 3 µm polishing paper. The RL measurements have been performed per IEC 61300-3-6 (Method 1, OCWR or Method 2, OTDR) at λ = 1 300 nm. The connector endface was characterized using a confocal microscope as shown in Figure 4. The data for scratch width, depth, and length were analysed and found to correlate with connector RL performance.

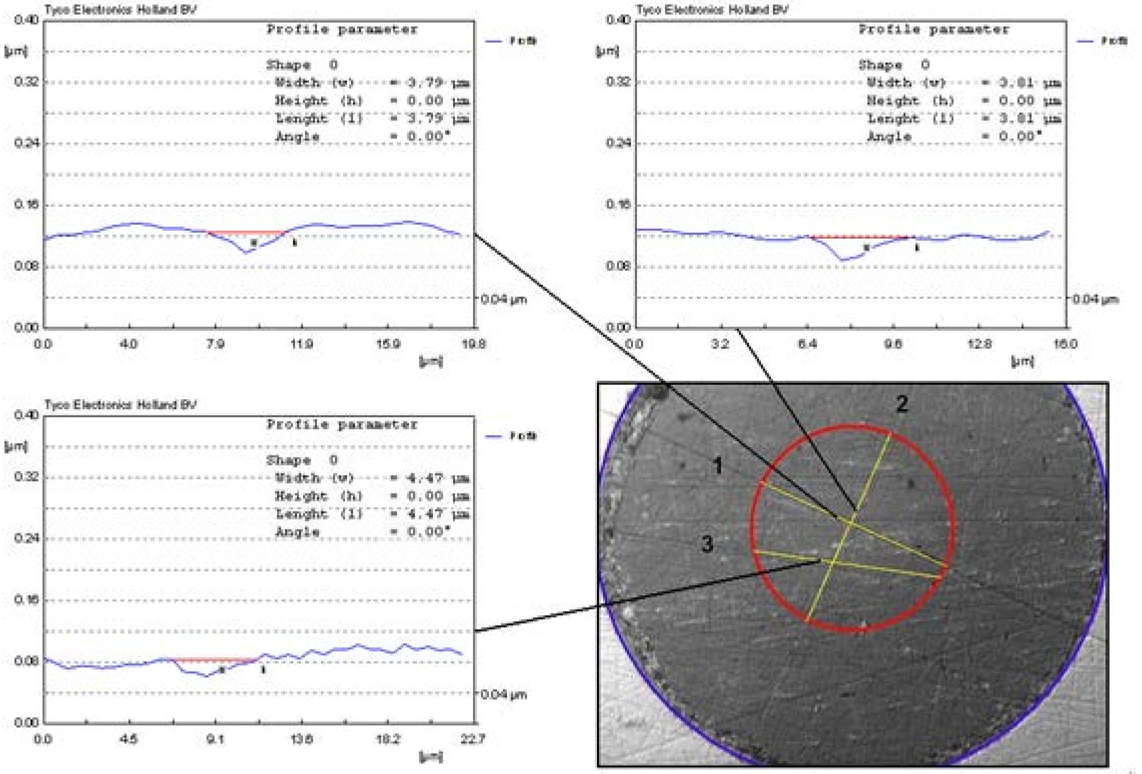


Figure 4 – Examples of characterized endfaces using confocal microscope [7]

It was found that all tested multimode samples exceed 20 dB RL as shown in Figure 5.

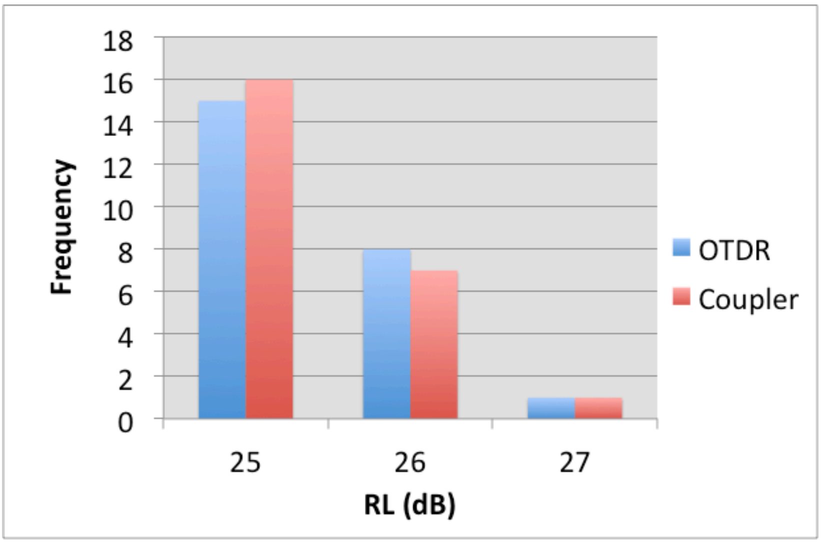


Figure 5 – RL random mated connectors, λ=1 300 nm [7]

Based on the study, the visual criteria for polished connectors, 20 dB RL, 50 µm was proposed [7].

7 Investigation of impact of contamination on optical performance of 2,5 mm and 1,25 mm connectors

7.1 General

This clause summarizes research performed by the iNEMI (International Manufacturing Electronics Initiative). The fibre optic signal performance project was focused on the development of a cleanliness specification for single- mode connectors. The influence of two grades of Airzona test dust on optical performance of single-mode fibres was investigated [2, 8].

7.2 Zone definitions

The impact of particle location on SC connector optical performance was studied in [2].

The iNEMI used image analysis software to measure the distance from the core centre to the closest edge of the particle. The dependence of delta attenuation, which is equal to A of the contaminated case minus A of the clean case, is shown in Figure 6a.

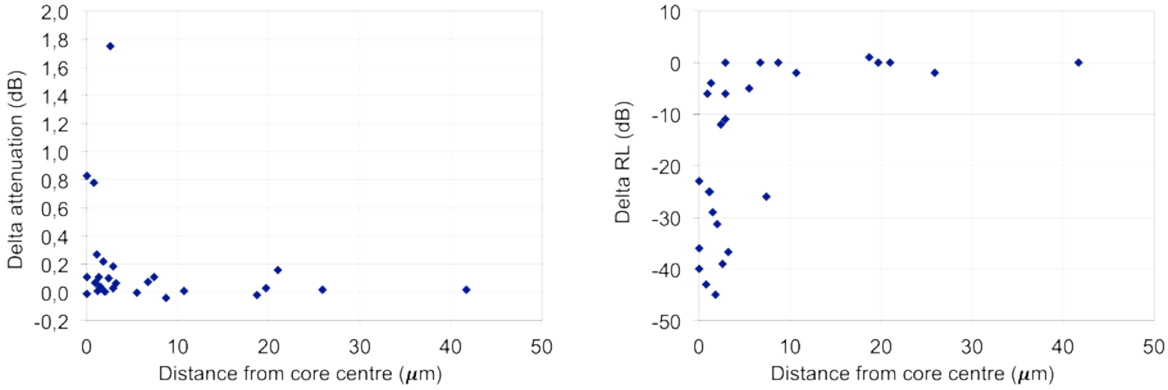


Figure 6a – Attenuation performance   **Figure 6b – RL performance**

Figure 6 – Influence of the particle location on performance

Particles located in the core area may result in catastrophic degradation of A. The delta A was from 0,2 dB to 1,8 dB. The graph of delta RL as a function of the distance from the centre of the core to the edge of the closest particle is shown in Figure 6b. The presence of particles in the core zone as well as the presence of clusters of particles in the cladding and ferrule areas may result in the catastrophic degradation of the RL with delta RL from 10 dB to 40 dB. Based on this study the core zone with a diameter of 25 μm was recognized as the most critical in terms of the connector performance.

The following zone system was applied to both 1,25 mm and 2,5 mm ferrules: Zone A, with a diameter of 25 μm; Zone B within the cladding area, (25 μm to 120 μm); the epoxy ring, zone C (120 to 130 μm) and Zone D within the contact area (130 μm to 250 μm diameter). The zones are shown on all connector images.

7.3 Experimental data for 2,5 mm ferrule connectors

Two examples of contaminated FC connectors are shown in Figure 7 and Figure 8 for samples FC01 and FC04, respectively. In Figure 7, FC01 after the fifth mating is an example of negligible contamination within Zone A. In Figure 8, FC04 after second mating, is an example of significant contamination in Zone A.

The A and RL mean and standard deviations for clean samples and the individual A, RL, delta A and delta RL data are shown in Table 2.

