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Development of Cleanliness Specification for Single - Mode Connectors

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Abstract

This paper summarizes research performed by the NEMI (National Electronics Manufacturing Initiative) Fiber Optic Signal Performance Project team. The project focused on the development of a cleanliness specification for single mode connectors. The influence of two grades of Arizona road dust on optical performance of single mode fibers is investigated.

The researchers record insertion loss, return loss, and fiber optic microscope images for each connector pair before and after contamination. Interferometry data including radius of curvature, apex offset and fiber undercut are also recorded for each test and reference connector. The changes of insertion loss and return loss as a function of distance of the closest particle from the core are investigated. Results of mathematical modeling of contaminated fibers are correlated with experimental data. The results show that contamination particles can prevent direct physical contact creating an air gap between two end-faces.

The area encompassed by a 25 µm diameter from the core is identified as critical. Particles located in this area, even if not directly on the core, result in an increase in insertion loss (a delta of 0.5 to 1.8 dB) and an increase in reflectance (a delta of 10 to 44 dB). Dust particles of 1-25 µm result in an air gap of up to 200 nm.

The NEMI team is collaborating with the International Electrotechnical Committee (IEC), Telecommunications Industry Association (TIA) and IPC (Optoelectronic Assembly and Packaging Technology). Specifications will be jointly submitted to IEC SC86B Working Group 6 (interconnecting devices) for incorporation with IEC 61300-3-35, and to IPC as a draft of the IPC-8497-01 standard. In addition, the project will collaborate with TIA and IPC on the development of cleaning methods and contamination assessment for multi-level optical assemblies.

Introduction

Fiber optic connector end-face cleaning is recognized as a necessity for optimal signal performance. The degree of cleanliness; however, is still open to debate. Currently there is no industry standard for fiber optic end-face cleanliness. This impacts the cost of manufacturing products that use fiber optics. End-customers are not in agreement with suppliers on the level of cleanliness required for fiber optic end-faces. Because of this, unnecessary cleaning may be done even though it does not impact signal performance.

Connector cleanliness has a significant impact on in-process yield and cause of returns. The NEMI Fiber Optic Signal Performance Team believed that there was a lack of scientific backing for many of the standards used by companies in the industry. A series of experiments was designed in order to evaluate the impact that contamination has on fiber optic signal performance. The analysis of experimental results was paired with mathematical modeling to solidify the work.

To our knowledge, three standards bodies are currently working on fiber optic end-face cleaning standards: IPC (Optoelectronic Assembly and Packaging Technology), IEC (International Electrotechnical Committee), and TIA (Telecommunications Industry Association). The work presented in this paper is being used as a basis for the draft IPC cleanliness standard. It has also been reviewed by the IEC and TIA committees that are developing their own respective standards.

The NEMI team already investigated the influence of polishing scratches and carbon particles on the optical signal performance of SC UPC connectors.[1-3] It was shown that polishing scratches and scratches made during connector cleaning, outside the fiber MFD (mode field diameter), have no impact on IL, (insertion loss), and RL, (return loss), of the mated optical connectors. Scratches within the MFD that are of two µm wide, or less, have no impact on IL. Any IL change observed is within the measurement uncertainty of the test equipment. Scratches within the fiber MFD can degrade the RL of mated connectors. In addition, particles on the core result in catastrophic failures. The presence of particles on the ferrule does not show any degradation in optical performance. Future studies are required to investigate the effects of particles when they are located at the cladding and close to the core area. Studies are also needed to focus on particle size, quantity, and material composition.

Experimental Methodology

The attempt was made to correlate changes in optical performance (IL, RL) with fiber optic images of corresponding connectors. Changes in optical performance were achieved through the application of contamination. Images revealed the number of particles, their size and their location at the connector end-faces. More than seventy cables, the DUTs, (device under the test), with SC/SC simplex connectors were used for the experiment. Block diagrams of the experiment are shown in Figure 1 and Figure 2. All DUTs and reference connectors were initially inspected and cleaned using a cleaning cassette, (Cletop or Optipop). End-face images were saved using the Westover Scientific Probe 1 fiber optic scope and FiberCheck software. Interferometry data including radius of curvature, apex offset and fiber undercut were recorded for each DUT and reference connector based on the Norland interferometer, model number NC-3000.

After initial measurements and cleaning, each DUT was mated and demated with the reference connector at least ten times. IL and RL data were recorded after each mating and demating cycle. The cleanliness of both the DUT and reference connector was controlled after each mating and demating operation using the fiber optic microscope. End-face images were saved after the first, fifth and the tenth matings. IL and RL were measured based on the Agilent 8164A measurement system. A block diagram for RL measurements is shown in Figure 3. IL was measured based on the standard experimental set up as described in.[4]

After clean measurements and images were recorded, Arizona road dust was manually applied to the cleaned end-face of the DUT. Two grades of Arizona Road Dust were used for the experiment: 1-5 um (ultra-fine) and 6-25 um (fine).[5] Some samples were contaminated in the core area and some samples were contaminated in the cladding and ferrule areas. In the case of contamination in the cladding and ferrule areas, we tried to keep the core zone free from contamination. Each DUT was inspected after contamination and another image was saved. The contaminated DUT was mated with a clean reference connector. IL and RL data were recorded. After demating, the images of both end-faces, (DUT and reference connector), were saved. Each DUT and reference connector was mated and demated five times. After each mating, IL and RL measurements were taken and fiber end-face images were saved for both connectors.

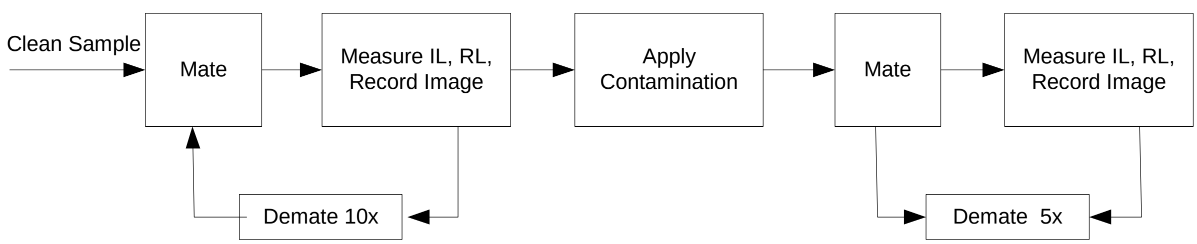


Figure 1 - Block Diagram of Design of Experiment

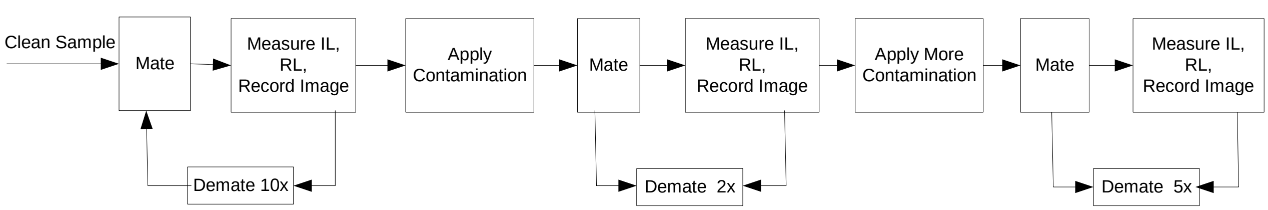


Figure 2 - Block Diagram of Alternate Design of Experiment

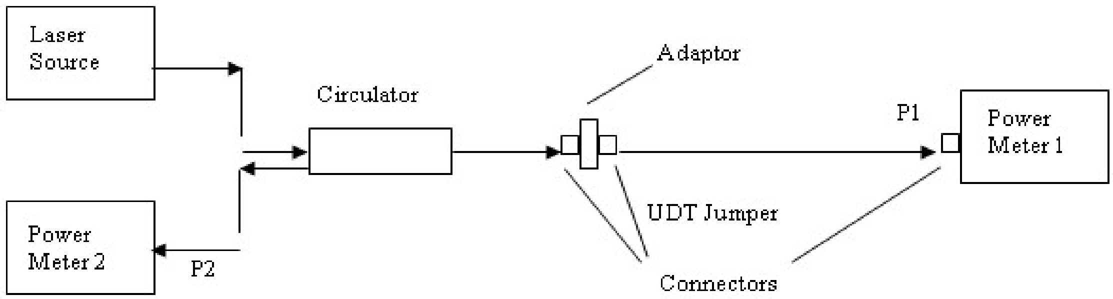


Figure 3 - RL Block Diagram

Note: The DUT is terminated by mandrel wrapping during the return loss test

Analysis of the end-face images was performed using Westover Scientific FiberChek software and VisionGauge software Version 6.88. The FiberChek software highlights contamination, pits, or cracks with color imaging. Different colors are user selectable and they highlight the different types of defects as well as user-defined zones.

The IL and RL data analysis was achieved using Minitab version 14 statistical software. The NEMI team used two different approaches for data analysis. The first approach required calculation of the standard deviations for IL and RL based on the repeatability test, (ten matings/dematings with the clean connector). For each individual case of contaminated connector, delta IL and delta RL were calculated as follows:

- Delta IL=Absolute value (IL clean-IL contaminated)
- Delta RL= Absolute value (RL clean-RL contaminated)

Next, the changes were compared to three standard deviations of IL and RL for the clean connector. The pass criteria were achieved when both delta IL and delta RL were within three standard deviations of IL and RL.

The second approach was based on hypothesis testing.[6] When comparing means between two samples, the null hypothesis is that there is no difference between the two means. In our case, the null hypothesis was that contamination did not impact the optical performance: IL clean was equal to IL contaminated and RL clean was equal to RL contaminated. The alternate hypothesis was that there was a difference between the population means, in other words, that IL and RL were different for the group of clean samples when compared to the contaminated samples. In our case, the clean group contains the IL or RL data for ten mating and demating operations of the specific connector. The contaminated group had the data set for IL or RL measurements for 5 mating/de-mating operations. If contamination was applied twice, as shown in Figure 2, two subgroups of contaminated samples were defined. The number of data points in the each group can be defined by the number of mating and demating operations. The following equations can be used in order to make the mean comparison and define if there is a significant difference between the group of clean and contaminated samples:

$$t_{Calc} = \frac{\overline{X}_1 - \overline{X}_2}{s_{Pooled}\sqrt{1/n_1 + 1/n_2}}$$

Where: X1and X2 are the means for the group of the clean and contaminated samples
n1 is the number of the data points (matings and dematings) for the clean group
n2 is the number of the data points (matings and dematings) for the contaminated group
S_{pooled} is the pooled sample standard deviation (consists of taking the square root of weighted average of the variances)

The null hypothesis is rejected if $t_{calc} < t_{df,\alpha}$ or $t_{calc} > t_{df,\,1-\alpha}$. Degrees of freedom (d.f.) = $n_1 + n_2 - 2$. The probability that the null hypothesis is rejected when it is true is denoted by α. Usually α=0.05. In this study, our team automated these calculations using the Minitab 2-T test.

The 2-T test allows the comparison of two means. In order to compare multiple means, the Minitab ANOVA test was used. In this test, the null hypothesis is that the means of all test groups, (clean, contaminated 1 and contaminated 2), are the same. The alternate hypothesis is that at least one mean of the contaminated group is different from the mean of the clean group. Acceptance or rejection of the null hypothesis can be made based on the significance level of the P-value. If P is greater than 0.05, the null hypothesis is accepted. If P is less than 0.05 the null hypothesis is rejected.

Experimental Data and Analysis

A typical image of a clean connector is shown in Figure 4. Based on previous data, the following zone system is included in the analysis: zone 1a, with a diameter of the 25 µm; zone 1b within the cladding area; the epoxy ring zone; zone 2 within the contact area; and zone 3, the remaining ferrule. The zones are shown on a clean connector in. Our previous study showed that loose contamination was transferred from a contaminated connector to an initially clean connector when the two are mated together.

The gradual contamination of a connector during test is shown in Figures 5 - 8. The experiment on this connector was performed as per the block diagram shown in Figure 2. The clean sample, 57A, has IL=0.25 dB+/-0.023 dB and RL=50+/-1 dB. The standard deviations for IL, (0.023dB), and for RL, (1dB), were calculated based on the IL and RL measurements for 10 mating and demating operations. The sample was contaminated as shown in Figure 5. Zone 1a was free of contamination. A small amount of contamination was randomly distributed in zones 1b, 2, and 3. After the contamination was applied, IL was 0.26 dB and RL was 51 dB. IL and RL measurements were compared for each individual contaminated connector. Delta IL was 0.01 and delta RL was 1 dB. The changes in IL and RL were within three standard deviations of IL and RL.

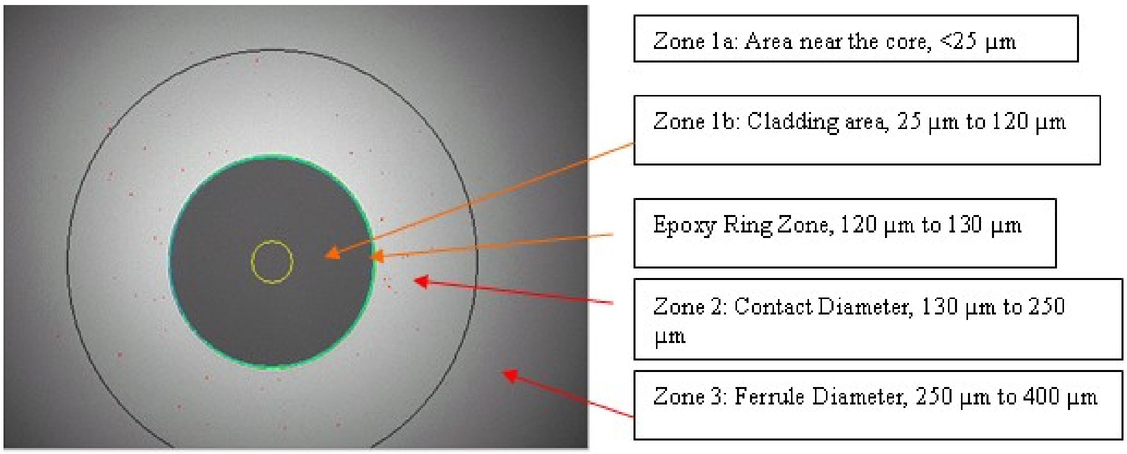
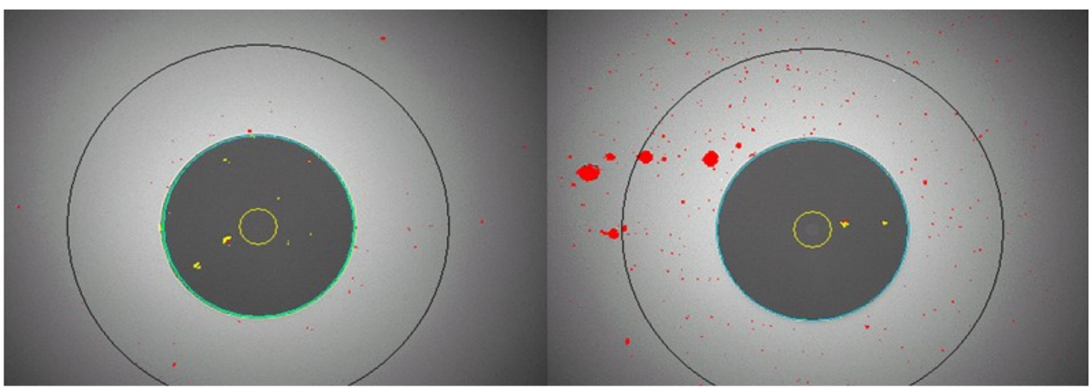


Figure 4 - Image Analysis of a Clean Connector using FiberChek Software



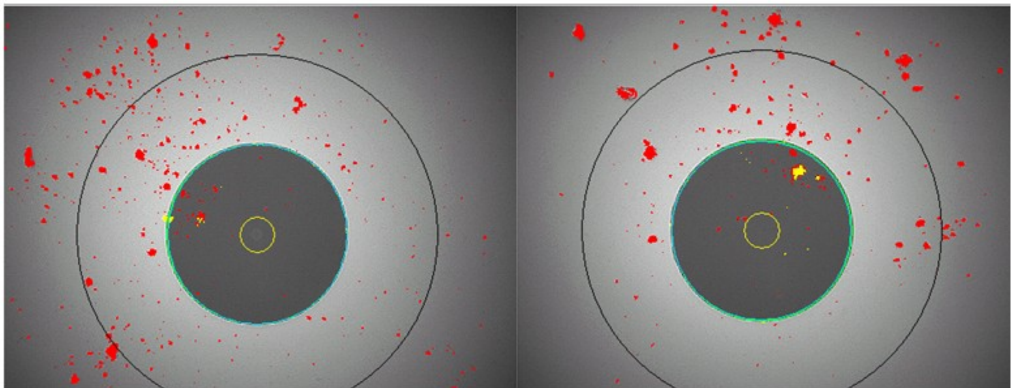
57A – 1st Mating **Reference Cable T17**

Figure 5 - Fiber optic microscope images of the DUT (left) and the reference fiber (right) after contamination and the first mating. The initial IL= 0.25dB, and the initial RL=50dB. The IL after contamination=0.26dB and RL after contamination=51dB. Three standard deviations of IL=0.07dB, three standard deviations of RL=3dB. The changes of IL and RL are within three standard deviations of the IL and RL for the clean fiber.

Figure 6 shows the same connector with slightly increased contamination. The contamination is still distributed in the cladding and ferrule zones. Zone 1a remains clean. Several particles are located at the border of zone 1a on the reference fiber, T17. Delta IL=0.01dB and delta RL=2dB. Both were within three standard deviations of the clean fiber. No significant changes in optical performance were identified.

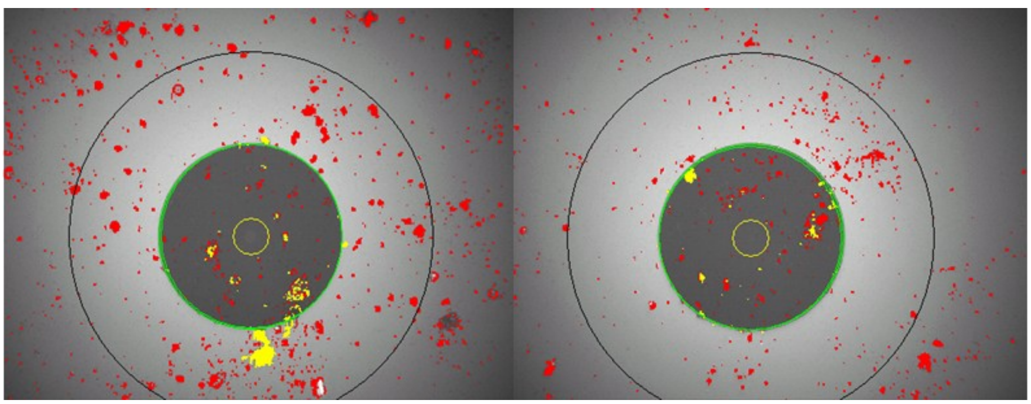
The level of the contamination was increased again as shown in Figure 7. It resulted in an increase in IL of up to 0.32 dB. Delta IL was equal to three standard deviations of the clean fiber; therefore, the DUT failed the pass/fail criteria for IL. The RL changes were within three standard deviations of the clean fiber.