The pass/fail, based on the first method of testing delta against a three standard deviation limit, is also shown in Table 2. As seen in this table, FC01 (after all mating) passed, as the contamination did not cause a significant increase in either A or RL.

After five matings/dematings the 25 μm zone remained clean. The A did not change. The RL change was within 3 standard deviations for the clean fibre. FC04 (second mating), Figure 8, failed, as it had a large particle blocking a significant portion of Zone A, resulting in a significant increase in A and decrease in RL (degraded performance). These changes were, in fact, much larger than the three standard deviation limit. The core stayed contaminated during the next matings/dematings. After five matings/dematings the optical performance was approximately the same as after the second mating/demating. The presented data are in good correlation with the previous data for SC connectors. The contamination of 25 μm zone resulted in a significant increase of the A and a reduction of RL. In many cases, the reduction of the RL was observed when a 25 μm zone was blocked and large clusters (>30 μm) of the particles were located in a cladding layer. The contamination of cladding and ferrule zone didn’t result in any significant changes in optical performance if the 25 μm zone was clean.

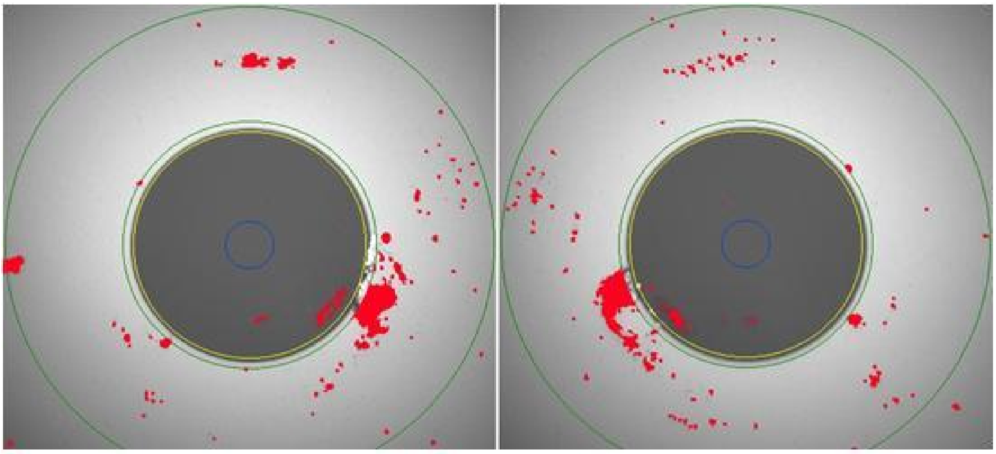


Figure 7a – DUT **Figure 7b – Reference fibre**

Figure 7 – FC01 images of DUT and reference fibre after contamination and fifth mating

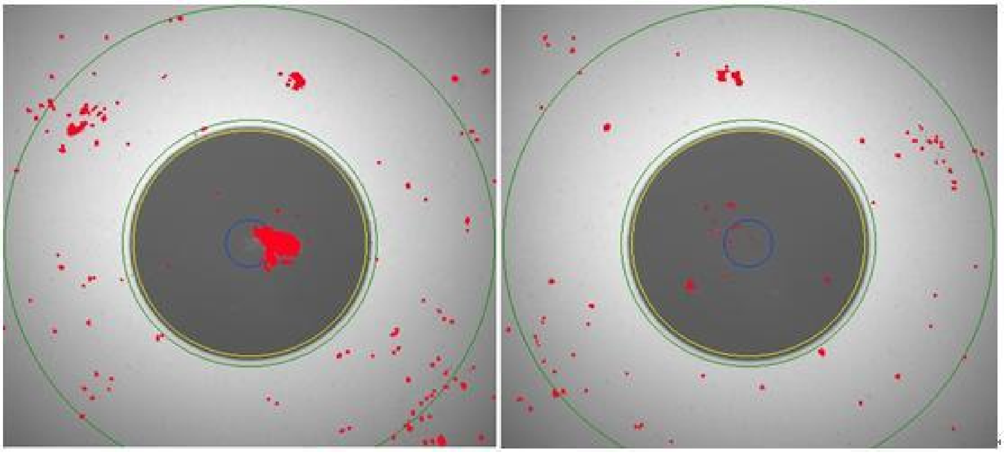


Figure 8a – DUT **Figure 8b – Reference fibre**

Figure 8 – FC04 images of DUT and reference fibre after contamination and second mating

7.4 Experimental data for 1,25 mm ferrule connectors (LC, MU)

The fibrescope image of LC07, a 1,25 mm connector, after the first mating, Figure 9, revealed one small particle located in Zone A. However the contamination distribution (at the first mating) had no impact on optical performance as shown in Table 2.

After the third mating/demating the particle distribution had been significantly changed. The particles moved from the ferrule and cladding areas towards the core of connector L07 and reference cable T07 as shown in Figure 10 and Figure 11. The DUT failed the pass/fail criteria for both A and RL.

The contamination level in Zone A area was further increased after fourth and fifth matings/dematings as shown in Figure 11. As expected, the A and RL both were degraded, as shown in Table 2.

Table 2 – A and RL statistics for representative samples

Sample ID	A mean dB	A 3σ[a] dB	RL mean dB	RL 3σ[a] dB	Delta A dB	Delta RL dB	Pass/fail
FC01 (clean)	0,04	0,02	54	3,0	––	–	–
FC01 (1st mate)	0,05	–	55	–	0,01	1	Pass
FC01 (5th mate)	0,04	–	55	–	0,00	1	Pass
FC04 (clean)	0,13	0,03	54	1,4	–	–	–
FC04 (2nd mate)	0,26	–	34	–	0,13	20	Fail
LC07 (clean)	0,11	0,02	53	1,0	–	–	––
LC07 (1st mate)	0,12	–	53	–	0,01	0,0	Pass
LC07 (3rd mate)	0,23	–	28	–	0,12	25,0	Fail
LC07 (5th mate)	0,57	–	19	–	0,46	34,0	Fail

[a] σ means standard deviation.

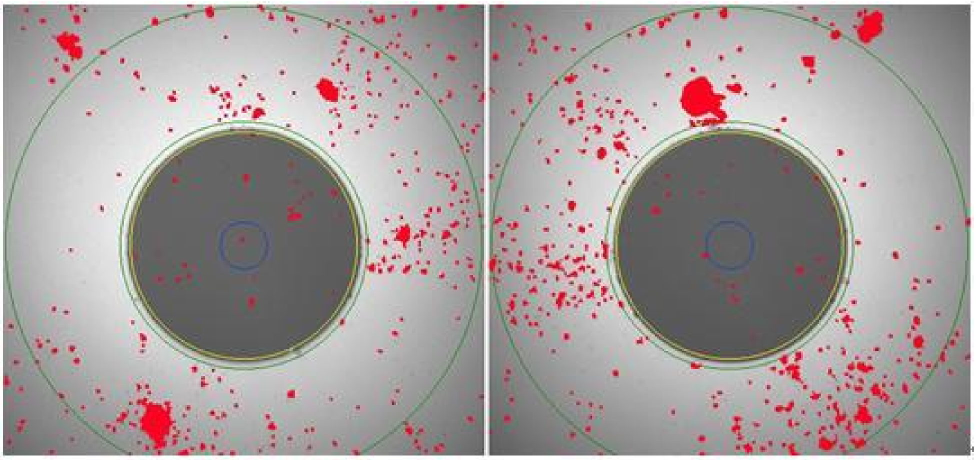


Figure 9a – DUT **Figure 9b – T07 reference fibre**

Figure 9 – LC07 images of the DUT and the T07 reference fibre after contamination and first mating

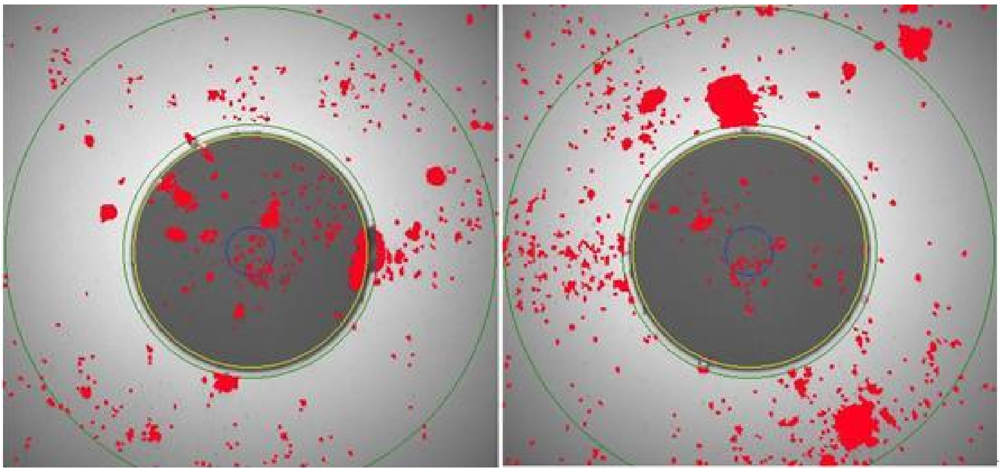


Figure 10a – DUT **Figure 10b – T07 reference fibre**

Figure 10 – LC07 images of the DUT and the T07 reference fibre after contamination and third mating