Contaminated connector 57A was mated with the reference connector T17 ten times. Eventually some contamination in the core zone was identified as seen in Figure 8.



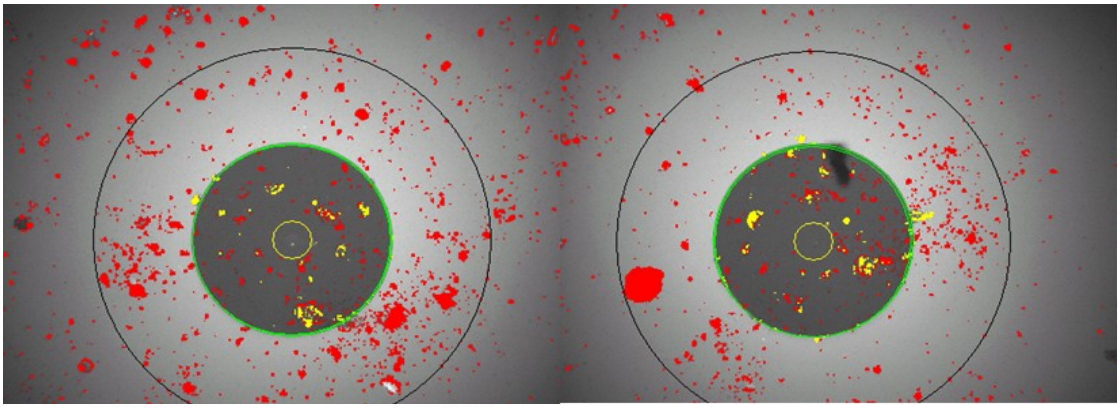
57A 2nd Dust Application **Reference Cable T17**

Figure 6 - Fiber optic microscope images of the DUT (left) and the reference fiber (right) after the second contamination. Initial IL= 0.25dB, Initial RL=50dB. After contamination, IL=0.26dB and RL =52dB. Three standard deviations of IL=0.07dB and of RL=3 dB. The changes in IL and RL are within three standard deviations of IL and RL for the clean fiber



57A – 3rd Dust Application **Reference Cable T17**

Figure 7 - Fiber optic microscope images of DUT, (left), and the reference fiber, (right), after the second mating of the third contamination. The initial IL= 0.25dB and RL=50dB. IL after contamination=0.32dB and RL =54dB. Three standard deviations of IL=0.07dB and RL=3dB. Delta IL was equal to the standard deviation of the clean fiber. The change in RL was within three standard deviations of clean value. The sample failed Pass/Fail criteria due to the changes in IL



57A -10th Mating After 3rd Dust App. Reference Cable T17

Figure 8 - The fiberscopic images of DUT (left) and the reference fiber (right) after the third of contamination, 10 mating. Initial IL= 0.25dB and RL=50dB. After contamination, IL=0.39dB and RL =47dB. Three standard deviations of IL=0.07dB and RL=3dB. The sample failed the pass/fail criteria for both IL and RL.

Delta IL was 0.14 dB which was greater than three standard deviations of the clean IL. Delta RL was 3 dB which was equal to three standard deviations of the clean RL. The sample failed the pass/fail criteria for both IL and RL.

Based on the presented data, contamination of zone 1a resulted in degradation in the optical performance. Contamination of the other zones did not change the optical performance.

The data for the sample 57A was also analyzed using the 2-T-test. The 2-T-test was to compare the means of IL and RL for specific clean and contaminated fibers. In this case, the group of clean fibers contains IL and RL measurements for ten mating and demating operations. The contaminated group contains data for IL and RL of the same sample after the contamination. If the sample was gradually contaminated as described in Figure 2, the group of contaminated samples can be divided into two subgroups according to the level of the contamination. The number of data points in each subgroup was defined as the number of the mating and demating operations. If the clean sample was mated and demated ten times, the number of data points in the clean group equals ten. In the case of five mating and demating operations of the contaminated fiber, the number of the data points in the contaminated group is five. The normality test for clean and contaminated samples was performed. The results are shown in Figure 9.

The coefficient P, which was calculated using Minitab-14 software, was 0.729 for the group of clean samples which had ten mating/demating cycles. P was 0.213 for the group of contaminated samples. Both distributions were normal based on P being greater than 0.05.[6]

The 2-T test was performed in order to compare the mean values of the clean group with those of the contaminated group. In this case the clean group has 10 data points since 10 mating/dematings cycles were performed. The contaminated group can be divided in to two subgroups – subgroup 1 and subgroup 2. Subgroup 1 had only two data points because only two mating and demating cycles were performed for the level of contamination, (shown in Figure 5 and Figure 6). Subgroup 2 had ten data points because ten mating and demating cycles were performed for the level of the contamination shown in Figure 7 and Figure 8. Based on the data, the mean of the IL of the clean samples is 0.25 dB and that of the contaminated samples, subgroup 1, was 0.27dB. Subgroup 2 had an IL mean of 0.36dB. The question of concern is whether there is a statistically significant difference between the clean group and contaminated samples, (subgroup 1 or subgroup 2). The data for the 2-T-sample test is presented in Table 1.

There was a 95 % confidence level that there was no difference between the IL for the clean group and the contaminated group (subgroup1). The significance level was 0.21 for IL data and 0.051 for RL data and was exceeded 0.05. For subgroup 2 the significance level was 0 for the IL data and 0.039 for RL data. In the both cases P is less than 0.05. The null hypothesis is rejected and the alternate hypothesis is accepted. There is a statistical difference between mean of IL for the clean group and the contaminated group (subgroup 2). Similar results were achieved with the ANOVA test which compared the IL means of all three groups, (clean, subgroup1 contaminated and subgroup 2), at the same time. The box-plot graph for IL data is shown in Figure 10.

Based on the 2-T-test there was no degradation of IL or RL measurements in subgroup1, (see Figure 5 and 6), when the contamination was distributed in the cladding areas or ferrule. At the same time, the contamination in the core zone resulted in the degradation of IL and RL for subgroup 2 (Figure 7 and Figure 8).

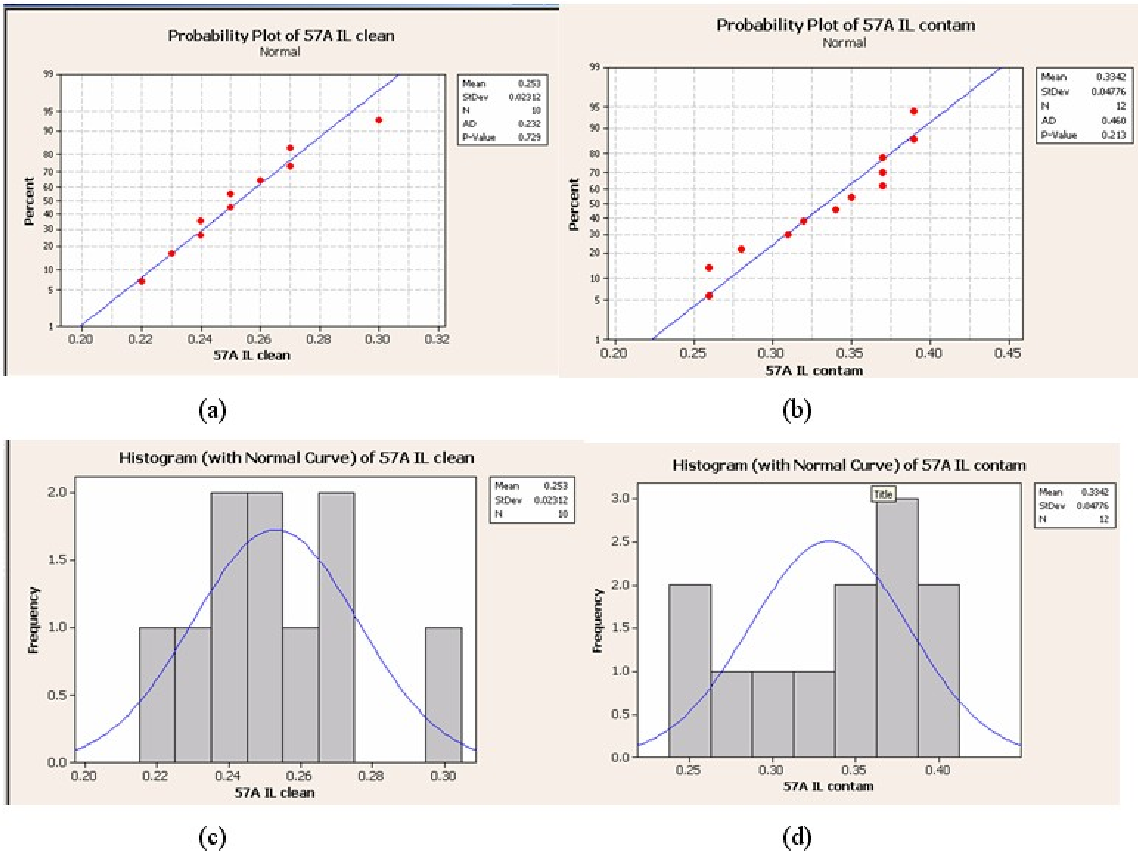


Figure 9 - Statistical Analysis - Normality Test for IL for Clean (a, c) and Contaminated (b,d) samples. P= 0.729 for Clean Group and P=0.213 for Contaminated Group. P>0.05 Means that the Distribution is Normal (95% Confidence Level)

Table 1 - Summary of the 2-T-Test Data

		Mean	**Std. deviation**	**T-test P-value**	**Image Reference**
Sample 57A					
IL	*Clean*	*0.25*	*0.023*	-	
	Subgroup 1	0.27	0.012	0.210	Figure 5, 6
	subgroup 2	0.36	0.029	0	Figure 7, 8
RL	Clean	50.2	1.03	-	
	subgroup 1	51.3	0.58	0.051	Figure 5, 6
	subgroup 2	48.0	2.60	0.039	Figure 7, 8
Sample 60A					
IL	*Clean*	*0.08*	*0.007*	-	
	subgroup 1	0.39	0.269	0.180	
	subgroup 2	0.60	0.026	0	Figure 13
RL	Clean	53.0	1.15	-	
	subgroup 1	54.0	1.00	0.239	
	subgroup 2	34.3	11.7	0.001	Figure 13
Sample 62B					
IL	*Clean*	*0.5*	*0.016*	-	
	contaminated	0.48	0.024	0.099	Figure 10,11
RL	Clean	53.0	1.05	-	
	contaminated	53.2	0.84	0.698	Figure 10, 11

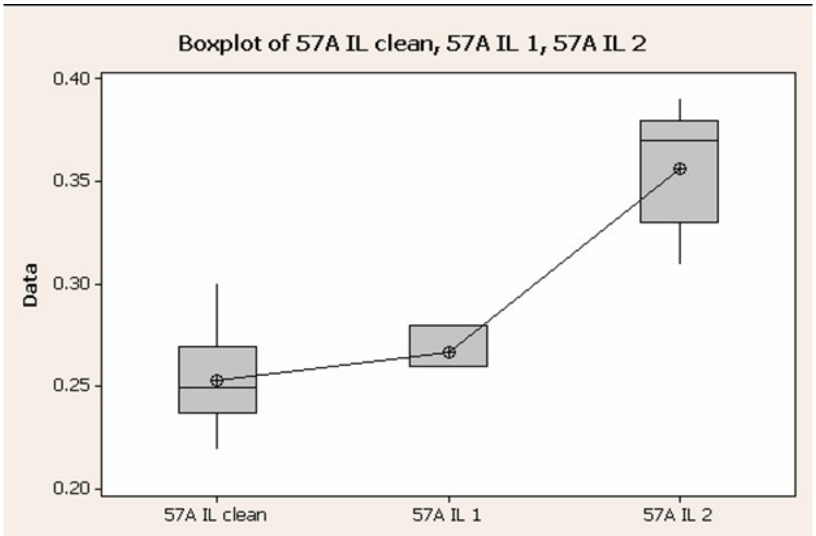


Figure 10 - Box-plot Graph for the IL of the Sample 57A: Clean (57A clean) and Contaminated, Subgroup 1 (57A IL 1) and Subgroup 2 (57A IL 2)

Figure 10 shows both the DUT and the source cable of the second mating of sample 62B. The insertion loss of the clean connector pair was 0.50 dB and the RL was 53 dB. The IL of the contaminated mating, shown in Figure 10, was 0.51 dB and the RL was 52 dB. Both the IL and RL were within three standard deviations of the clean sample; therefore, there is not a statistically significant change in the measurements of the contaminated connector over the clean connector. This result coincides with the theory that contamination outside of the contact diameter does not impact signal performance, provided an air gap is not present. Although there is a large particle present in the ferrule region, it is outside of the contact diameter so the chance of creating an air gap is reduced. There is no visible contamination in the MFD. Contamination is not seen until the edge of the cladding layer.

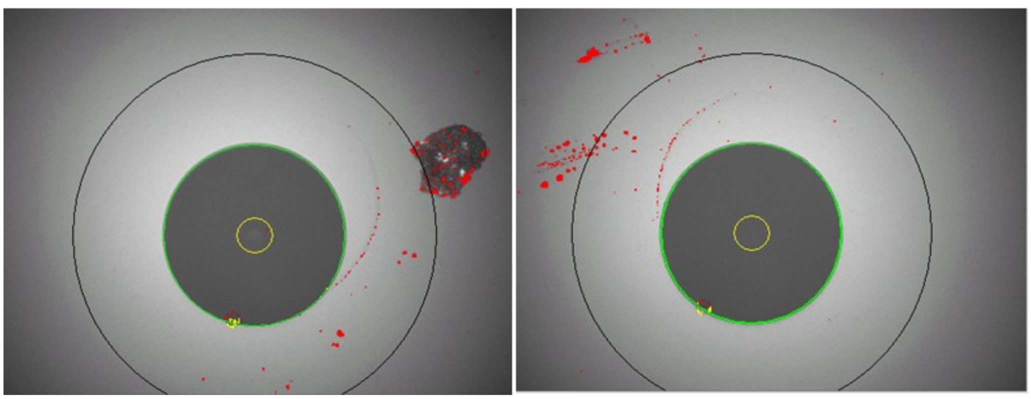


Figure 10 – Sample 62B Second Mating

Fiber optic microscope images of the DUT (left) and the reference connector (right), after the second mating. Initial IL=0.50dB, initial RL=53dB, IL after contamination=0.51dB, and RL after contamination=52dB. Three standard deviations of IL=0.047dB and three standard deviations of RL=3dB. The changes of IL, RL are within three standard deviations of the IL and RL for the clean fiber.

Figure 11 shows the DUT and source cable after the fifth mating. The contamination is similar to the second mating. The IL after contamination was 0.45 dB and the RL after contamination was 54 dB. Both samples were still within three times the standard deviation of the clean connector pair. The changes in IL and RL are due to experimental variation and are not significant.

The clean samples had P= 0.132 and the contaminated samples had P = 0.74. Since P is greater than 0.05, we can say with 95% confidence that the samples are both normal. The 2-T-test can be performed on this sample since it is normal. The 2-T-test gives an IL P value of 0.099 and an RL P value of 0.698 (see Table 1). Since both P values are greater than 0.05, we can say with 95% confidence that there is no statistical change in the samples.

Sample 62B demonstrates a case where there is significant contamination in the ferrule area, some contamination in the cladding and no contamination in the MFD. Both statistical methods of analysis show that there is no statistically significant change in the values of IL and RL from the clean connector to the contaminated connector.

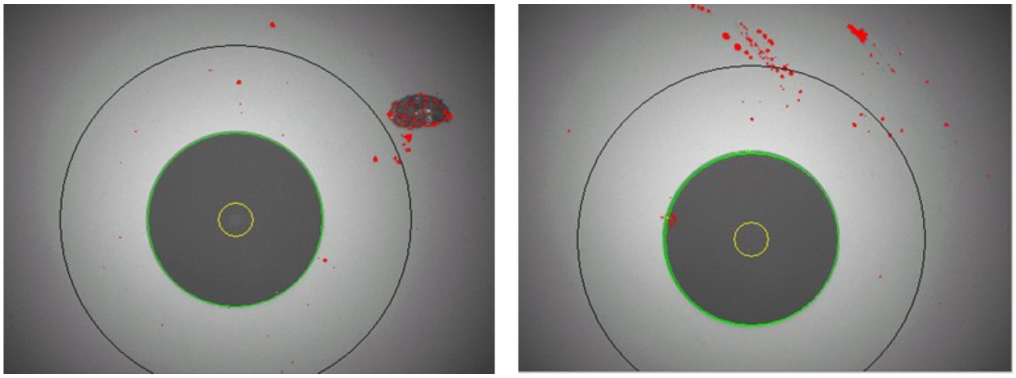
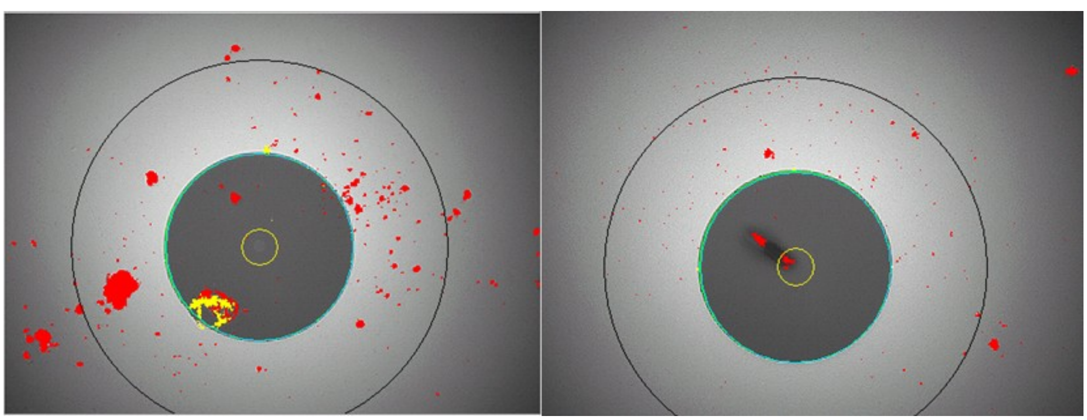


Figure 11 - Sample 62B Fifth Mating

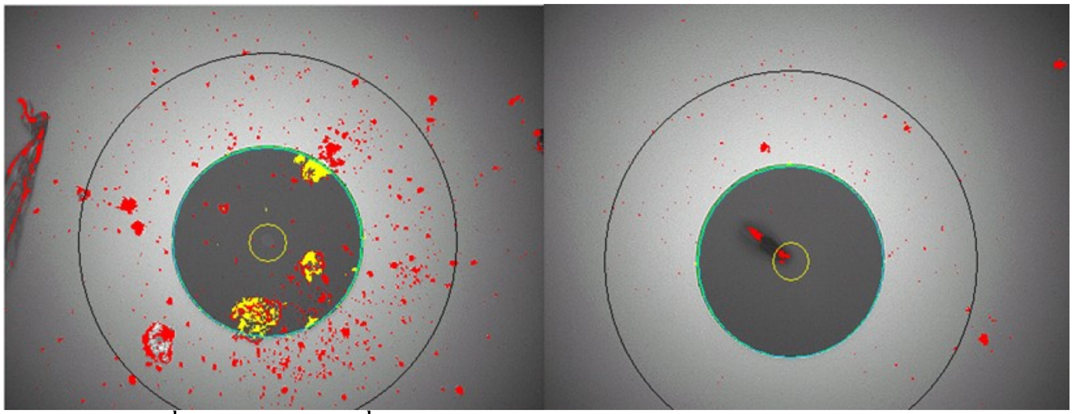
Fiber optic microscope images of the DUT (left) and the reference connector (right), after the second mating. Initial IL=0.50dB, initial RL=53dB, IL after contamination=0.45dB, and RL after contamination=54dB. Three standard deviations of IL=0.047dB and three standard deviations of RL=3dB. The changes of IL and RL are within three standard deviations of IL and RL for the clean fiber.

The reference cable for sample 60A had contamination in zone 1a as shown in Figure 12. The IL increased more than eight times. The RL changes were within three standard deviations for RL of the clean fiber. The introduction of particle clusters in the cladding area resulted in the degradation of the RL as shown in Figure 13. RL dropped from 53dB down to 24 dB. The IL increased significantly compared to the clean fiber. The coefficient P was zero based on the 2-T-test for the sample 60A, showing a significant difference between optical performance of clean and contaminated samples. Finally, sample 60A was cleaned after ten mating and demating cycles. The large clusters were removed by the cleaning process. RL increased up to 52 dB. IL was still high, (0.41 dB), due some non-removable contamination in the core area as shown in Figure 14.



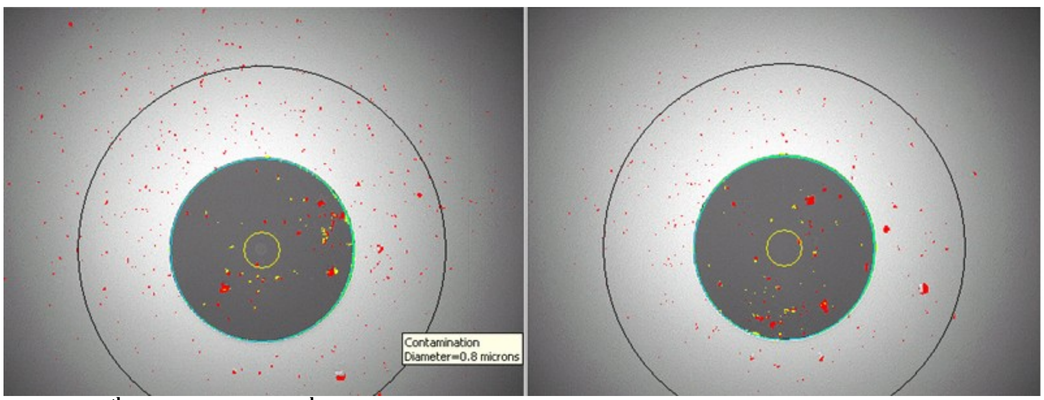
60A – 3rd Dust Application **Reference Cable T19**

Figure 12 - Fiber Optic Microscope Images of DUT (left) and the Reference Fiber (right) After the First Mating. IL Clean=0.08 dB, RL Clean=53B, IL Contaminated=0.61dB, RL Contaminated=54dB, Three Standard Deviations of IL=0.02 dB, and Three Standard Deviations for RL=3.5dB.



60A 2nd Mating After 3rd Dust App Reference Cable T19

Figure 13 - Fiberscopic images of the DUT (left) and the reference fiber (right) after the second mating. IL clean=0.08 dB, RL clean=53B, IL contaminated=0.63B, and RL contaminated=24 dB. Three standard deviations of IL=0.02 dB, and three standard deviations of RL=3.5dB.



60A 10th Mating after 3rd Dust App. Reference Cable T19

Figure 14 - Fiberscopic images of the DUT (left) and reference fiber (right) after 10 mating/demating cycles followed by the cleaning process. IL clean =0.08 dB, RL clean=53 dB, after contamination and cleaning IL=0.41dB and RL=52 dB. Three standard deviations of IL=0.02 dB and three standard deviations of RL=3.5dB.

Based on the presented experimental data, contamination of the cladding and ferrule did not result in a significant change of IL or RL. Contamination in the core resulted in a significant increase in IL. The contamination of zone 1a and the presence of the clusters of the particles in the cladding area/ ferrule may result in degradation of RL performance of up to 20 or 30 dB. The data analysis based on the comparison of each individual contaminated fiber with three standard deviations of IL and RL data for the clean fiber was in good correlation with the 2-T-test.

Critical Parameters

Based on the presented data, the level of the degradation of the IL and RL depends on the distance of the closest particle from the core, particle size and number of the particles. The NEMI team used VisionGauge software to measure the distance of from the core center to the closest edge of the particle. The dependence of delta IL, which is equal to IL contaminated minus IL clean, is shown in Figure 15.

Particles located in the core area may result in catastrophic degradation of IL. The delta IL was from 0.2dB to 1.8dB. The graph of delta RL as a function of the distance from the center of the core to the edge of the closest particle is shown in Figure 16. 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 10dB to 40dB.

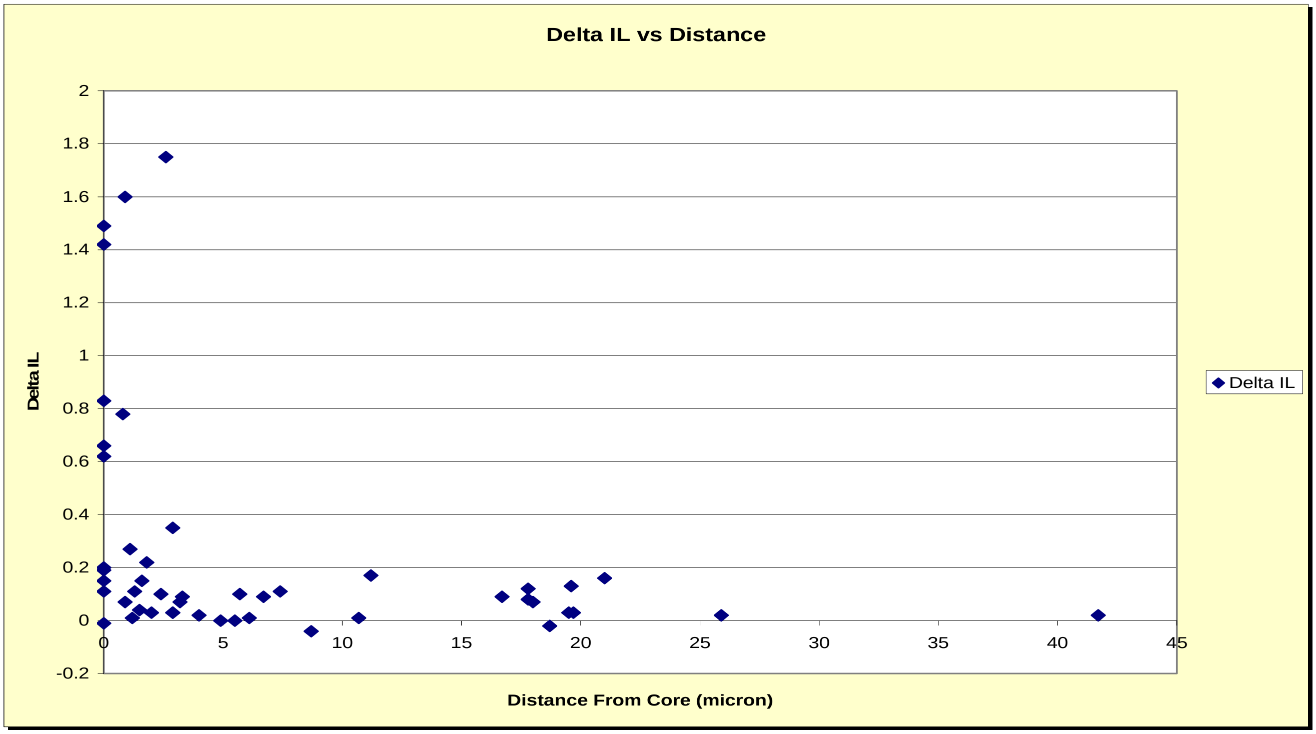


Figure 15 - The Influence of the Particle Location on the IL Performance

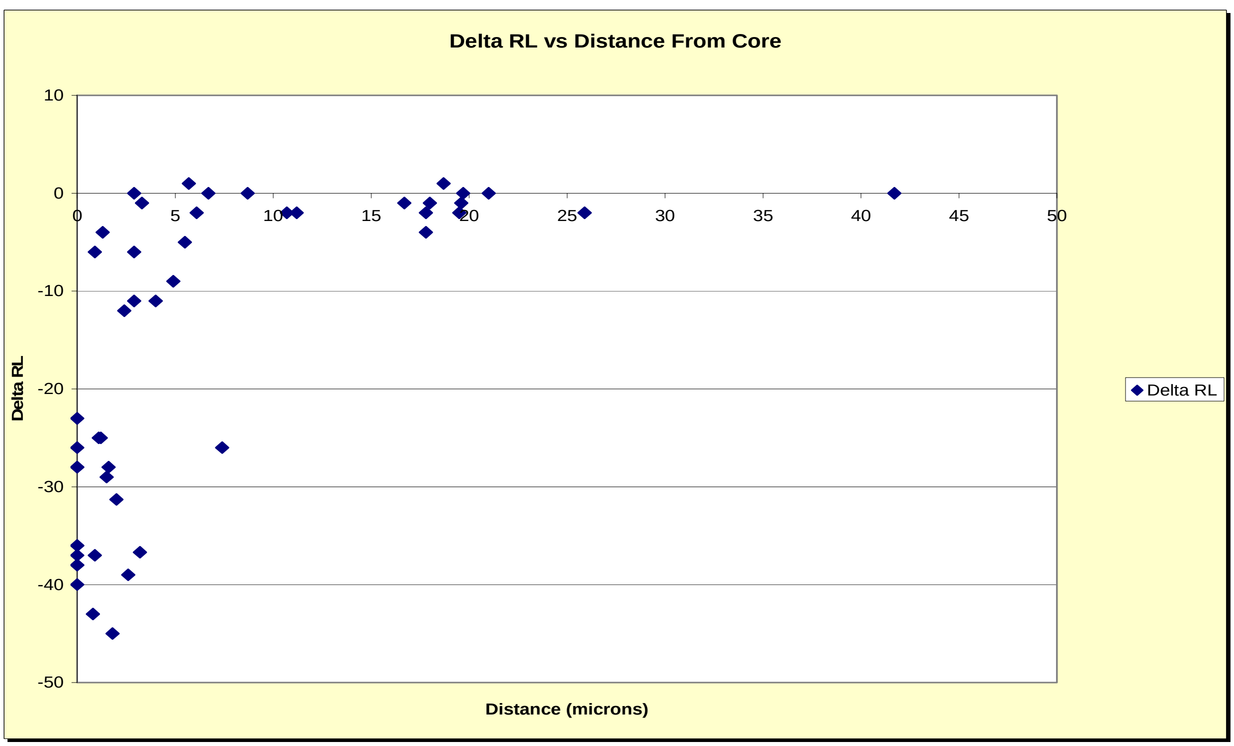


Figure 16 - The Influence of the Particle Position on the RL Degradation

Return Loss Modeling

The model of the RL data for contaminated samples was developed in.[3] The air gap created by trapped particles between the two ferrule end-faces is called the contamination layer and is characterized by the thickness, d_c, and the refractive index, n_c. In the case of contamination with micro-particles that do not block the core of the fiber, n_c=1 and the contamination layer can be characterized by thickness only. A diagram identifying the contamination layer is shown in Figure 17.

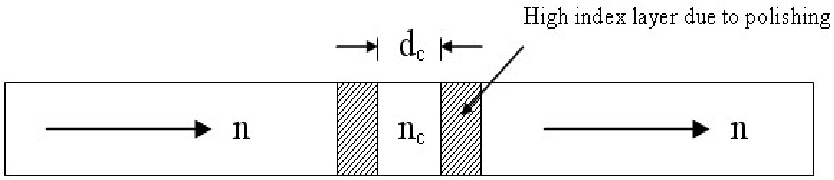


Figure 17 - Connector Model with Contamination Layer

RL was calculated taking into account the effects of undercut, axial compression and apex offset.[7-9] The undercut values ranged from 0 nm to 28 nm. Less than 10 % of all connectors have a protrusion within a range from 3nm to 12 nm. Apex offset of the DUTs was in the range of 3 µm to 45µm. The reference connectors had an undercut of 3 nm to 48 nm and an apex offset of 7µm to 37µm.

An air gap is applied to the model, and its thickness is calculated using the measured RL values. If the experimental and calculated RL match, then we can conclude that the model explains the RL.

Figure 18 shows the calculated RL where the contamination layer, in addition to geometric parameters, is considered and compared with the measured RL. As seen on the plot, the calculated RL values follow the measured RL values closely. The model can explain 52 out of 54 samples (about 96.3%) with a difference between the calculated and measured values of less than 2dB. Only two connectors have a difference of 3 to 4 dB between measured and calculated values. The thickness of the calculated contamination air gap falls within the range of 1 to 200 nm. A histogram of the calculated contaminated layer thickness is shown in Figure 19. Thirty-six out of fifty-four samples, approximately 66.7%, have a calculated air gap thickness of less than 10 nm. Forty-nine out of fifty-four samples, approximately 90.7%, have a calculated air gap thickness of less than 50nm. Based on modeling results, only two samples show the presence of an air gap greater than 150 nm.

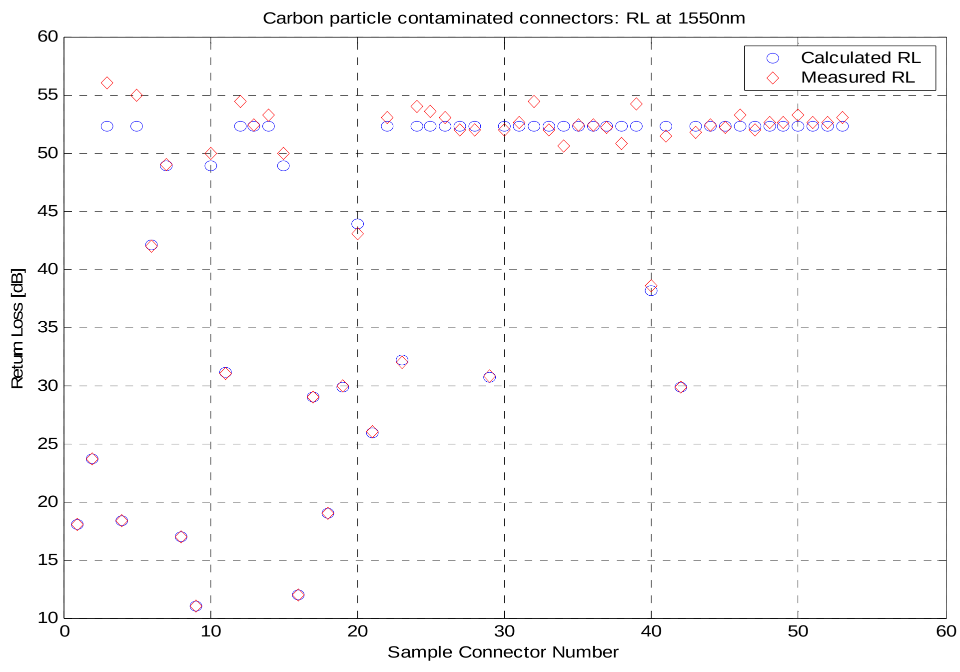


Figure 18 - Measured (diamonds) and Calculated (circles) RL at 1550 nm with an Air Gap Caused by Geometric Factors and Contamination

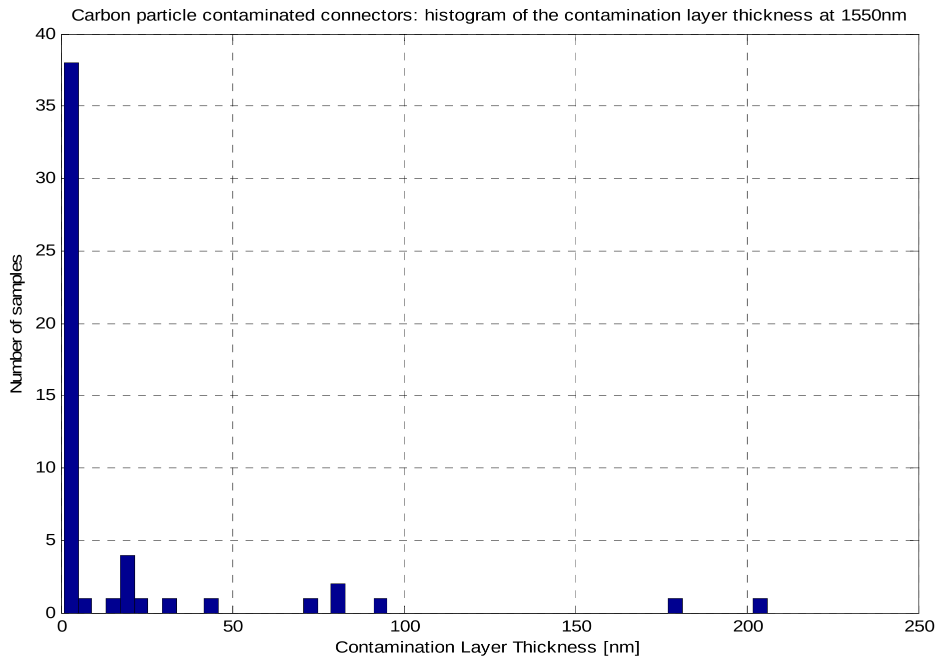


Figure 19 - A Histogram of the Calculated Contamination Layer Thickness at 1550 nm

Based on the experimental and modeling data, the presence of particles can result in an air gap between the DUT and the reference connector causing degradation in RL. The samples with particle contamination in zone 1a as well as clusters of particles demonstrated a catastrophic degradation of the RL as illustrated in Figure 20 and Figure 21.