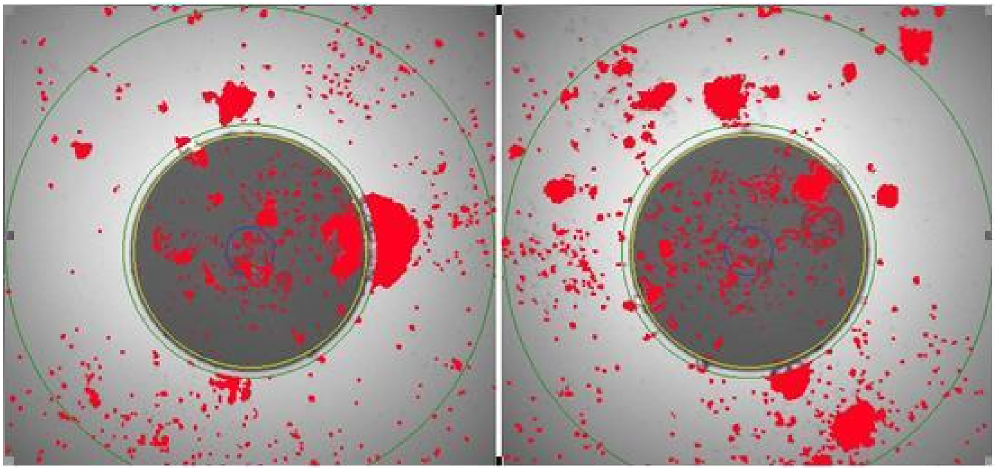


Figure 11a – DUT **Figure 11b – T07 reference fibre**

Figure 11 – LC07 images of the DUT (Figure 11a) and the T07 reference fibre (Figure 11b) after contamination and fifth mating

Approximately 60 % of all investigated LC and MU connectors demonstrated the particle movement during the series of matings/dematings operations, with a corresponding increase of A of 0,5 dB to 1,1 dB. The physical mechanism of the particle movement has to be further investigated. SC and FC connectors appear to be more resistant to particle movement during repeated mating/demating operations.

Contamination can also prevent direct physical contact creating an air gap between two connector endfaces. An air gap of less than 200 nm for SC connectors was calculated based on the RL of clean and contaminated connectors, as well as on geometric parameters (apex offset, radius of curvature and fibre undercut) of the DUT and reference connector [2].

Overall, the contamination has similar impact on the optical performance of 2,5 mm and 1,25 mm connectors.

7.5 Image analysis

A correlation between A and RL and the distance from the core to the edge of the nearest particle was reported in [2]. It was a much more complex and difficult task to investigate the potential correlation between A and RL and multiple particles distribution. The three main characteristics of interest are the particle's area, diameter and location relative to the fibre centre. The occluded area feature of the image software computes the occluded area for annular regions centred on the cladding [8]. The occluded area is the total particle area, for all particles, within that annular region. An example of the occluded particle area binary image is shown in Figure 12a for the fibrescope image shown in Figure 12b. The image has the particle binary data colour-coded to identify within which annular ring a portion of each particle is contained. The black background is the ferrule region, the light grey background is the fibre cladding and core, and the white background is the epoxy zone. The width of the each ring, shown in Figure 12a, was 5 μm, although the ring width used in the analysis was finer at 2,5 μm.

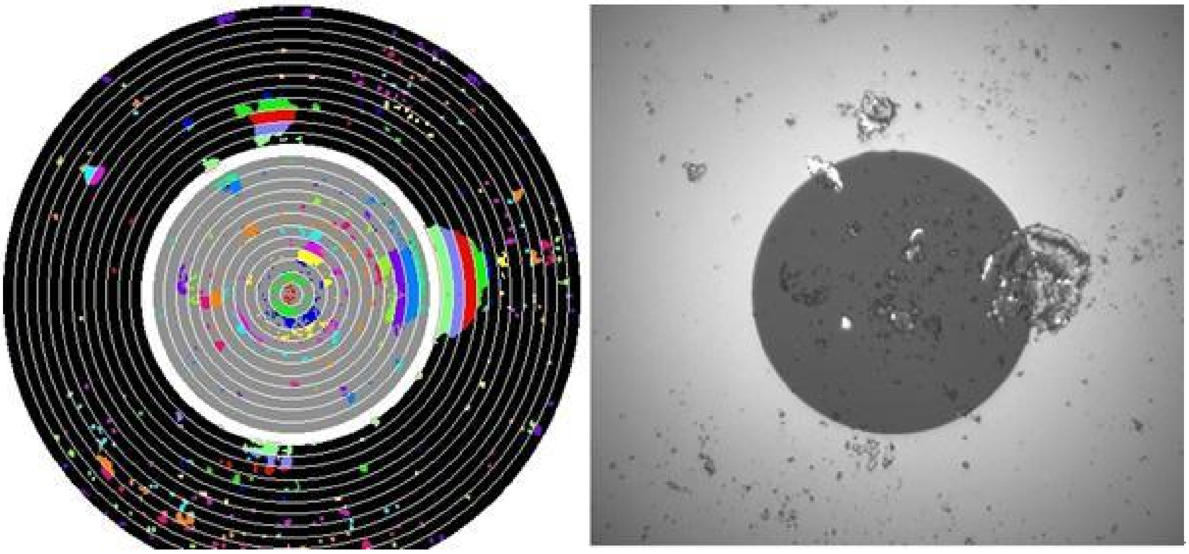


Figure 12a – 5 μm annular rings

Figure 12b – Fibrescope image

Figure 12 – Labelled detected particles with 5 μm annular rings and fibrescope image for LC07-WD-5M

7.6 Gaussian weighted per cent occluded area

Normalizing by both area and a Gaussian weighting function, based on a model of the intensity distribution of the fundamental fibre mode, yields the Gaussian weighted per cent occluded area (GWPOA). The GWPOA is a single valued figure of merit representing the overall cleanliness of the endface.

The intensity distribution of fundamental fibre mode [9] is expressed as

$$I_O \exp(-2r^2/\omega_f^2),$$

where

I_O is the peak intensity;

r is the radial position;

ω_f is the mode-field radius of single-mode fibre.

To account for the effect of this intensity profile on the attenuation, the Gaussian weighting factor, $\Gamma = \exp(-2r^2/\omega_f^2)$ was introduced. This weighting factor can be applied to the occluded particle areas to weight the particle's blocking effect based on the intensity profile. The GWPOA is defined as

$$\text{GWPOA} = \frac{\sum_{0}^{N} a_i \Gamma_i}{\sum_{0}^{N} A_i \Gamma_i} \times 100\ \% \tag{1}$$

where

a_i is the size of particle;

Γ_i is the Gaussian weighting factor;

A_i is the area of the i^{th} ring.

For $i = 0$, the ring is a circle centred on the fibre centre.

The mode field diameter of SMF-28 is 10,4 µm at 1 550 nm. The GWPOA was calculated for 96 images. The graph of delta attenuation versus GWPOA is presented in Figure 13. The analysis does not include the particle effect of the mating reference connector. The correlation between the data points and the fitted curve is 0,82. The theoretical relationship between A and the GWPOA is of great interest for further investigation.