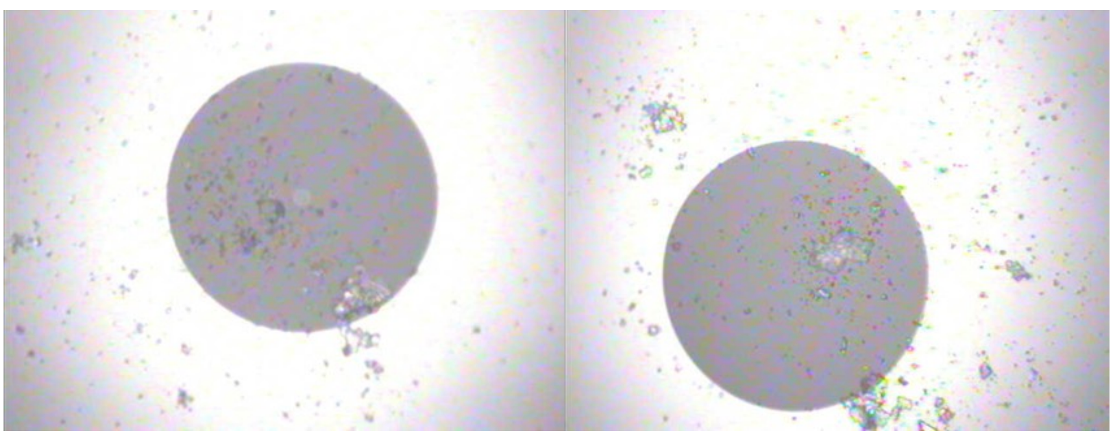


Figure 20 - Fiber Optic Microscope Images of Connector #1 B (left) and Reference Connector (right) The average IL clean=0.1 dB, RL clean=57 dB, IL contaminated =0.36 dB, and RL contaminated= 12dB. The thickness of the air gap was approximately 180 nm

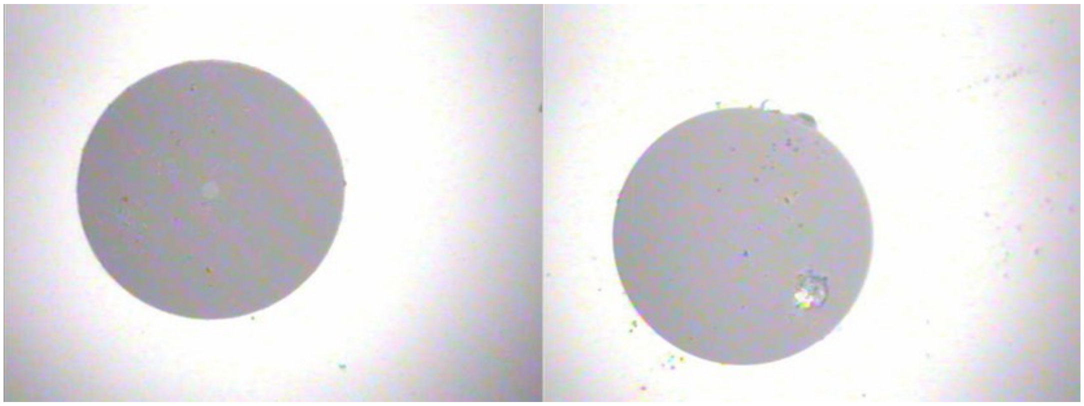


Figure 21 - Fiber Optic Microscope Images of the Connector #19B (left) and a Reference Connector (right) An average IL clean=0.02dB, RL clean=55dB, IL contaminated=0.03 dB, RL contaminated=24dB. The calculated thickness of the air gap was ~80 nm.

Contact Diameter

The diameter of the contact spot between two mated connector ferrules is dependent on the ferrule contact force, the ferrule materials and the spherical radii of the mated ferrules. The contact force for a mated pair of SC connectors lies in a range of 4.9 N to 8.8 N. This is determined by the spring rate of the biasing springs in each plug, the distance between of the mechanical surfaces that secure the plug housings to the adapter and the frictional drag on the ferrules created by the forces between the ferrules and the resilient alignment sleeve of the adapter.

A relationship for determining the ferrule contact spot diameter and the end-face deformation between two mated plugs has been developed using finite element analysis.[9-11] For this analysis, the materials comprising the ferrule are the fused silica fiber, the epoxy adhesive used to bond the fiber to the ferrule and the ceramic zirconia material of the ferrule itself.

The end-face deformation equation that relates the maximum contact force of 8.8 N and the material properties as a function of ferrule end-face radius is:

$$h(R) = 2368 \cdot R^{-0.795}$$

The contact diameter between the mated ferrule end-faces is:

$$d_{contact} = \sqrt{2 \cdot h(R_1) \cdot R_1 - h(R_1)^2} + \sqrt{2 \cdot h(R_2) \cdot R_2 - h(R_2)^2}$$

Where:

$$h(R_2) = 2368 \cdot R_2^{-0.795}$$

$$h(R_1) = 2368 \cdot R_1^{-0.795}$$

And:

R_1 = End-face radius of ferrule 1

R_2 = End-face radius of ferrule 2

Given the end-face geometry of the test jumpers and the reference jumpers used in the experiments, an estimation of the end-face deformation of the mated connector pairs was made to insure physical contact between the fiber cores. The calculations showed that all connector pairs would have physical contact between the fiber cores when mated. Additionally, the contact diameter at the mated ferrule end-faces between connector pairs was estimated. The contact diameters were calculated to be between 155 µm and 185 µm for the mated test jumpers and the reference jumpers.

For the purposes of this paper the set of end-face conditions that would result in the largest contact diameter is of particular interest because particles that lie outside of the contact diameter are less likely to influence the mated-pair optical performance than those that lie within the contact diameter. The largest contact diameter occurs when the contact force between ferrules is at its largest value and the when the ferrule spherical end-face radii of both ferrules are also at their maximum values. For a connector pair having zirconia ferrules, a contact force of 8.8 N and equal end-face radii of 30 mm, the estimated value for the contact diameter is 195 µm. It is recommended that particles that lie within a 250 µm diameter zone be limited in size to prevent loss of physical contact between the fiber cores.

Standard Specification Proposal
Based on the experimental results and statistical analysis presented in this paper, along with our previous research,[1-3] the NEMI team has developed a proposal for an inspection criteria matrix for SM UPC connectors. The proposal was presented at the IEC Working Group 6 meeting in Warsaw in September 2004 and was well received.

The Inspection criteria matrix is presented in Table 2. The area 1a with a diameter of less than 25 um is considered the most critical in terms of optical performance. No contamination and scratches are allowed in this zone, zone 1a. The pass/fail criteria for cladding zone, (zone 1b); epoxy ring zone; contact diameter, (zone 2); and ferrule diameter, (zone 3); are based on experimental results for IL and RL as well on cosmetic requirements. (See Figure 22.)

Table 2 - Inspection Criteria for SMF Pigtail and Patchcord Connectors

			Allowable Visible Contamination [1,2,3]	
Zone	**Description**	**Diameter**	**Non-Removables** [4]	**Scratch Width** [5]
1a	Area Near Core	< 25 um	None	None
1b	Cladding	25 um to 120 um	NRs < 2 um are Acceptable Total of 5 NRs < 5um None > 5um	None > 5 um
--	Epoxy Ring Zone	120 um to 130 um	Any	Any
2	Contact Diameter	130 um to 250 um	None > 10 um	None > 10 um
3	Ferrule Diameter	250 um to 400 um	None > 30 um	Any

Note 1: Any contaminants that are removable must be cleaned from the end-face.
Note 2: Any contaminants that fall across multiple zones are subject to the most stringent criteria.
Note 3: Always use the largest (major) diameter when measuring the size of contaminants.
Note 4: Non-Removable contaminants (NRs) are defined as “permanent non-linear features”. This is equivalent to the IEC definition of “pits”.
Note 5: Scratches are defined as “permanent linear surface features”.
Note 6: Magnification is 200X. Recommended fiberscope is Westover M#FV-200 fiberscope with video card

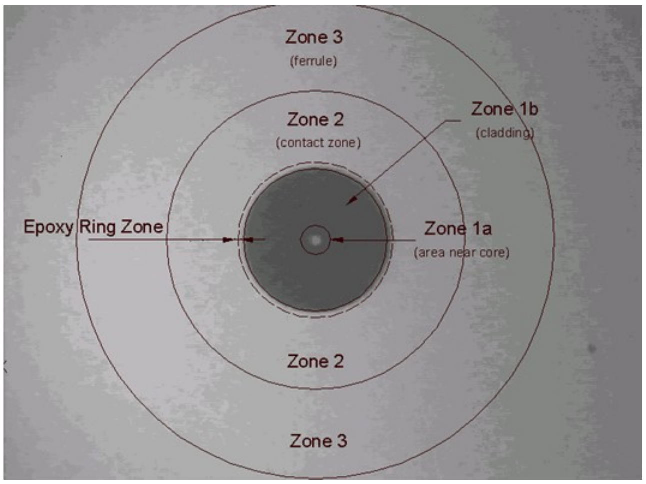


Figure 22 - Ideal SMF SC UPC Ceramic-Ferrule Endface

Conclusions

The influence of Arizona road dust particles of 1-5 um and 6-25 um on the optical performance of single mode SC connectors was investigated. Contamination of zone 1a near the core, (diameter of 25 um), with Arizona road dust resulted in an increase of IL with changes up to 1.8 dB. The contamination of zone 1a near the core, (diameter 25 um), along with the presence of clusters of particles with a diameter of more than 30um in the cladding layer may result in catastrophic changes of RL with changes of 10-40 dB. It was shown that Arizona road dust of 1-5 um and 6-25 um on the cladding outside the 25 um zone 1a and the ferrule did not produce any performance degradation. Contamination with particles can prevent direct physical contact creating an air gap between two end-faces. The thickness of the air gap was calculated based on the RL data and was between 1nm and 200 nm. The Arizona road dust data is in good correlation with the previous data for carbon particles which was reported at the IEC Meeting in Locarno, in April, 2004. The inspection criteria for SMF pigtail and patchcord connectors was proposed based on the experimental data for Arizona road dust particles and previous NEMI research for carbon particles and scratches. A proposal for inspection criteria for SMF pigtail and patchcord connectors has been recently presented to the IEC at their meeting in Warsaw, in September 2004, and it was well received by the IEC members. The acceptance of an industry standard for SM connectors will result in significant cost savings to fiber optics industry due to the elimination of insufficient cleaning and over cleaning and the reduction of contaminated non-conformance material.

A NEMI team is planning to continue the research for SM connectors including ST, FC, LC and MU connectors. Further research will focus on the development of a cleanliness specification for MM connectors and receptacle modules.

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Development of Cleanliness Specification for Single- Mode Connectors

APEX-2005, Anaheim, CA

February 22, 2005

Presenter: Tatiana Berdinskikh-Ph.D,

Celestica International Inc.

Authors

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- Randy Manning, Tyco Electronics
- Tom Mitcheltree, Cisco Systems
- Thomas Ronan, Aerotech
- Heather Tkalec, Alcatel
- Frank (Yi) Zhang, Avanex

Presentation Outline

- Introduction
- Experimental Methodology
- Data and Analysis
- Critical Parameters
- Return Loss Modeling
- Inspection Criteria
- Conclusions and Recommendations

Introduction

- The paper summarizes research performed by the NEMI (National Electronics Manufacturing Initiative) Fiber Optic Signal Performance team

. Currently there is no industry standard for fiber optic end-face cleanliness

. This impacts the cost of manufacturing products that use fiber optics. End-customers are not in agreement with suppliers on the level of cleanliness required for fiber optic end-faces

- Connector cleanliness has a significant impact on in-process yield and cause of returns
- There was a lack of scientific backing for many of the standards used by companies in the industry
- The work presented in this paper is being used as a basis for the draft IPC cleanliness standard. It has also been reviewed by the IEC and TIA committees that are developing their own respective standards.

Our Objective:

- Update the criteria in IEC doc "61300-3-35: Basic test and measurement procedures" based on quantitative data
- Harmonize our recommendations across all vendors/CMs/OEMs to achieve a true international standard

Summary from Montreal IEC-2003:

- Scratches and particles within 25um diameter definitely affect SMF performance
- Scratches outside of 25um definitely do NOT affect SMF performance
- Further investigation needed on particles outside 25um

Summary from IEC meeting, Locarno, Apr, 04, presented by the NEMI team

- Small Carbon particles on the ferrule did not show any performance degradation
- Small Carbon particles on the cladding outside the 25 um zone do not significantly impact performance
  - e.g., Up to 17 particles on cladding outside of 25um…no impact
- Contamination particles can prevent direct physical contact creating an air gap between two endfaces
- Further investigation is needed for contamination located at cladding and ferrule areas
- Investigate the influence on the Arizona dust particles on the optical signal performance

Design of the Experiment

Procedure

- >70 SMF cables with SC connectors
- 2 grades of Arizona dust powder: 1-5 um and 6-25 um
- Each cable mated and de-mated 5 times
- Total of 350 experimental points including IL, RL and fiberscopic images for the test cable and reference cable before and after contamination
- Geometry measurements have been performed for test and reference connector
- Reference cable has been replaced after each 5 mating/ de-mating operations

Experimental Methodology

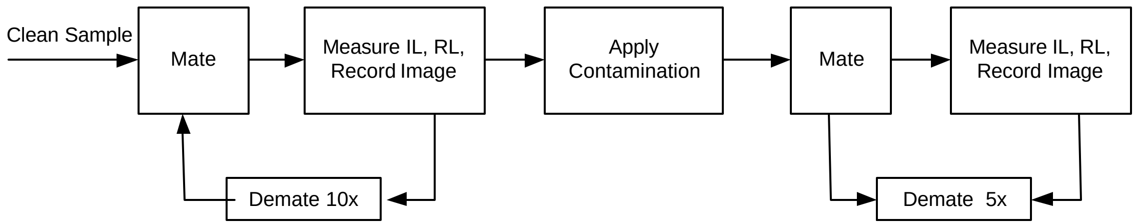


Figure 1. Block Diagram of the Design of the Experiment

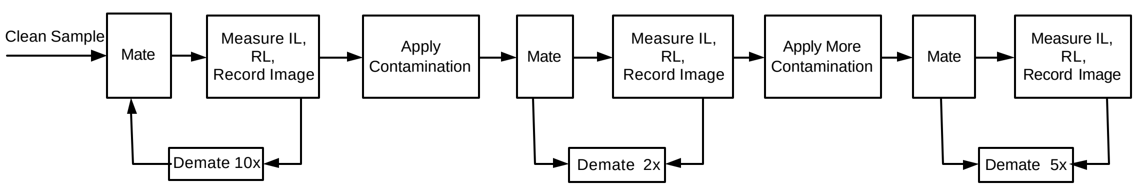


Figure 2. Block Diagram of alternate Design of Experiment

Experimental Methodology

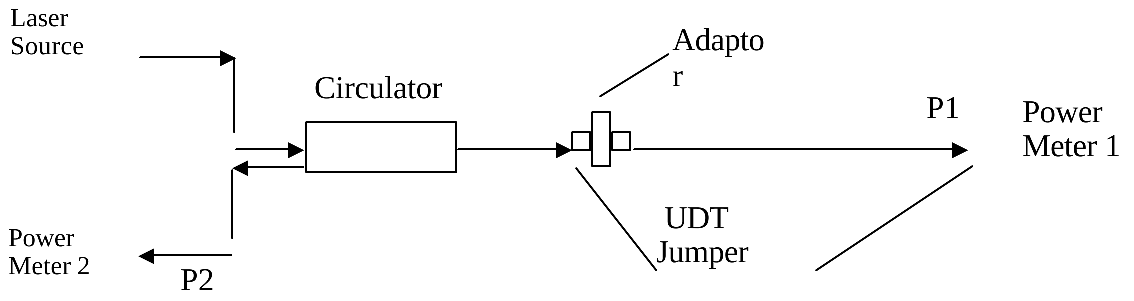


Figure 3. RL Block Diagram

Design of the Experiment

- Repeatability experiment
  - Mate/demate clean test fiber and clean reference fiber 10 times
  - Measure IL/RL
  - Save the fiberscopic images after each mating/de-mating operation
- Analysis the experimental data using Westover Scientic software “ Fiber Check”
- Data analysis
  - Calculate STDEV for clean fiber :SDTDEV (IL) and STDEV (RL)
  - Calculate Delta (IL)= IL(contaminated)-IL(clean)
  - Calculate Delta (RL)=RL(clean)-RL (contaminated)
  - Compare Delta (IL) with 3SDTDEV(IL)
  - Compare Delta (RL) with 3SDTDEV(RL)
  - Failed criteria: Delta (IL)> 3SDTDEV(IL) or Delta (RL)>3SDTDEV(RL)

Data Analysis

- 2 ways approach for the Data Analysis
- The first approach required calculation of the standard deviations for IL and RL based on the repeatability test, (ten matings/dematings with the clean connector).
- For each individual case of contaminated connector, delta IL and delta RL were calculated as follows:
- Delta IL=Absolute value (IL clean-IL contaminated)
- Delta RL= Absolute value (RL clean-RL contaminated).
- The pass criteria were achieved when both delta IL and delta RL were within three standard deviations of IL and RL.
- The second approach for the data analysis was based on the hypothesis testing

Hypothesis Testing

- Null Hypothesis (Ho): No difference between the two means (IL clean= IL contaminated, RL clean= RL contaminated)
- Alternate Hypothesis (Ha): there was a difference between the population means
- The number of the data points in each group can be defined by the number of mating/demating operations for each group

$$t_{Calc} = \frac{\overline{X}_1 - \overline{X}_2}{s_{Pooled}\sqrt{1/n_1 + 1/n_2}}$$

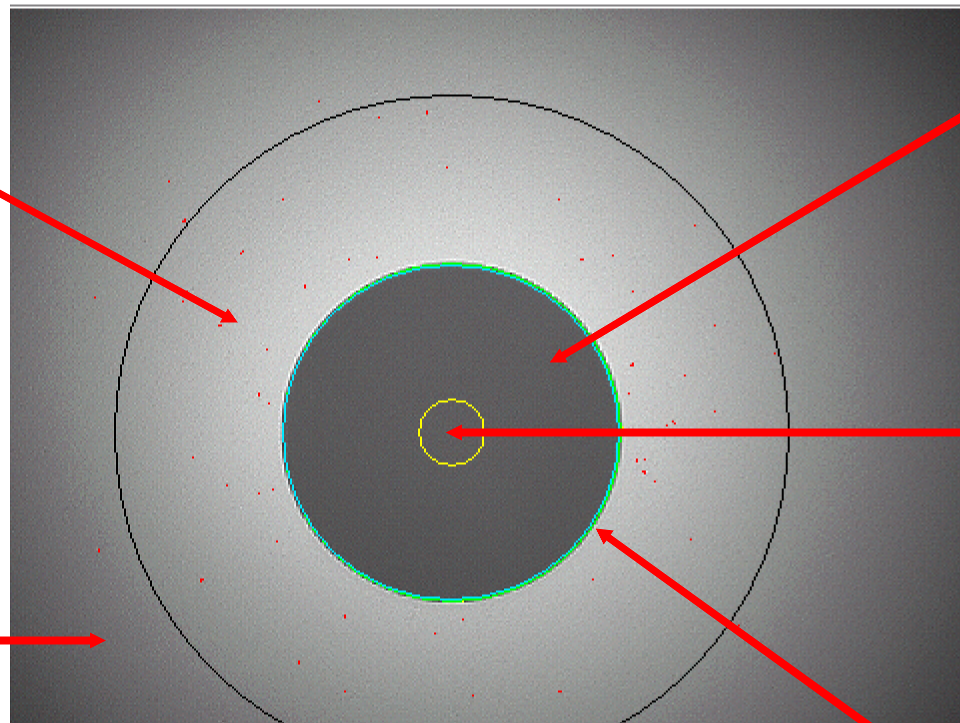
- Where: X1and X2 are the means for the group of the clean and contaminated samples
- n1 is the number of the data points (matings and dematings) for the clean group
- n2 is the number of the data points (matings and dematings) for the contaminated group
- Spooled is the pooled sample standard deviation (consists of taking the square root of weighted average of the variances)
- The null hypothesis is rejected if t calc < t df,a or t calc>t df, 1-a . Degrees of freedom (d.f.) = n1 + n2-2. The probability that the null hypothesis is rejected when it is true is denoted by a. Usually a=0.05. In this study, our team automated these calculations using the Minitab 2-T test.

Zones definition (Fiber Check Analysis)

Contact Diameter

130um<d<250um

Cladding, 25um<d<120um



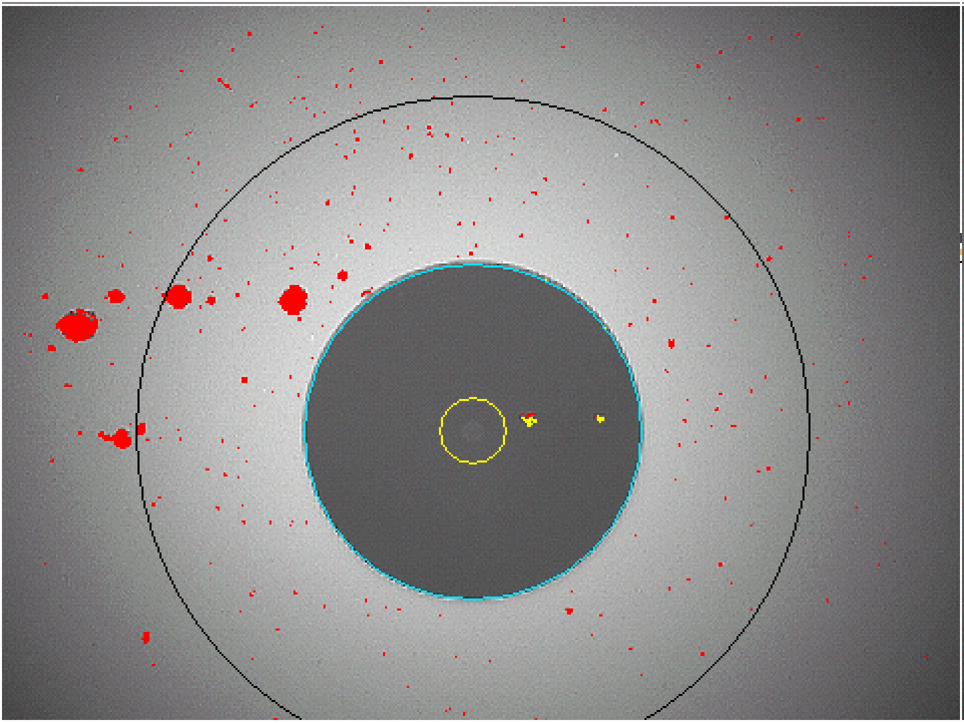
Area near the core, d<25um

Ferrule Diameter

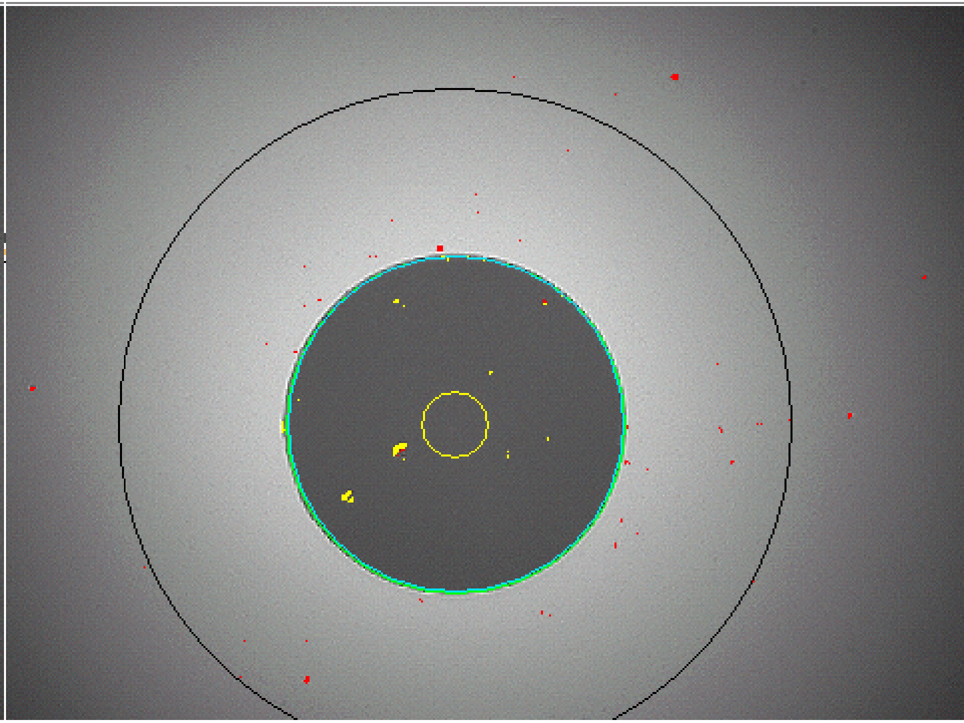
250um<d<400um

Epoxy Ring Zone, 120um<d<130um

Clean Fiber



57A-1st Mating



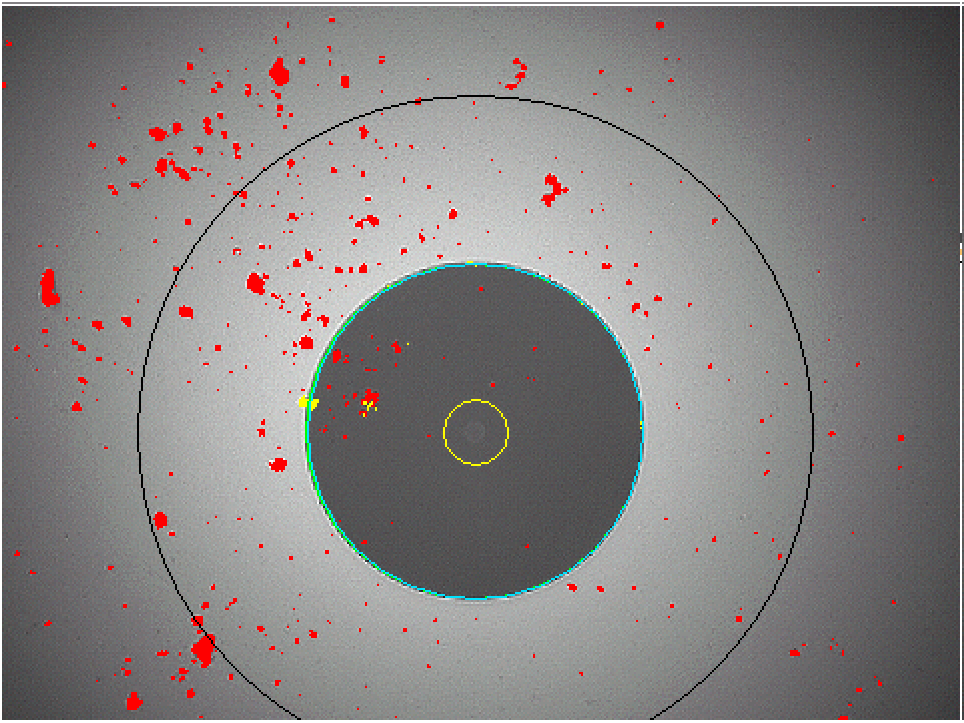
Reference Cable T17

Initial IL:	0.25dB
Initial RL:	50dB

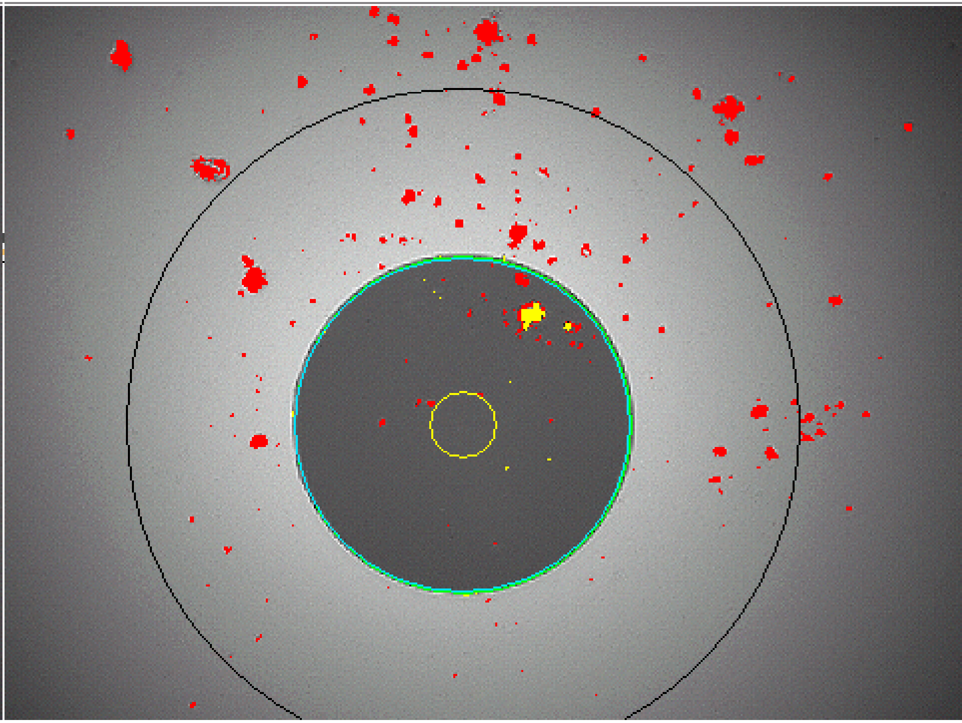
IL after contamination:	0.26dB
RL after contamination:	51dB

Standard Deviation of IL:	0.023dB
3 x Standard Deviation of IL:	0.069dB
3 x Standard Deviation of RL:	3dB

Passed: Within 3 Standard Deviations of Clean Fiber



57A-2nd dust application



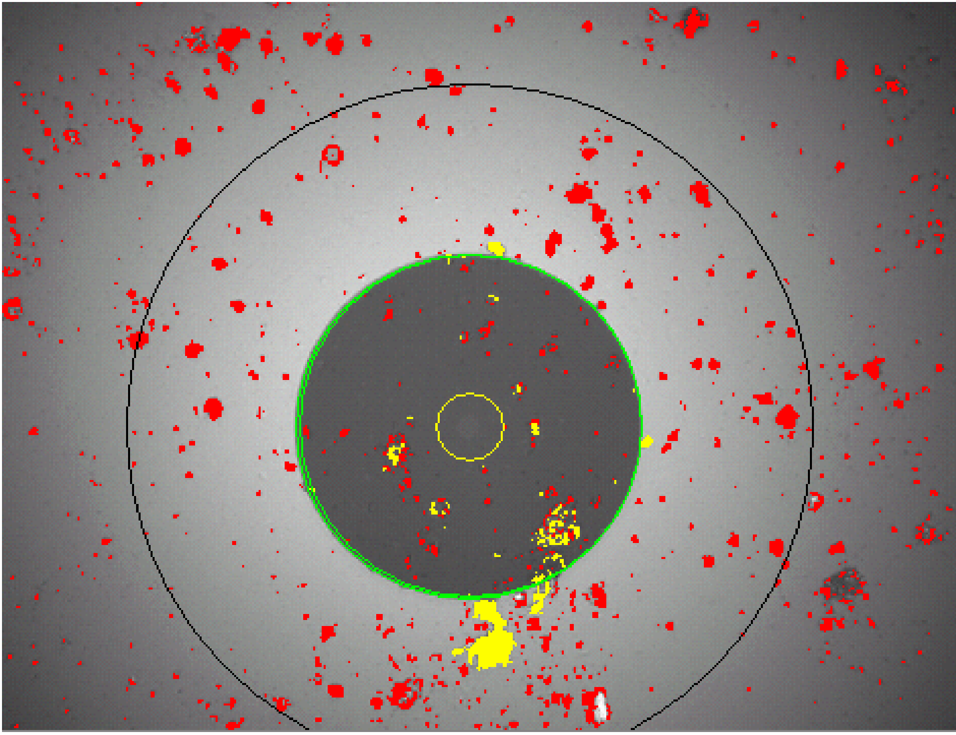
Reference Cable T17

Initial IL:	0.25dB
Initial RL:	50dB

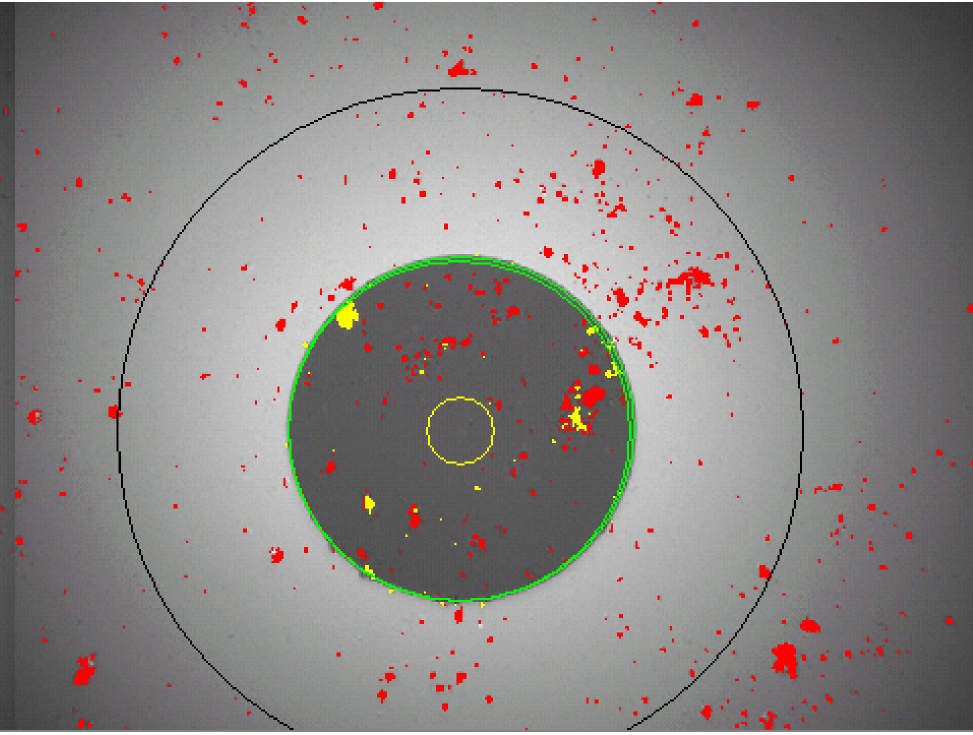
IL after contamination:	0.26dB
RL after contamination:	52dB

Standard Deviation of IL:	0.023dB
3 x Standard Deviation of IL:	0.069dB
3 x Standard Deviation of RL:	3dB

Passed: Within 3 Standard Deviations of Clean Fiber



57A-3rd Dust Application



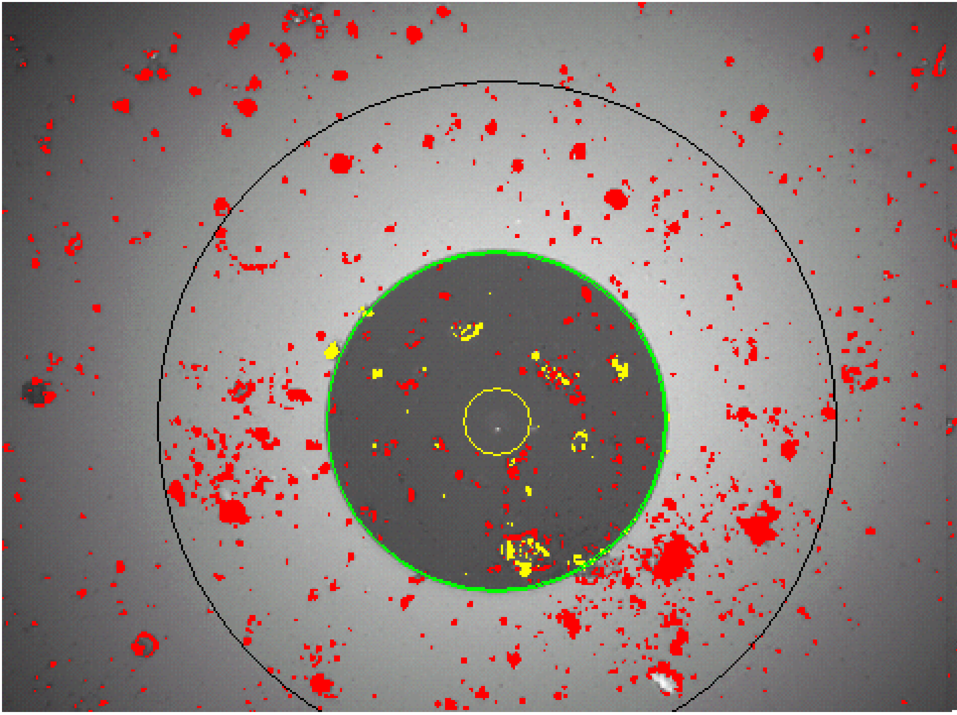
Reference Cable T17

Initial IL: 0.25dB
Initial RL: 50dB

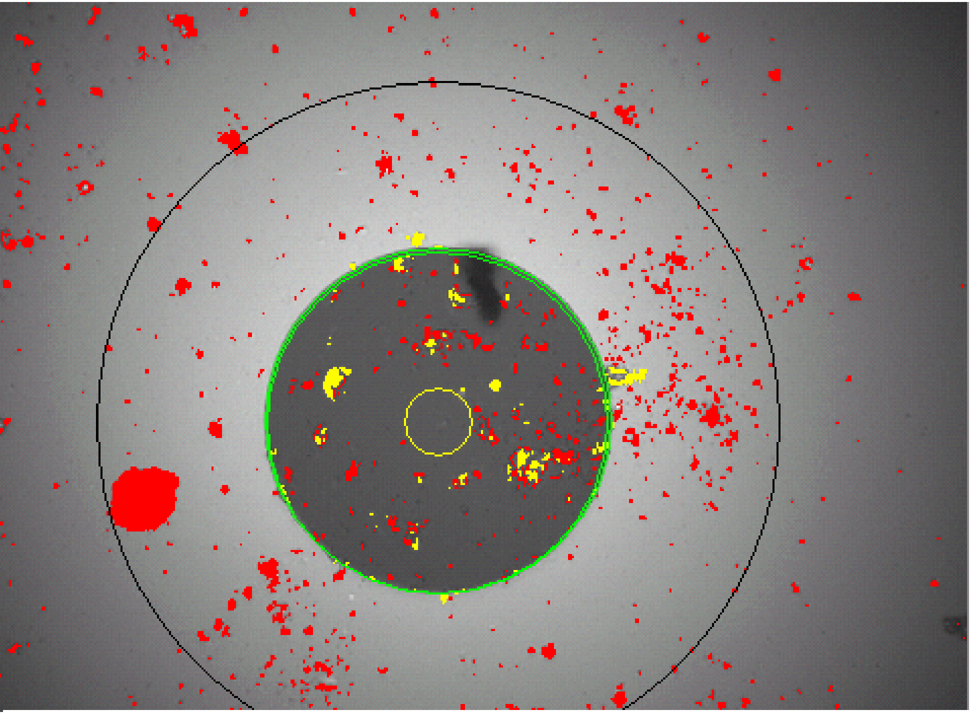
IL after contamination: 0.32dB
RL after contamination: 54dB

Standard Deviation of IL: 0.023dB
3 x Standard Deviation of IL: 0.069dB
3 x Standard Deviation of RL: 3dB

The sample failed Pass/Fail Criteria



57A-10th mating after 3rd dust app.