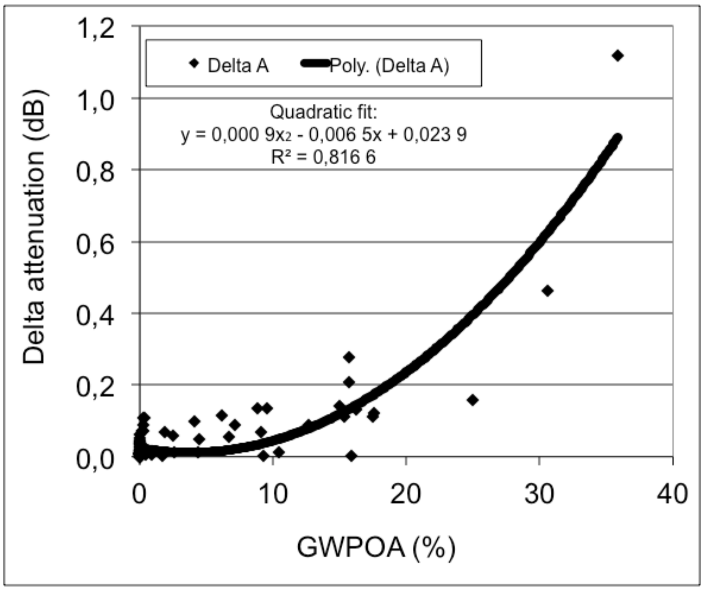


Figure 13 – Delta attenuation versus GWPOA

7.7 Inspection criteria matrix

Based on our previous research for scratches and contamination, as well as, on the experimental data described in this paper, the inspection criteria matrix, Table 3, is proposed for 2,5 mm and 1,25 mm ferrule PC connectors, SM fibre. The area with a diameter of less than 25 µm, Zone A, is considered the most critical in terms of optical performance. No contamination and scratches are allowed in Zone A. The pass/fail criteria for the cladding zone (Zone B), the adhesive zone (Zone C), contact zone (Zone D), are based on experimental results for A and RL as well as on cosmetic requirements. The maximum size of the contact zone of 250 µm is defined on the conservative approach of the contact diameter calculation for SC connectors [2].

Table 3 – Inspection criteria for SMF pigtail and patch cord connectors, RL >45 dB

Zone/description	Diameter µm	Allowable defects and scratches	
		Defects	Scratches
Zone A: Core zone	0 to 25	None	None
Zone B: Cladding zone	25 to 120	No limit <2 µm 5 from 2 µm to 5 µm None >5 µm	No limit ≤3 µm None >3 µm
Zone C: Adhesive	120 to 130	No limit	No limit
Zone D: Contact	130 to 250	None =>10 µm	No limit

8 Correlation study between contamination and signal degradation in single-mode APC connectors

8.1 General

This clause summarizes the correlation study between contamination and scratches on single-mode APC connectors and signal degradation leading to an acceptance criteria matrix. The research has been published by Photonics North 2009 conference, Quebec City, Quebec, Canada, May 2009 [10].

A group of 25, high quality, patch cords with SC/APC connectors on each end was tested in a pristine state for baseline performance (both the average and standard deviation of RL). Starting with pristine connectors and introducing only a small amount of loose particulate, it was studied how particles are redistributed during successive matings. Next, the effect of scratches on SC APC connectors using a similar design of experiment was studied.

8.2 Experimental data and analysis for SM APC connectors

From previous study on SM PC connectors, it was predicted that the core zone would be highly sensitive to contamination. For this reason, a sample set was divided into two groups. Group A contained samples where dust touched or overlaid the 9 µm core. Group B contained samples with dust on the cladding, but not touching the core. Typical pictures of the connector endfaces from Group A and B are shown in Figure 14.

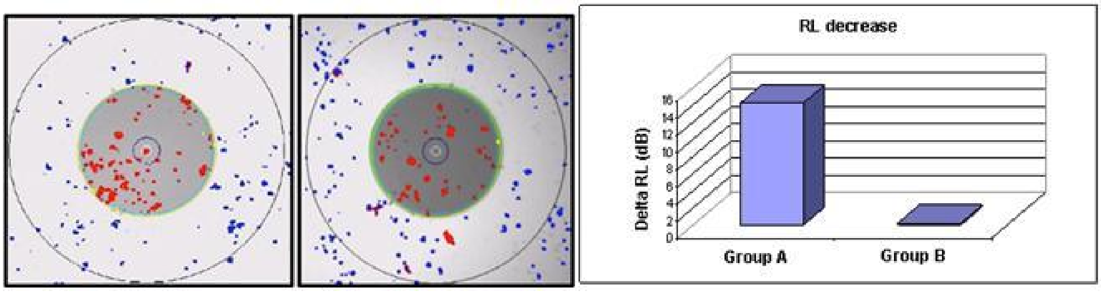
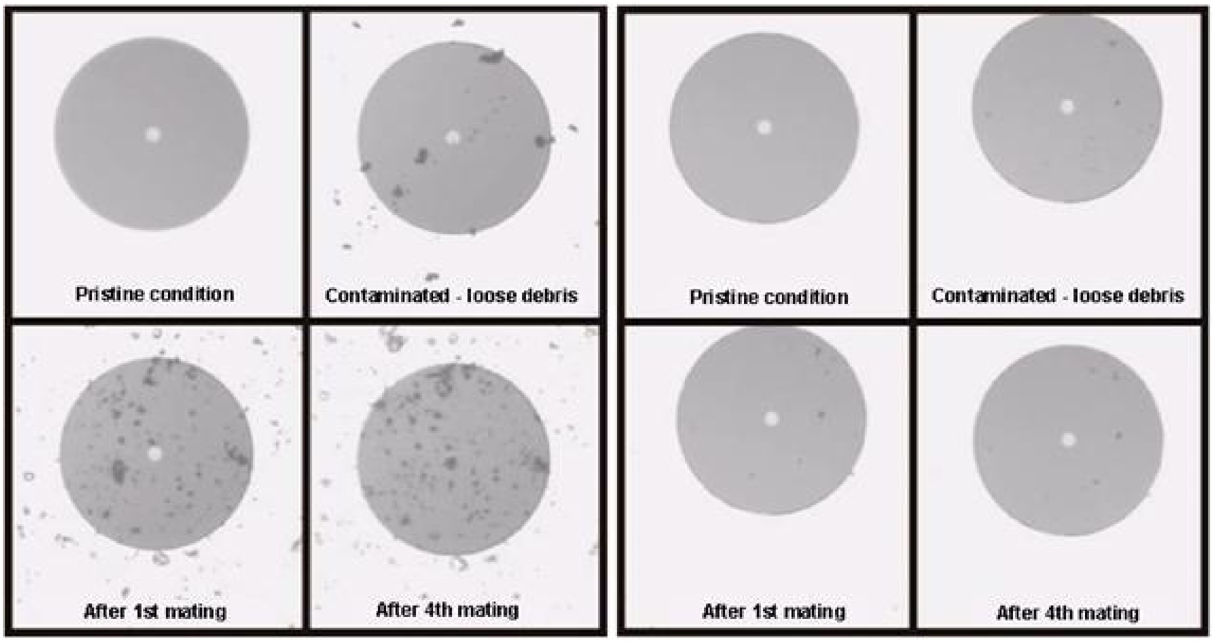


Figure 14 – Left to right: Group A, Group B and average return loss decrease by group

As predicted, connectors in Group A demonstrated a dramatic decrease in average return loss of 14,2 dB. In comparison, Group B, where dust was present on the cladding but the core was clear, demonstrated a negligible change in return loss of 0,15 dB. It was concluded that strict limitations on contamination in the core zone are required. Analysing Group B and establishing failure thresholds for the cladding then became the focus of the study. While contamination on the cladding does not always create signal degradation, it does in some instances. Further, it has long been postulated that contamination on the cladding can relocate during successive matings. To understand this problem, the behaviour of relatively large particles (~10 μm diameter) versus small particles (<5 μm diameter), was investigated as shown in Figure 15. Loose particles were deposited on pristine connectors and mated successively.



NOTE 1 Four images at left are relatively large particles (~10 μm) “exploding” and spreading across fibre.

NOTE 2 Four images at right are small particles (< 5 μm) that do not demonstrate significant movement under successive matings.

Figure 15 – Behaviour of relatively large particles versus small particles

Further investigation established that particle migration during successive matings also occurs on the ferrule within the contact zone (approximately <250 μm), but does not seem to be an issue beyond that zone.

In parallel, the effect of scratches on APC connectors was investigated, It was found, as shown in Figure 16, that even large numbers of scratches, including scratches across the core, do not measurably degrade back reflection (return loss). This was contrary to the results for PC connectors and was consistent with the design theory that underlies APC connectors.