Reference cable T17

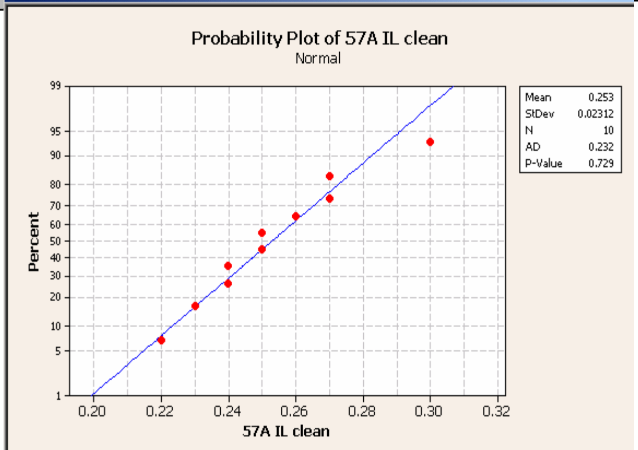
Initial IL:	0.25dB
Initial RL:	50dB

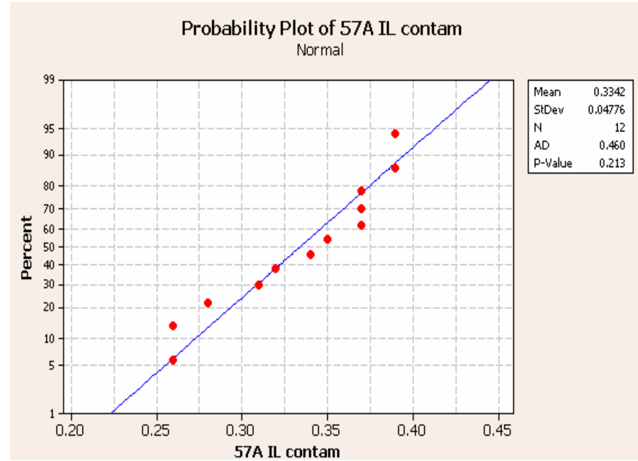
IL after contamination:	0.39dB
RL after contamination:	47dB

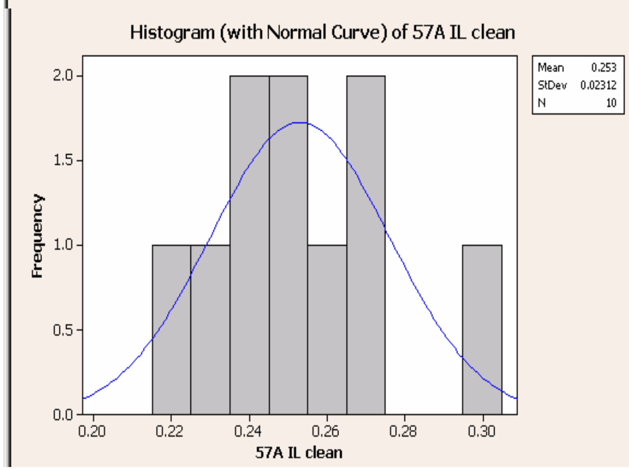
Standard Deviation of IL:	0.023dB
3 x Standard Deviation of IL:	0.069dB
3 x Standard Deviation of RL:	3dB

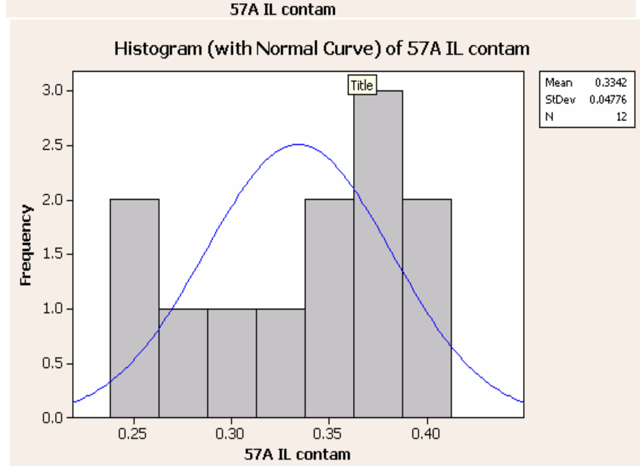
Failed: Not Within 3 Standard Deviations of Clean Fiber

Normality Test









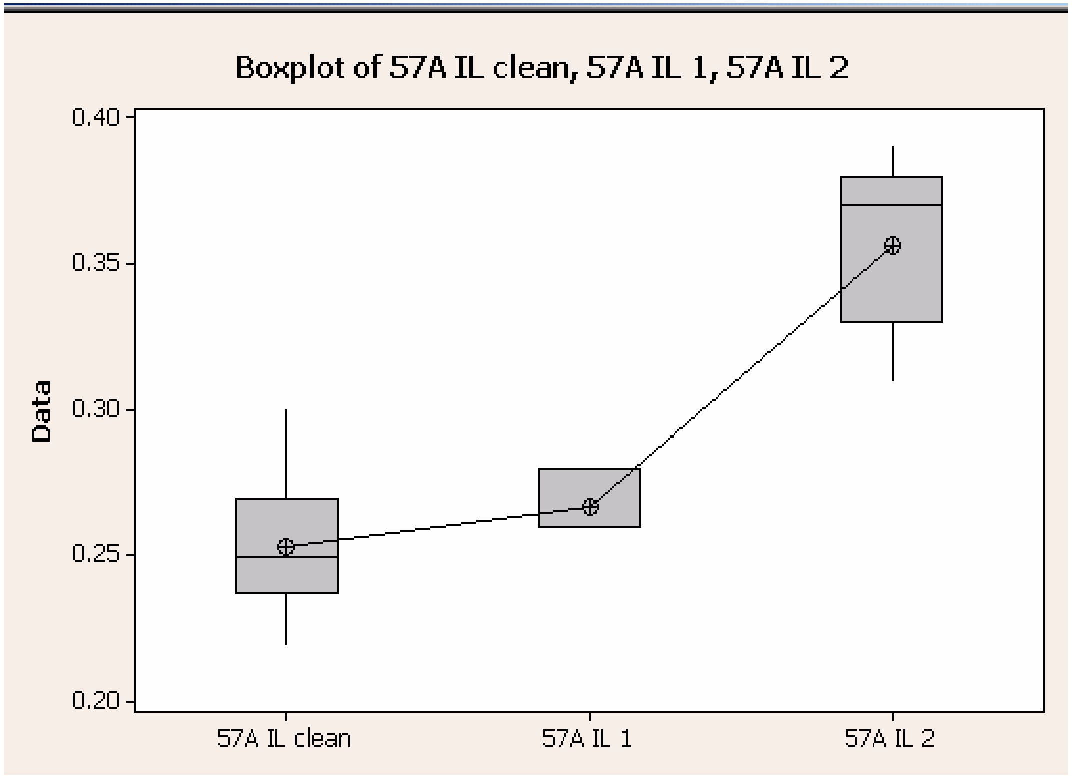
P= 0.729 for clean group and P=0.213 for contaminated group.
P>0.05 means that the distribution is normal (95% confidence level)

2-T-Test Data

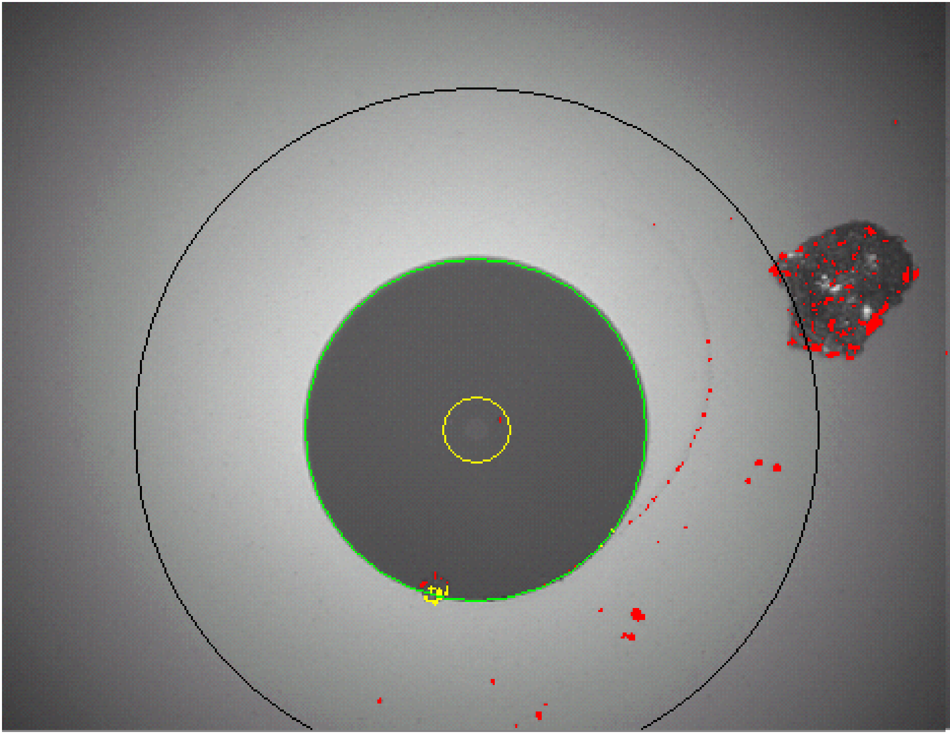
Table 1- Summary of the 2-T-test data

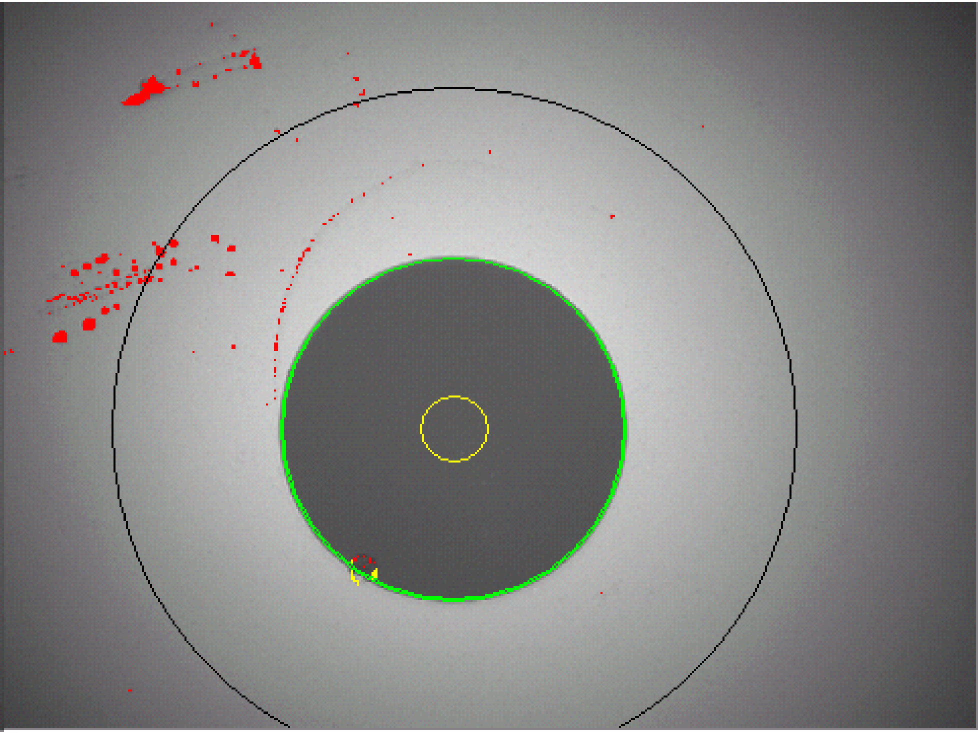
		Mean	Std. deviation	T-test P-value	Image Reference
Sample 57A					
IL	*Clean*	*0.25*	*0.023*	-	
	Subgroup 1	0.27	0.012	0.210	Figure 5, 6
	subgroup 2	0.36	0.029	0	Figure 7, 8
RL	Clean	50.2	1.03	-	
	subgroup 1	51.3	0.58	0.051	Figure 5, 6
	subgroup 2	48.0	2.60	0.039	Figure 7, 8
Sample 60A					
IL	*Clean*	*0.08*	*0.007*	-	
	subgroup 1	0.39	0.269	0.180	
	subgroup 2	0.60	0.026	0	Figure 13
RL	Clean	53.0	1.15	-	
	subgroup 1	54.0	1.00	0.239	
	subgroup 2	34.3	11.7	0.001	Figure 13
Sample 62B					
IL	*Clean*	*0.5*	*0.016*	-	
	contaminated	0.48	0.024	0.099	Figure 10,11
RL	Clean	53.0	1.05	-	
	contaminated	53.2	0.84	0.698	Figure 10, 11

Anova Test Results



Box-plot graph for the IL of the sample 57A: clean (57A clean) and contaminated, Subgroup 1 (57A IL 1) and Subgroup 2 (57A IL 2)





62B- 2nd mating

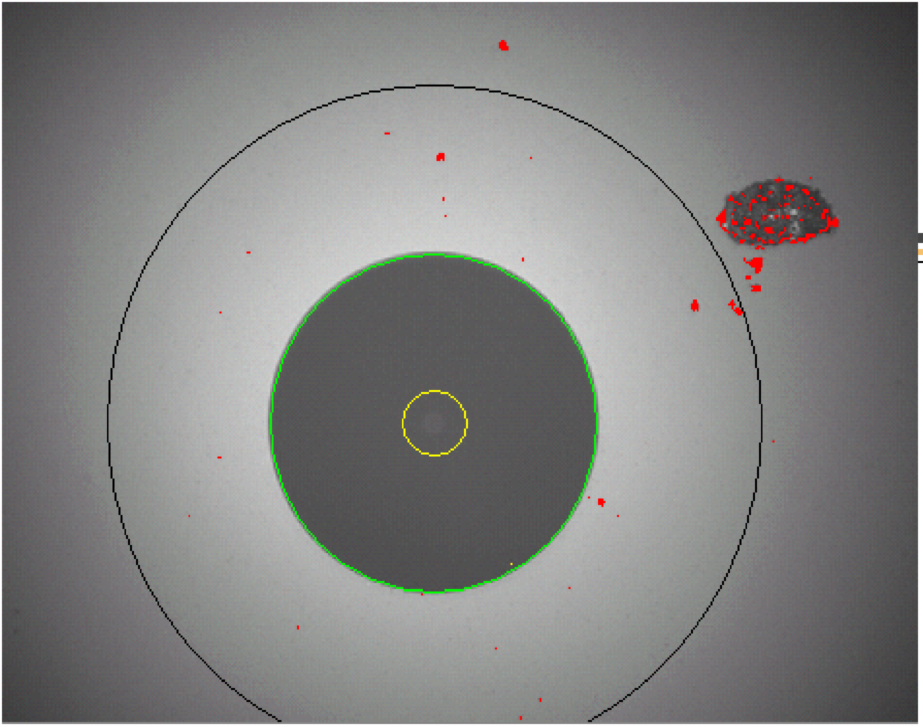
Reference Cable T22

Initial IL: 0.50dB
Initial RL: 53dB

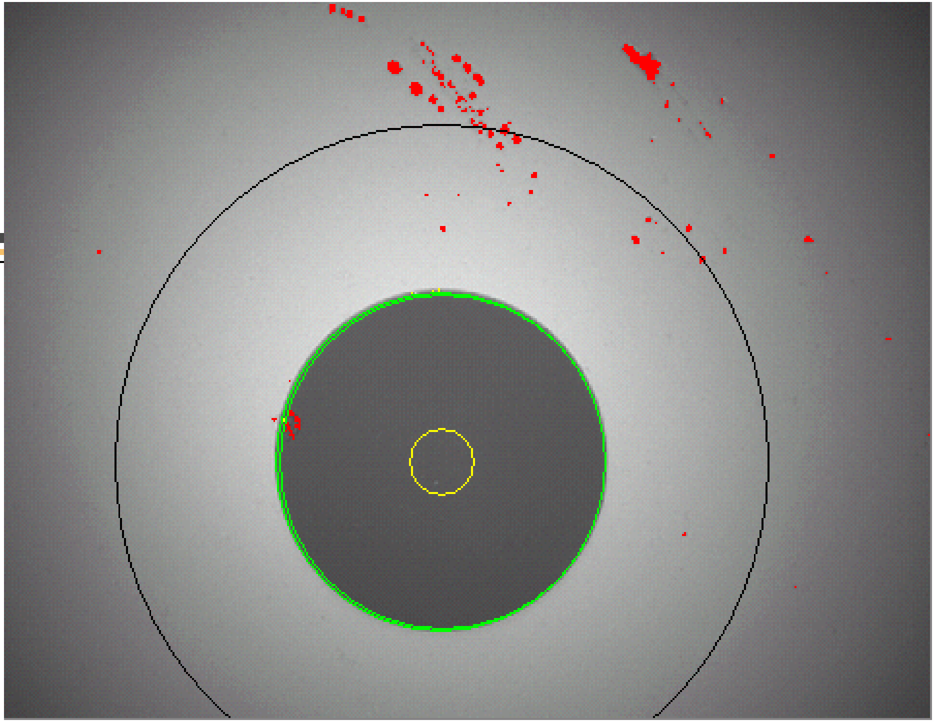
IL after contamination: 0.51dB
RL after contamination: 52dB

3 x Standard Deviation of IL:	0.047dB
3 x Standard Deviation of RL:	3 dB

Passed: Within 3 Standard Deviations of Clean Fiber



Sample 62B 5th Mating



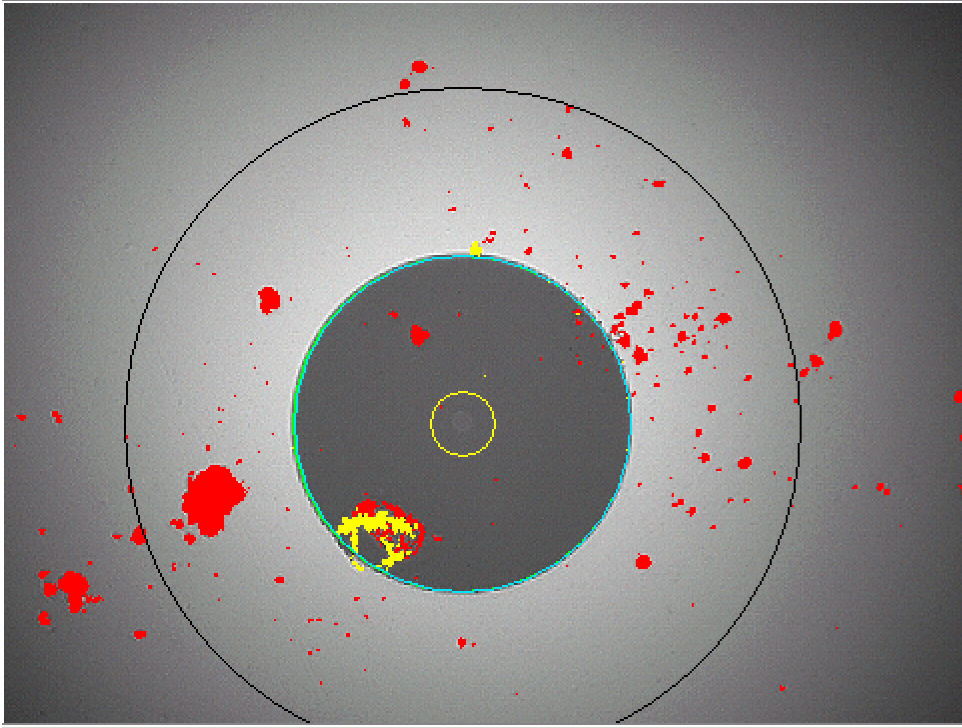
Reference Cable T22

Initial IL:	0.50dB	IL after contamination:	0.45dB
Initial RL:	53dB	RL after contamination:	54dB

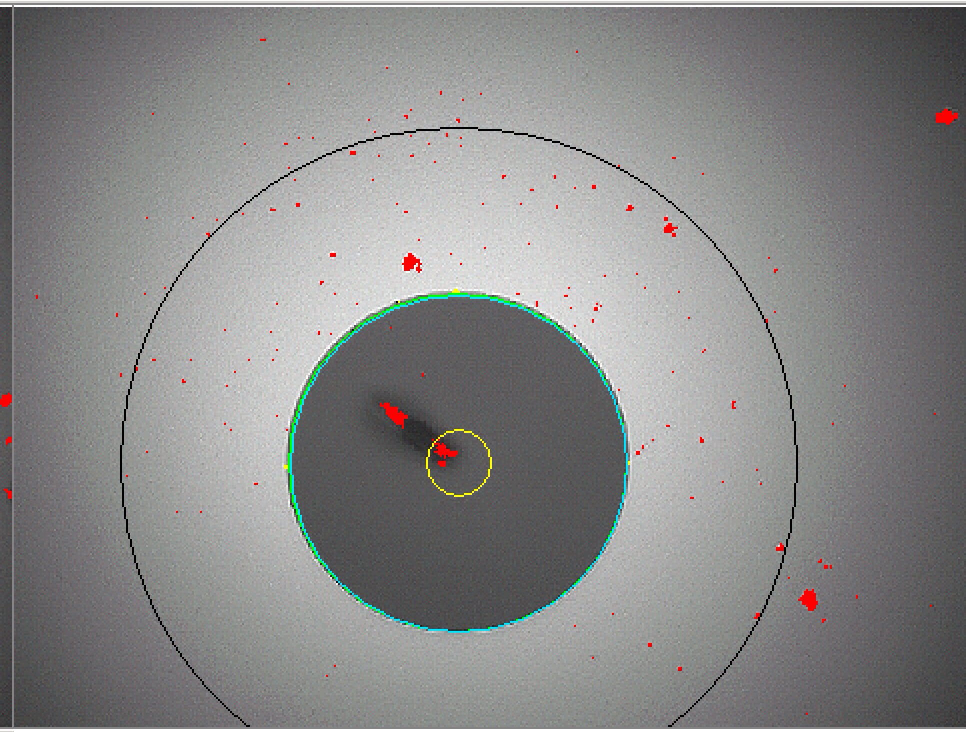
3 Std Dev IL=0.047 dB

3 Std Dev RL=3 dB

Passed: Within 3 Standard Deviations of Clean Fiber



60A-3rd dust application

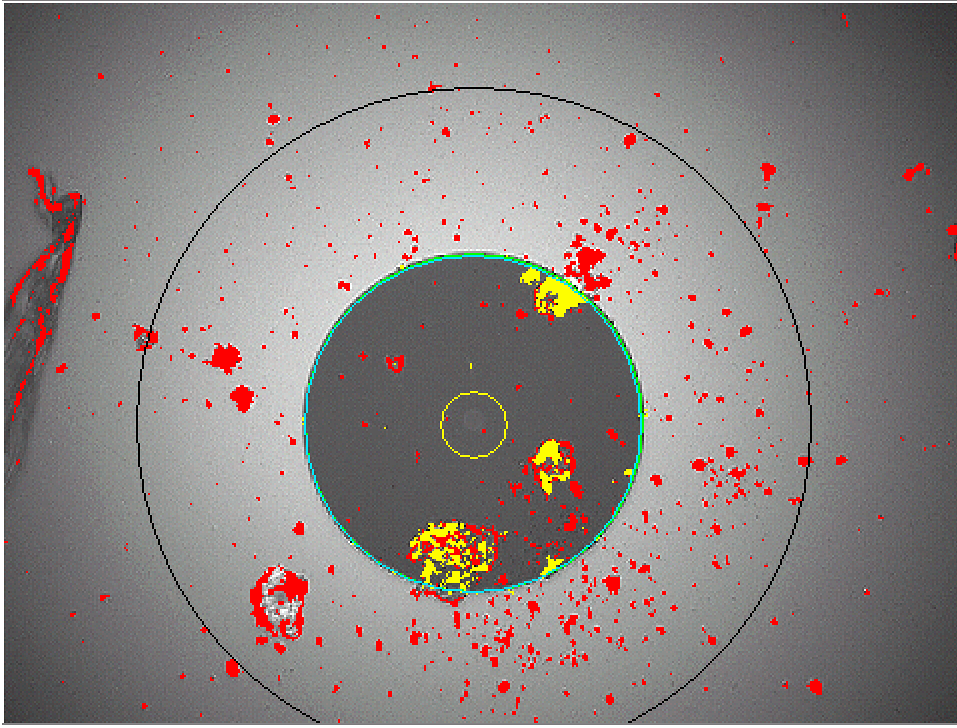


Reference Cable T19

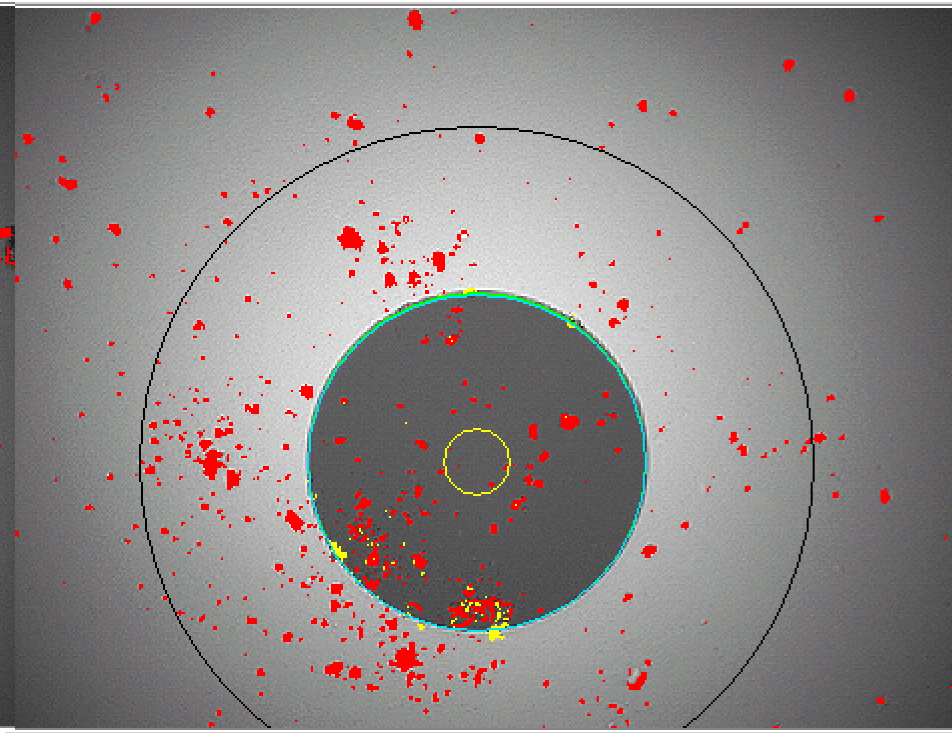
Initial IL:	0.08dB	IL after contamination:	0.61dB
Initial RL:	53dB	RL after contamination:	54dB

Standard Deviation of IL:	0.007dB
3 x Standard Deviation of IL:	0.021dB
3 x Standard Deviation of RL:	3.5dB

Failed



60A-2nd mating after 3 rd dust app.

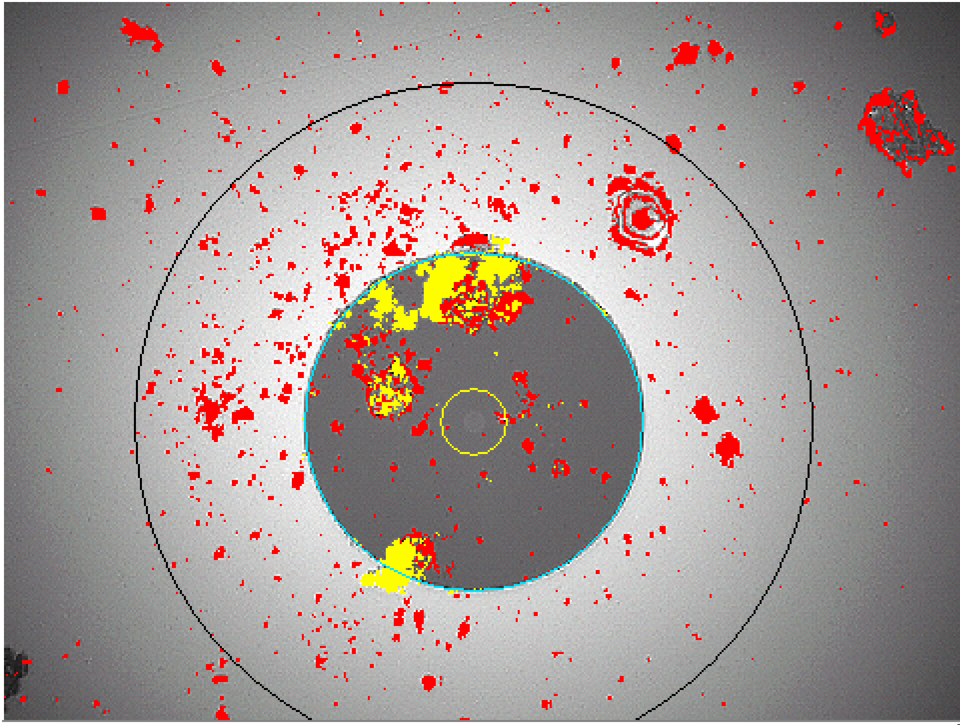


Reference Cable T19

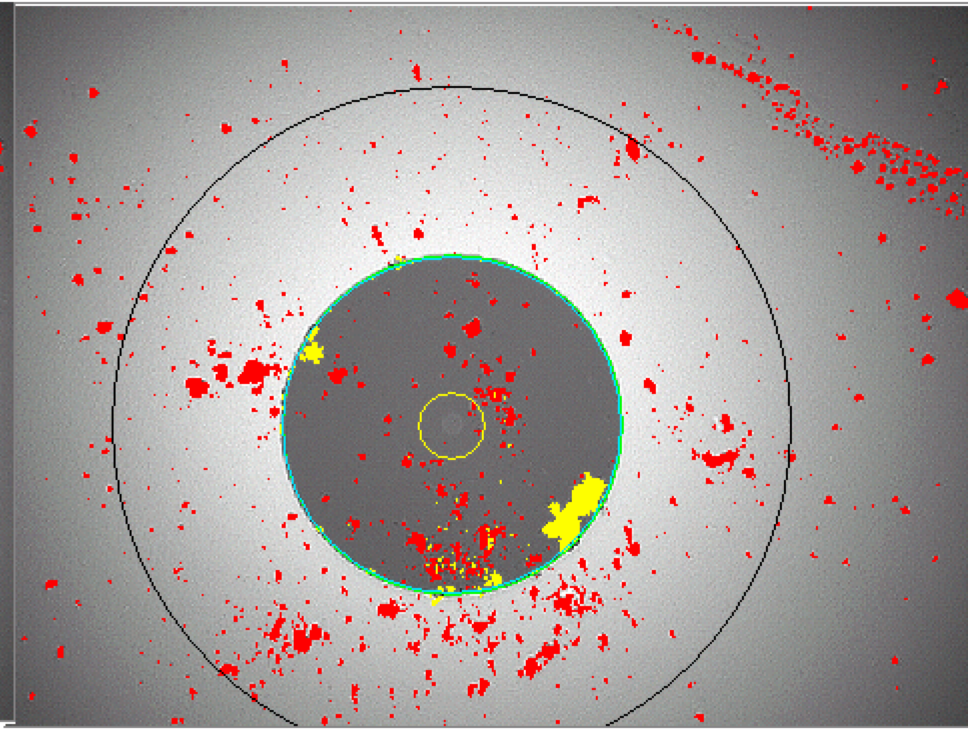
Initial IL:	0.08dB	IL after contamination:	0.63dB
Initial RL:	53dB	RL after contamination:	24dB

Standard Deviation of IL:	0.007dB
3 x Standard Deviation of IL:	0.021dB
3x Standard Deviation of RL:	3.5dB

Failed



60A-10 th mating after 3rd dust app.

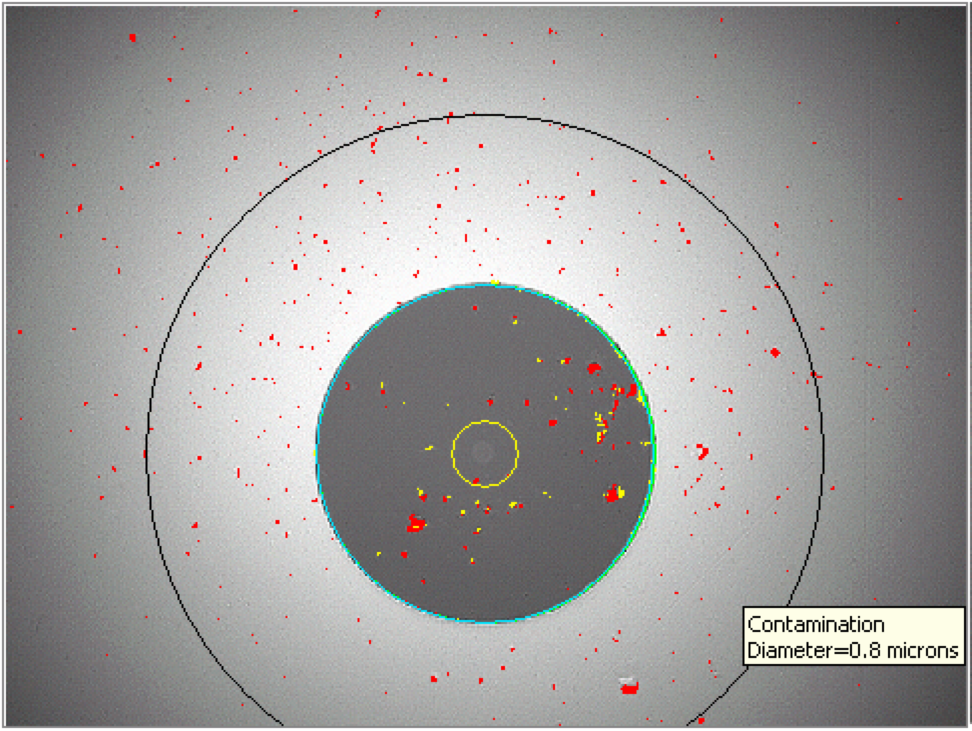


Reference Cable T19

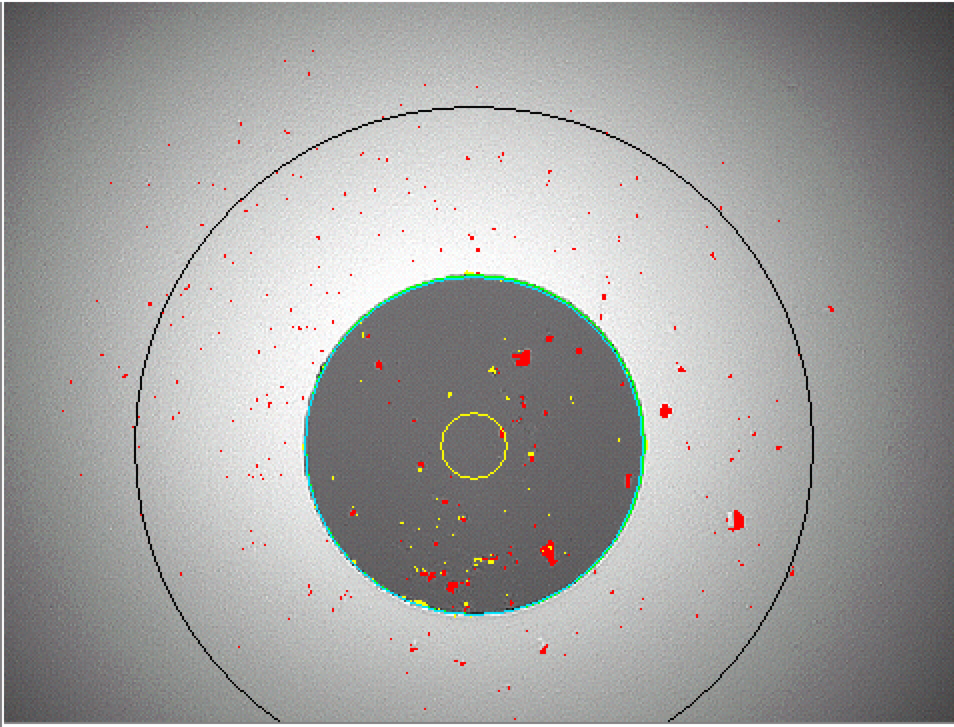
Initial IL:	0.08dB	IL after contamination:	0.60dB
Initial RL:	53dB	RL after contamination:	25dB

Standard Deviation of IL:	0.007dB
3 x Standard Deviation of IL:	0.021dB
3 x Standard Deviation of RL:	3.5dB

Failed



60A-10th mating after 3rd dust app.