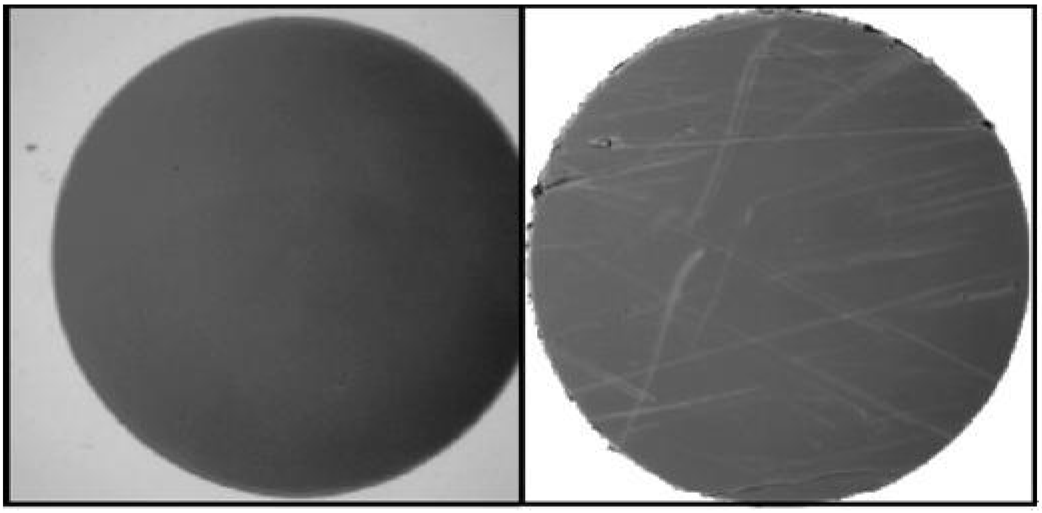


Figure 16 – Test connector in pristine condition (RL= 67,5 dB) and after scratches applied (RL= 68,5 dB)

8.3 Inspection criteria matrix

Based on the experimental data described in a previous paper [10], an inspection criteria matrix is proposed for SM APC connectors as shown in Table 4. For practicality, contamination and all other defects are grouped under the single heading of “defects”. Scratches are controlled separately. Zone A is tightly controlled for defects and a limit of four scratches is placed as a demonstration of workmanship and process control. Zone B is governed partly by the experimental results for signal degradation (RL) and partly by the threat that particles in this zone are highly likely to redistribute to Zone A during successive matings. As particles below 5 μm in diameter are unlikely to move during mating cycles, it is practical to allow a small number of particles between 2 μm and 5 μm in a cladding zone. Zone C is prone to minor edge chipping, epoxy spread and other defects that are nearly impossible to discern from fixed particulate matter. Further, as this zone is relatively far from the core, there are no defined failure conditions. Zone D is unlikely to contribute to signal degradation but some level of control is needed to address the threat of particle migration during mating cycles. It is technically reasonable to establish no limit on scratch count for these outer three zones.

Table 4 – Inspection criteria for single-mode APC pigtail and patch cord connectors

Zone/description	**Diameter** μm	**Allowable defects and scratches**	
		Defects Number & width	**Scratches**
Zone A: core	0 to 25	None	≤ 4 scratches
Zone B: cladding	25 to 120	No limit ≤ 2 μm 5 from 2 to 5 μm None > 5 μm	No limit
Zone C: adhesive	120 to 130	No limit	No limit
Zone D: contact	130 to 250	None =>10 μm	No limit

Clause 8 focused on the impact of contamination and scratches on signal performance of SM APC optical connectors. Contamination led to clear proof that contamination touching or on the core creates dramatic signal degradation and is unacceptable. While previous iNEMI studies have shown that scratches on the core in PC connectors are highly problematic, the APC connectors were remarkably robust. Moving out from the core zone, the limit on defects is progressively more relaxed with the primary focus on removing large loose particles to prevent the possibility of migration onto the core during successive matings.

9 Development of cleanliness specifications for single-mode, angled physical contact MPO connectors

9.1 General

This clause summarizes the iNEMI research on development of cleanliness specification for single-mode, angled physical contact MT fibre optic connectors. The research has been presented at the OFC/NFOEC 2008 conference [11].

The group of experimental samples included eight SM, MPO jumpers with low-loss MT angled physical contact ferrules. Each MPO connector contained one row of 12 fibres. An interferometer was used for fibre endface geometry characterization of the MT ferrules. Attenuation and RL for the MPO jumpers were measured using a multi channel back reflection meter. Source wavelength was 1 550 nm. In order to investigate the impact of the scratches on optical performance of MPO connectors, the scratches were manually introduced to the connectors' endfaces. The experimental methodology in this case was the same as shown in Figure 1. More than 250 mated fibre pair data points were gathered. The effect of particle redistribution on the MPO connector endfaces after repetitive series of matings/dematings was investigated.

9.2 Core zone analysis

For the single-mode fibre used in the low-loss APC MPO assemblies in this experiment, the mode field diameter (MFD) at 1 550 nm is 10,4 μm ± 0,5 μm. Many of the fibre tips studied during the MT analysis were contaminated in this critical core zone of the fibre. For these samples, with increased contamination in the core zone, a definite trend of increasing signal degradation in both A and RL was observed. The GWPOA was calculated for each image using the image analysis software. Figure 17 illustrates the change in A and actual RL as a function of the GWPOA metric. The signal degradation can be a function of blocked or reflected transmitted power and/or Fresnel losses due to loss of physical fibre contact between the mated connectors.

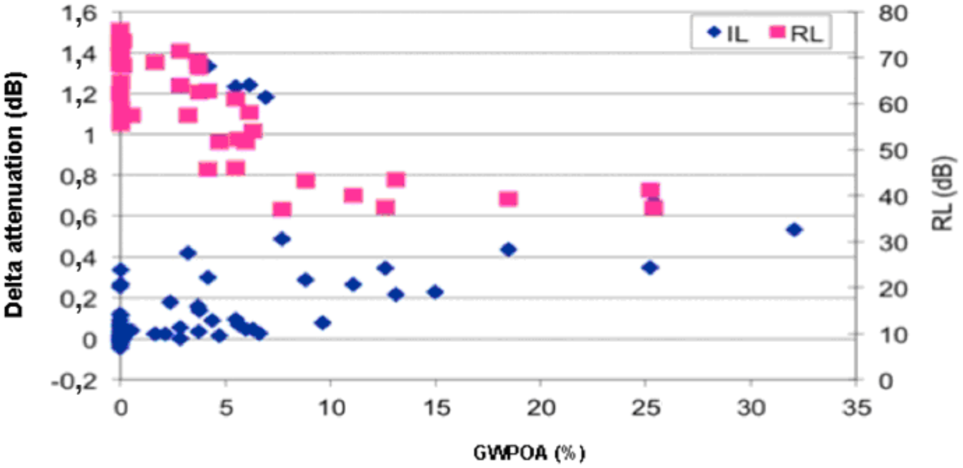


Figure 17 – Impact of contamination in core zone for SM APC MPO connectors

9.3 Cladding zone analysis

Once confirmation of signal degradation was established with virtually any quantifiable contamination in the core zone, the focus of the experimentation was shifted to the study of the impact of contamination outside of the core zone. Contamination outside of the core zone can result in signal degradation due to the loss of physical contact of the fibre pair.

Multi-fibre, monolithic ferrules present a complex geometrical challenge in bringing all mated fibre pairs into physical contact. The ferrules are prepared such that the fibre tips protrude from the surface of the ferrule by an amount typically ranging from 1 µm to 3 µm. Common manufacturing and polishing techniques often yield fibre tip distributions where the fibres in the centre of the ferrule protrude slightly more than the fibres on the ends of the ferrule. This phenomenon can result in varying fibre tip contact forces across the ferrule array [12]. Figure 18 illustrates the changes of A (delta A) and RL data for 12 channels of contaminated MT connector and the positional tendency of loss of physical contact failures to occur on outer fibres in the array.

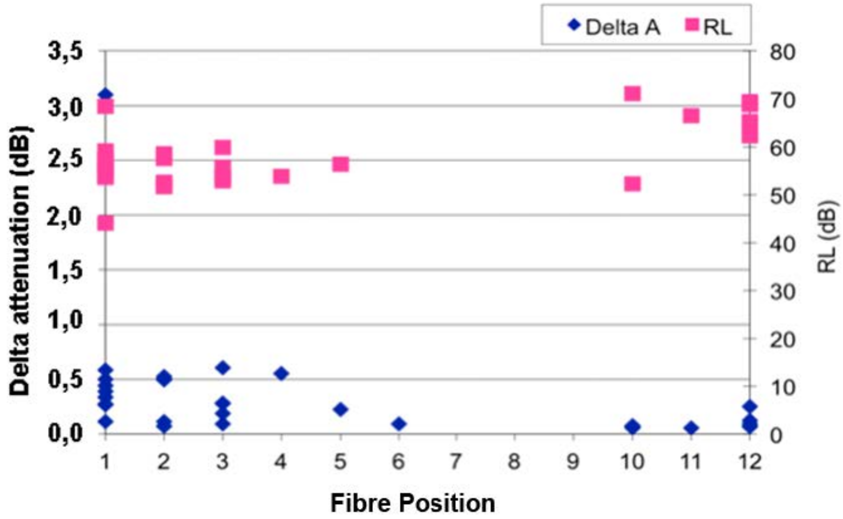
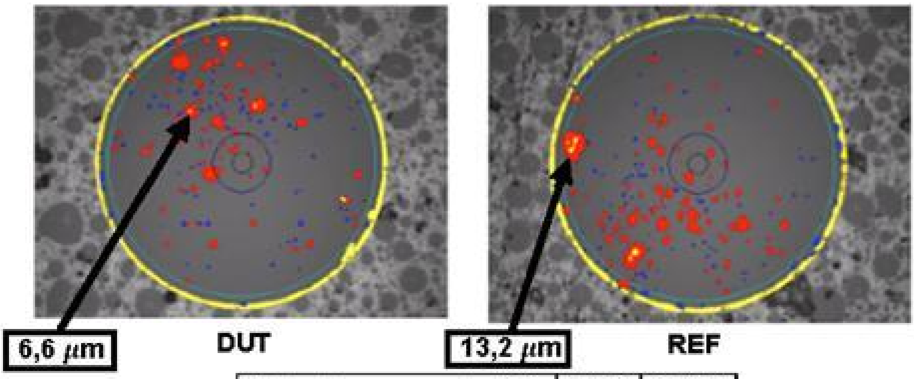


Figure 18 – Contamination failures due to loss of physical contact by fibre position for connections of angled MT ferrules

In order to examine the impact of contamination in the cladding zones, fibre tips with no contamination in the core but with varying amounts of cladding contamination were studied. Many cases exhibited severe contamination in the cladding zones with no noticeable impact to signal performance. Figure 19 shows one of many such examples.

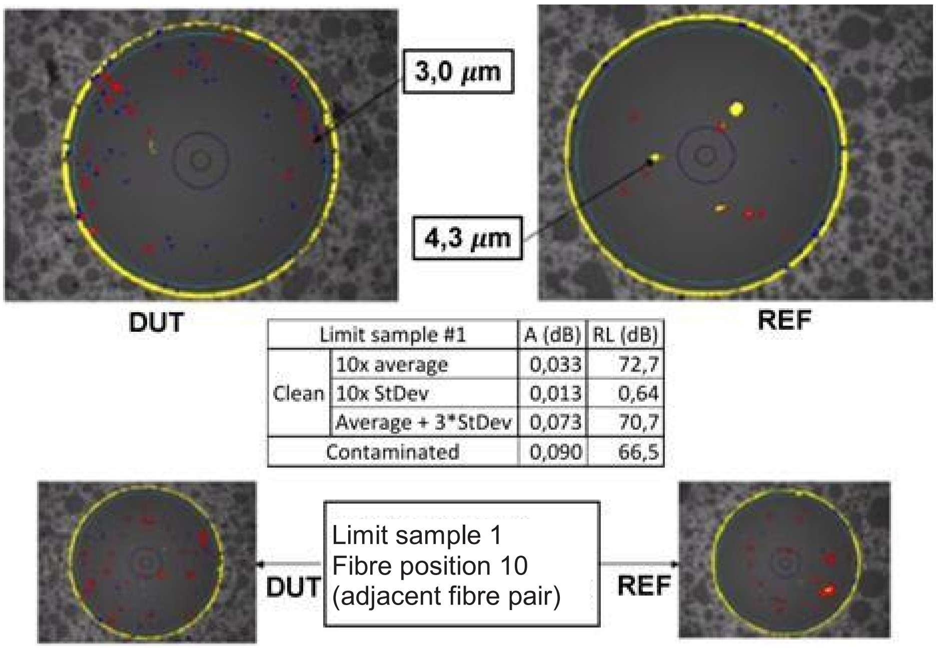


Robustness example #62		A (dB)	RL (dB)
Clean	10X average	0,045	73,5
	10X StDev	0,011	1,7
	Average + 3*StDev	0,078	68,4
Contaminated		0,020	73,0

Figure 19 – Endface images of DUT and reference connector showing no impact to signal performance

Sixty-five (65) fibre pair samples were found with significant occluded area in the cladding that had no impact on signal performance. Some fibre pairs had up to 30 % occluded area on cladding with no signal degradation. However, there were some fibre pairs in the cladding contamination study that did exhibit signal degradation. There are nine data points, which had minimal cladding contamination (<5 % OA from 12,5 μm to 115 μm) with some impact to signal performance. These samples are considered to be specification limit samples, as the concluded acceptance criteria must ultimately fail these data points to be effective.

Each of the specification limit samples had much more severe contamination in neighbouring fibres. Specification limit sample #1 is illustrated in detail in Figure 20. This sample highlights the contamination on the fibre pair under test in addition to the more severely contaminated neighbouring fibre pair (fibre position 10). When compared with the sample data points from Figure 18, this analysis suggests that severely contaminated fibre pairs in an array of fibres on an MT ferrule can impact signal performance on other fibre pairs in the array.

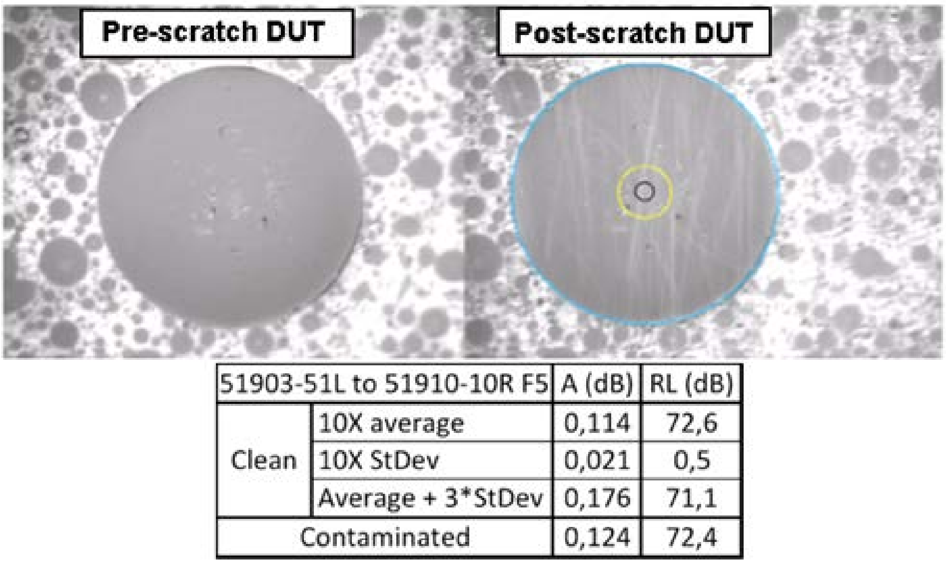


Limit sample #1		A (dB)	RL (dB)
Clean	10x average	0,033	72,7
	10x StDev	0,013	0,64
	Average + 3*StDev	0,073	70,7
Contaminated		0,090	66,5

Figure 20 – Minimal MT/APC contamination on limit sample #1 with signal degradation

9.4 MT APC scratch analysis

The impact of fibre endface scratches on signal performance was also examined for MT connectors. It was found that for low power applications, no restrictions for light scratches on the fibre tips are required. Figure 21 illustrated a typical scratch analysis data point with the pre-scratch and post-scratch images compared with A and RL performance. No noticeable impact of light scratches was observed.



51903-51L to 51910-10R F5		A (dB)	RL (dB)
Clean	10X average	0,114	72,6
	10X StDev	0,021	0,5
	Average + 3*StDev	0,176	71,1
Contaminated		0,124	72,4

Figure 21 – Typical lack of impact on signal performance of light scratches on MT/APC connections

10 Conclusion

In early research the impact of scratches on optical performance (RL) on fibre optic connectors was predicted based on modelling data. It was shown that RL performance depends on the number of the scratches, different sizes and scratch location [6]. At the same time the impact of scratches was investigated experimentally for SM connectors [1]. It was found that scratches across the core resulted in severe changes of RL (delta RL >4 dB) and the scratches outside of MFD have practically no impact on connector optical performance. The experimental data on the impact of scratches on RL of MM connectors were presented at IEC SC86B/WG4 and WG6 meetings in Charlotte in 2005. It was shown that all tested MM samples exceed the 20 dB RL requirement.

Since 2002, the iNEMI has conducted experiments to compare the effects of specific contamination and polishing scratches on the optical performance of SM fibre optic connectors. The underlying support for the cleanliness specification was the experimental and theoretical analysis of contamination and optical performance parameters, A and RL. The iNEMI compared the influence of Arizona dust particles on optical performance of 2,5 mm and 1,25 mm connectors. The similarities and some differences in optical performance of contaminated 2,5 mm ferrule (SC, FC) and 1,25 mm ferrule (LC, MU) connectors were found. The zone of 25 μm diameter was identified as critical zone in terms of the contamination influence on optical signal performance for all types of investigated PC connectors. Particles or scratches in this zone can affect signal performance; therefore, cleanliness guidelines should reflect this.

During the course of this investigation, several other observations were made:

a) First, in 60 % of all examined LC and MU connectors, a series of five repeated matings/dematings operations resulted in an increase of attenuation of 0,5 dB to 1,1 dB due to particle movement from the ferrule and cladding areas towards the core. SC and FC connectors appear to be more resistant to particle movement during repeated mating/demating operations.
b) Second, the correlation of the A changes to the particle sizes and distribution by the introduction of Gaussian weighted per cent occluded area was explained. For computer based inspection methods, using an occluded area might have been a more direct measure of the total blocked area than a particle count based method.

c) Based on the study for SM APC connectors, a contamination touching or on the core creates dramatic signal degradation and is unacceptable. Scratches practically have no impact on optical performance of APC connectors. The data for SM APC MPO connectors was in good correlation with findings for 2,5 mm (SC, FC) and 1,25 mm ferrule (LC, MU) connectors. It was shown that contamination of the 25 μm zone might result in increase of A for MPO connectors (observed A delta maximum ~ 1,5 dB) and decrease of RL (observed RL delta maximum ~ 21 dB). Based on these findings the core zone has to be clean in order to sustain good signal performance.

d) The investigated MPO connectors provided examples of significant robustness in terms of no impact of contamination in the cladding zone for optical performance. There were some reported cases when lower levels of contamination in the cladding zone (per cent occluded area <5 %) exhibited signal degradation; however, each of these samples had neighbouring fibres with much higher amounts of contamination. This suggests that large amounts of contamination on a single fibre pair in the array can cause loss of physical contact on less contaminated fibre pairs in the array. Furthermore, impact of contamination on signal performance was most likely observed on outer fibres in the array where contact force is expected to be the lowest [12].

e) Finally, this investigation has led to proposed acceptance criteria for different types of single-mode connectors including PC, APC and APC MPO connectors.

The research has been used as a baseline for the development of IEC 61300-3-35 [4]. Continuing efforts will include development of a cleanliness specification for receptacle type of devices [13, 14].

Annex A
(informative)

The nature of particle redistribution during series of matings/dematings

A.1 General

An attempt was made to study the nature of particle redistribution during series of matings/dematings and how to reduce it. This Annex discusses the experimental data on accumulation of particles near the core during repetitive fibre matings and dematings for 2,5 mm ferrule connectors and MPO connectors. A new metric, centre of particles, R_c was proposed in order to characterize the distribution of particles at the connector endface. Based on our data, R_c decreased during the series of mating/demating cycles, demonstrating movement of particles toward the core. A correlation between the R_c and the charge that resulted from the connector cleaning process was found. The generation of more electrostatic charge during the cleaning process usually demonstrated a stronger effect of the particle movement and accumulation near the core. It was also shown that the effect could be reduced by application of ionized air or by a fluid cleaning instead of dry cleaning process, both methods neutralizing the electrostatic charge at the connector endface.

A.2 Accumulation of particles near the core during repetitive fibre matings and de-matings for 2,5 mm ferrule connectors

During repetitive connector mating and de-mating cycles, dust particles can accumulate and re-distribute at the connector as shown in Figure 9, Figure 10 and Figure 11. One of the potential mechanisms responsible for the particle accumulation, re-distribution and their movement in the core area is the force from electrostatic charge. This phenomenon can cause fibres, which on initial inspection may appear to have a clear core that is acceptable for use, to have particles migrate to the core after repeated mating/de-mating operations. The experimental methodology to study the nature of this phenomenon is shown in Figure A.1. Arizona test dust was applied to a clean sample (test connector) fibre. The sample was mated with a reference connector. Images were recorded using an optical microscope at 100×, 200×, and 400× magnifications. The sample and reference connectors were de-mated and mated for a total of five cycles with the same set of images recorded between each mating and de-mating cycle.

Alternatively, an air ionizer was used in some experiments. In experiments with the air ionizer, the connector was exposed to ionized air for 30 – 120 s after the cleaning process and then a dust was applied.

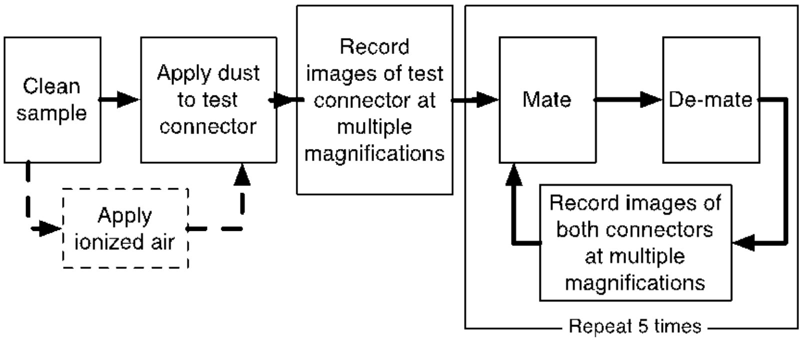


Figure A.1 – Experimental methodology block diagram

Before the dust application, the connector endface was cleaned using a dry cleaning or a cleaning solvent. Two types of commercially available dry cleaning cartridges (type 1 and type 2) as well as fibre wipes were used. In some experiments fibre wipes with cleaning solvent were applied. Two different types of fibre connector cleaning fluids were evaluated. Both types of cleaning solvents were based on a hydrofluorocarbon and alcohol blend families. The connector adaptors were cleaned before each experiment using the cleaning swabs.

A Faraday cup was used to measure the charge on a fibre tip after the cleaning process [15].

The dust particle distribution on the connector endfaces can be described by a single parameter R_c which is called the centre of particles. The concept is similar to the centre of mass or gravity used to describe the point of the equivalent resultant gravitational force for an object. Therefore, the particle centre position can be defined as:

$$R_\mathrm{c} = \frac{\sum_0^N r_i a_i}{\sum_0^N a_i} \tag{A.1}$$

where

r_i and a_i are the i^th particle radial position and area, respectively;

N is the total number of particles included in the R_c calculation.

Based on our data, R_c decreased during the series of mating/demating cycles, demonstrating movement of particles toward the core [15].

The relationship between the particle centre moving speed and the charge is shown in Figure A.2. A correlation between the R_c and the charge that resulted from the connector cleaning process was found. The generation of more electrostatic charge during the cleaning process usually demonstrated a stronger effect of the particle movement and accumulation near the core. It was also shown that the effect could be reduced by application of ionized air or by a fluid cleaning instead of dry cleaning process, both methods neutralizing the electrostatic charge at the connector endface. The application of cleaning fluid resulted in the reduction of particle centre movement speed by at least a factor of three. In experiments with another cleaning fluid a reduction of particle centre movement speed by a factor of eleven was achieved. Clearly, these significant reductions in particle accumulation by applying ionized air and/or using cleaning fluids were good techniques for minimizing movement of particles during the service life of connectors in optical systems.

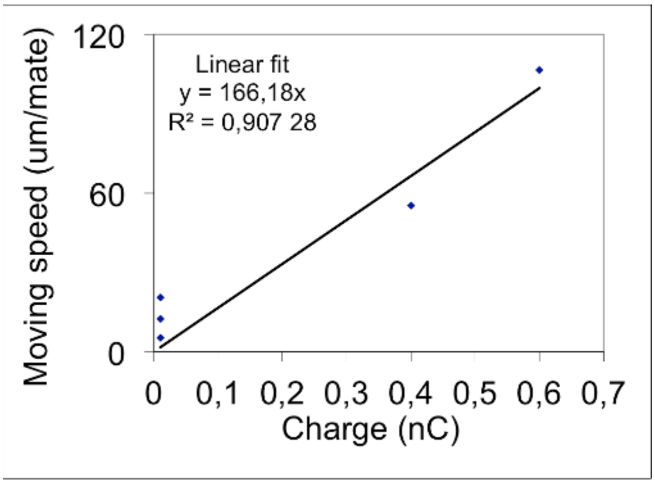
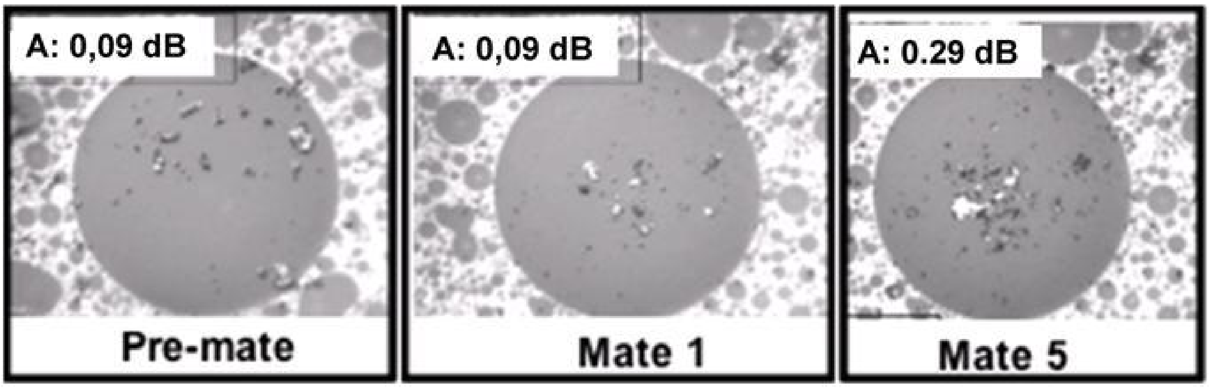


Figure A.2 – Relationship between the particle centre moving speed and the charge

A.3 Redistribution of particles during series of repetitive matings/de-matings for MPO connectors

The particle redistribution at the connector endface can cause significant impact on A and RL. Figure A.3 shows an example of particle redistribution observed on a sample MPO connector. There is significant contamination that has been redistributed in the core and cladding areas after 5 matings/de-matings.



NOTE 1 Far left figure shows contaminated connector endface before mating.

NOTE 2 Middle figure shows connector after first mating, A = 0,09 dB.

NOTE 3 Far right figure shows fifth mating, A = 0,29 dB.

Figure A.3 – Particle migration and the A signal degradation of MPO connector (channel 2) after series of matings/de-matings

The evolution of R_c for an MPO connector during a series of 5 repetitive matings/de-matings is shown in Figure A.4. Based on collected data, R_c decreased during the series of mating/de-mating cycles, demonstrating movement of particles toward the core for all channels. The mechanism of particle re-distribution at MT connector endface during a series of repetitive matings/de-matings requires further investigation.

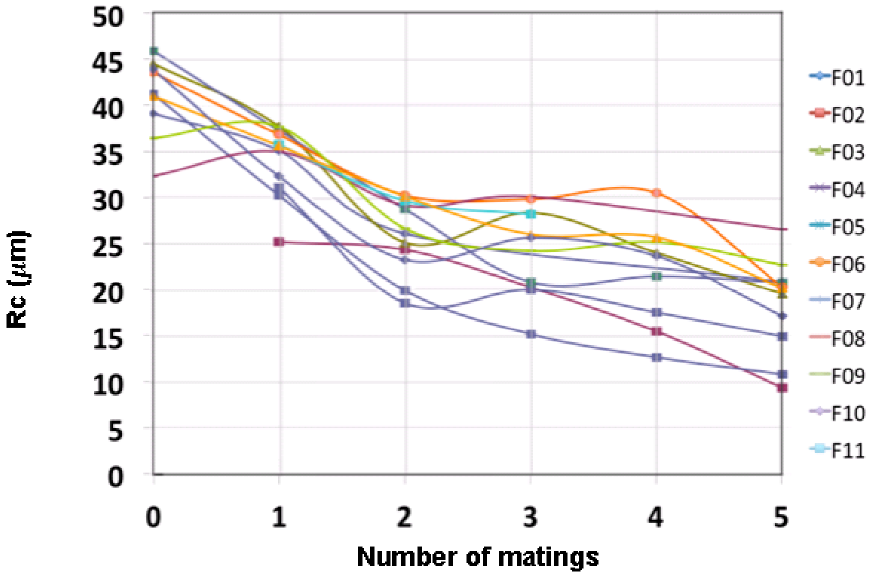


Figure A.4 – Evolution of particle centre position for channel 1-11 of an MPO connector pair

Overall the level of contamination of the connector endface increased after 5 mating/de-matings. It can be caused by particle migration from the cladding and ferrule areas due to ESD effects. Another potential mechanism is the crushing of large particles (with diameter >5 um) which are then spread across the connector endface. This phenomenon creates a risk of blocking the core area and catastrophic signal degradation.

A.4 Attenuation changes and separation factor

To correlate the measured attenuation with the particle area, the property of Gaussian intensity distribution of the fundamental fibre mode and the parameter of GWPOA is used. To further count the fact that the particles can have a combination of vertical or horizontal splits during connection for attenuation measurement and separation of the DUT and reference connectors' endfaces for inspection, a separation factor, s, which takes into consideration this particle splitting effect is introduced [11]. Figure A.5 shows the measured and calculated delta A versus GWPOA.

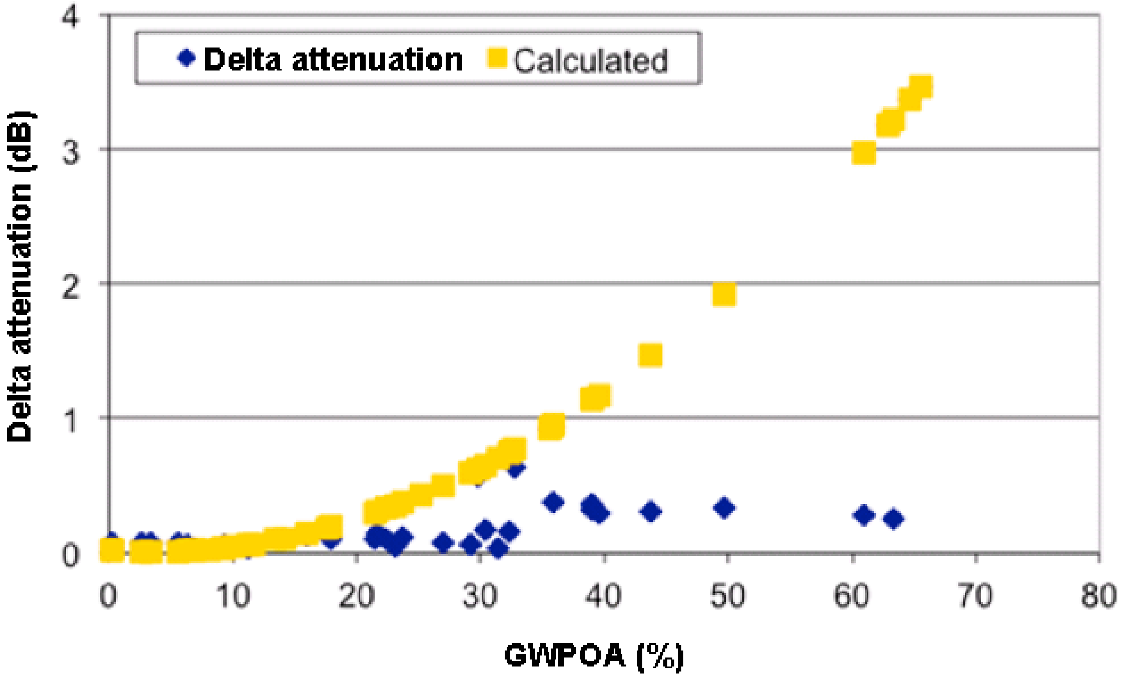


Figure A.5 – Measured and calculated delta attenuation as functions of GWPOA

There are 4 out of 45 data points with differences of more than 1 dB, and 6 of them between 0,5 dB and 1 dB with a higher GWPOA value from endface particle size measurement. The possible reasons for the large GWPOA are

a) particles move to the centre after the connection pairs are separated into DUT and reference connectors for inspection,

b) particles are very thin or transparent and allow light to pass through,

c) error for centre estimation.

Finally, an inspection criteria matrix is proposed for SM angled physical contact MT connectors [11]. All connector pairs with signal degradation due to contamination would have failed the proposed criteria for at least one of the mated fibre pairs in the array. It is strongly recommended that all removable particles be cleaned and the connector endface thoroughly inspected before use in order to prevent the degradation of optical signal due to a dust migration during multiple matings/de-matings.

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