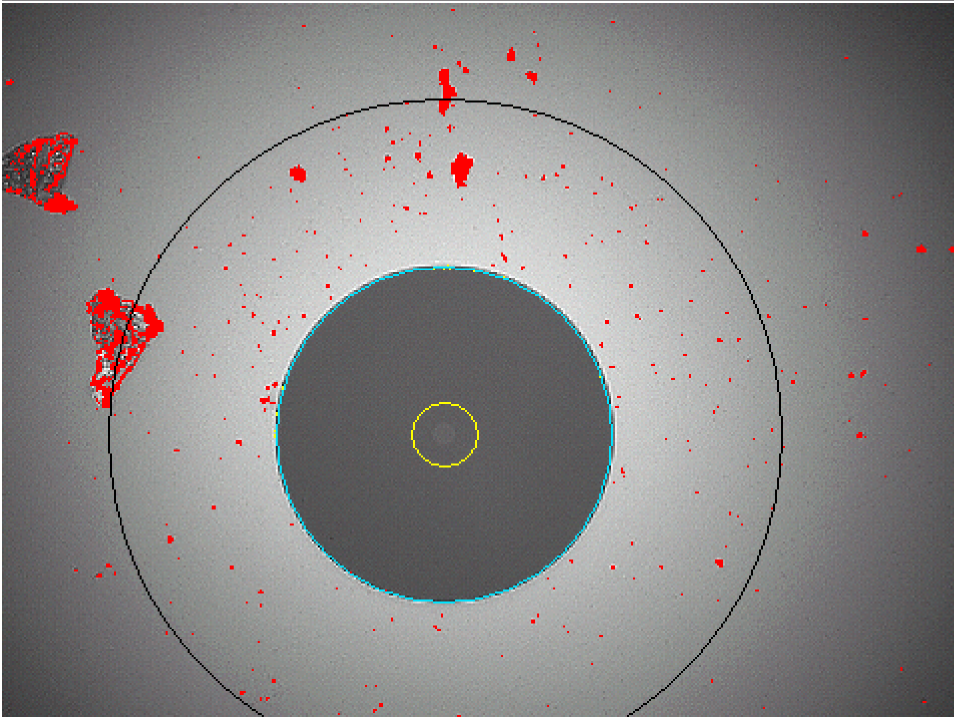
Reference Cable T19

After 10 mating /demating operations for contaminated fiber and cleaning process

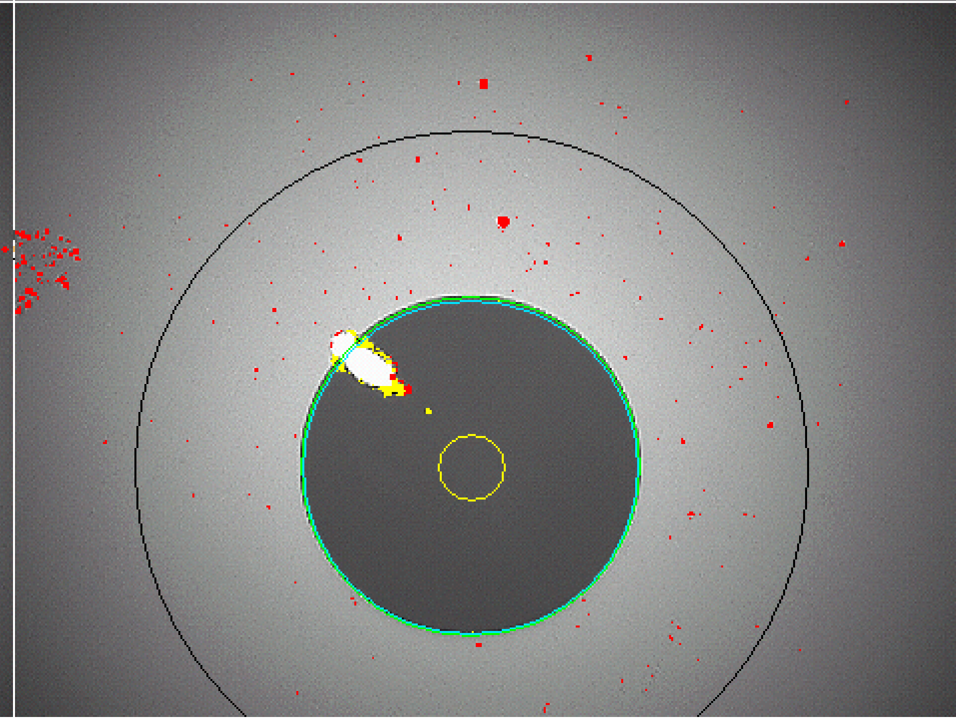
Initial IL:	0.08dB	IL after contamination:	0.41dB
Initial RL:	53dB	RL after contamination:	52dB

Standard Deviation of IL:	0.007dB
3 x Standard Deviation of IL:	0.021dB
3 x Standard Deviation of RL:	3.5dB

Failed



61A-3rd mating



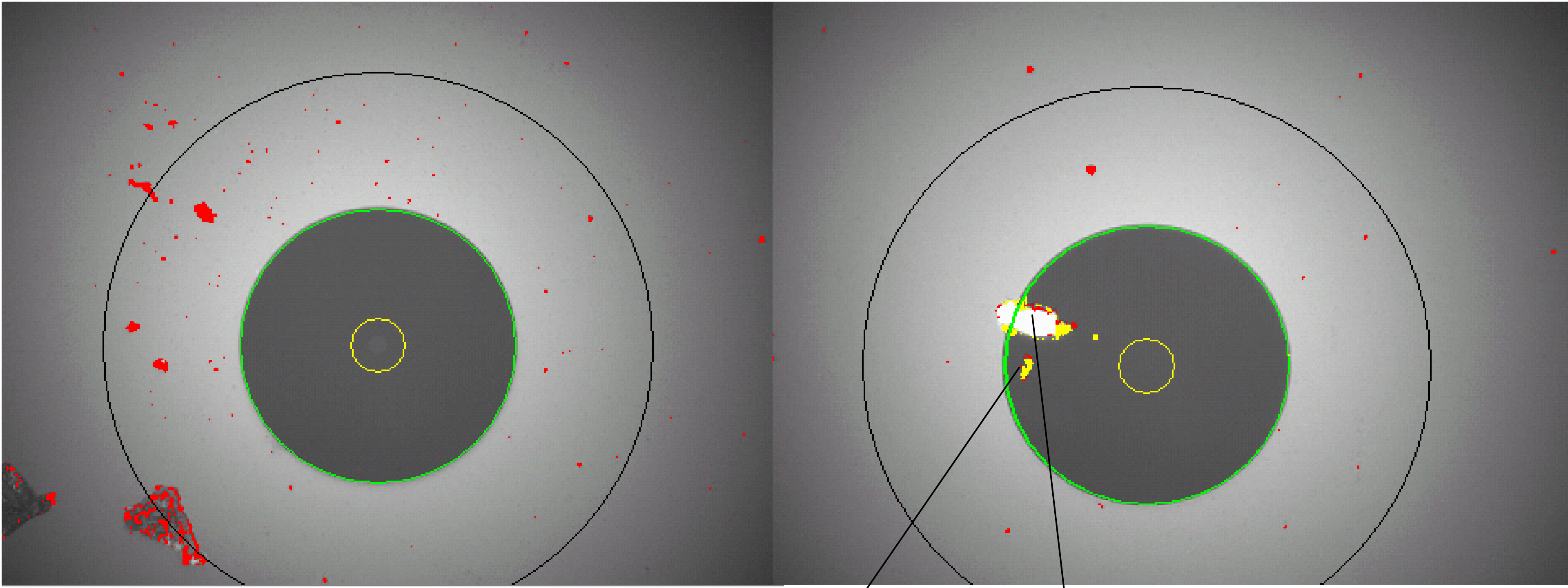
Reference Cable T20

Initial IL:	0.07dB
Initial RL:	53dB

IL after contamination:	0.08dB
RL after contamination:	53dB

3 x Standard Deviation of IL:	0.024 dB
3 x Standard Deviation of RL:	1.90 dB

Passed: Within 3 Standard Deviations of Clean Fiber



10.5 um

~20 um

61A- 4th mating

Reference Cable T20

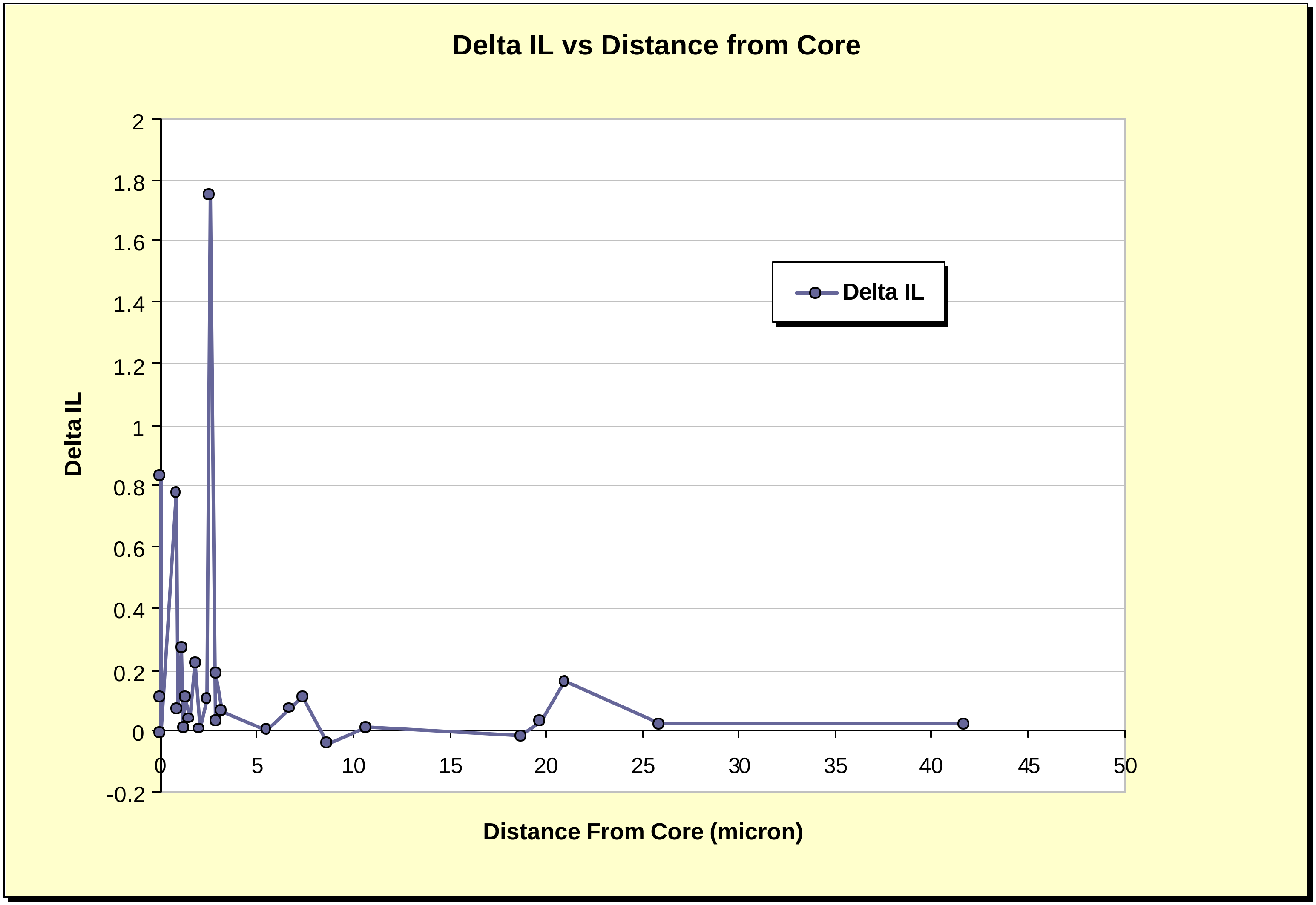
Initial IL: 0.07dB
Initial RL: 53dB

IL after contamination: 0.07dB
RL after contamination: 54dB

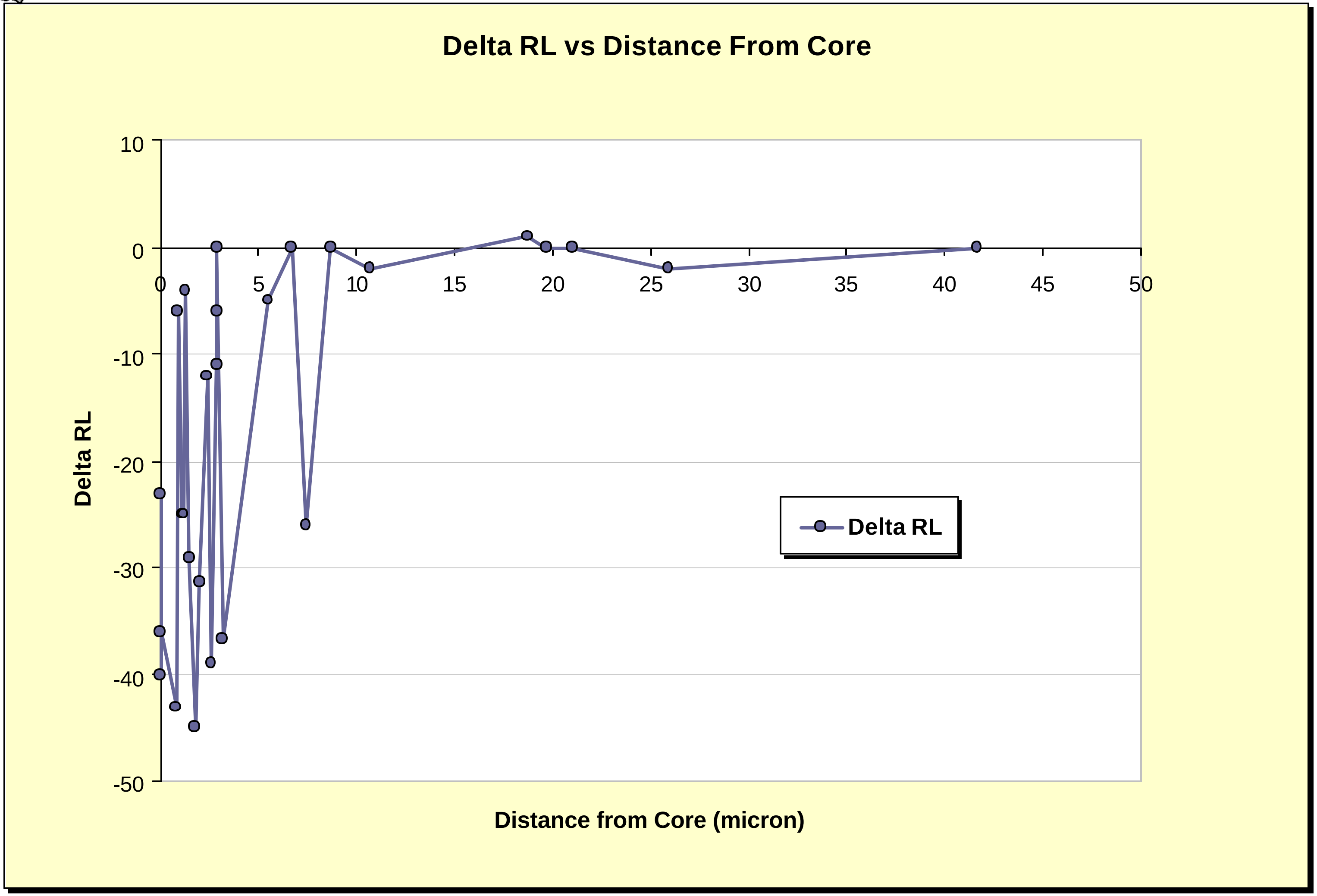
3 x Standard Deviation of IL: 0.024 dB
3 x Standard Deviation of RL: 1.90 dB

Passed: Within 3 Standard Deviations of Clean Fiber

The Factors Affected on the Optical Performance

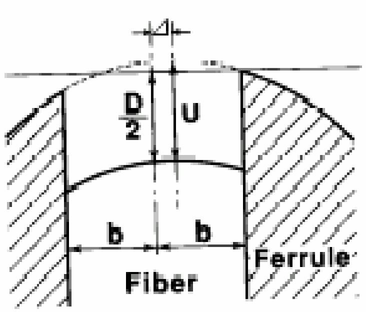


The Factors Affected on Optical Performance



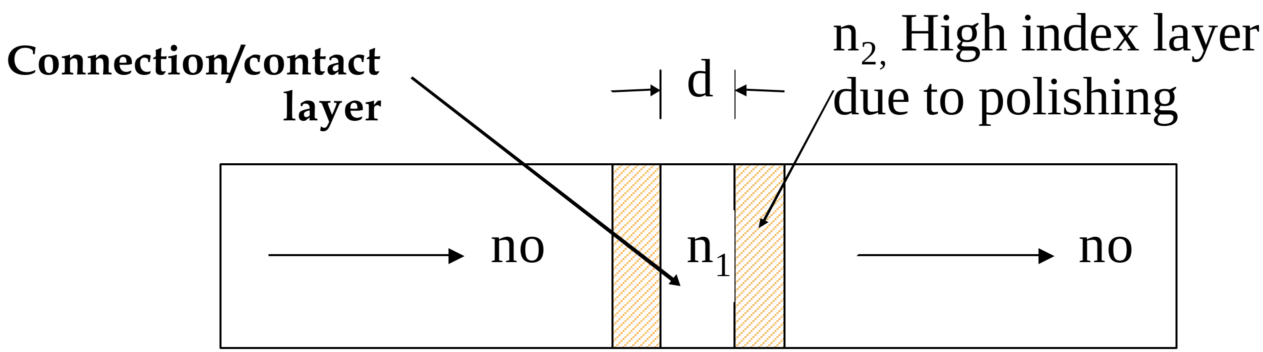
The following factors have been taken into the consideration:

- Higher index layer due to the polishing
  - $n=1.4677$ (SMF-28), $n_1=1$, $n_2 = 1.476$, $h=30nm$
- Geometric parameters (radius of the curvature, apex offset and fiber undercut)
- Axial force of the spring loaded connector
- Overall air gap is the sum of gaps generated by the test and reference connector (D/2)



$$D/2 = (U + b\Delta/R) - b^2/(2R)$$

T. Shintaku, " J. Lightwave Technology, V.11, #2, 241-247

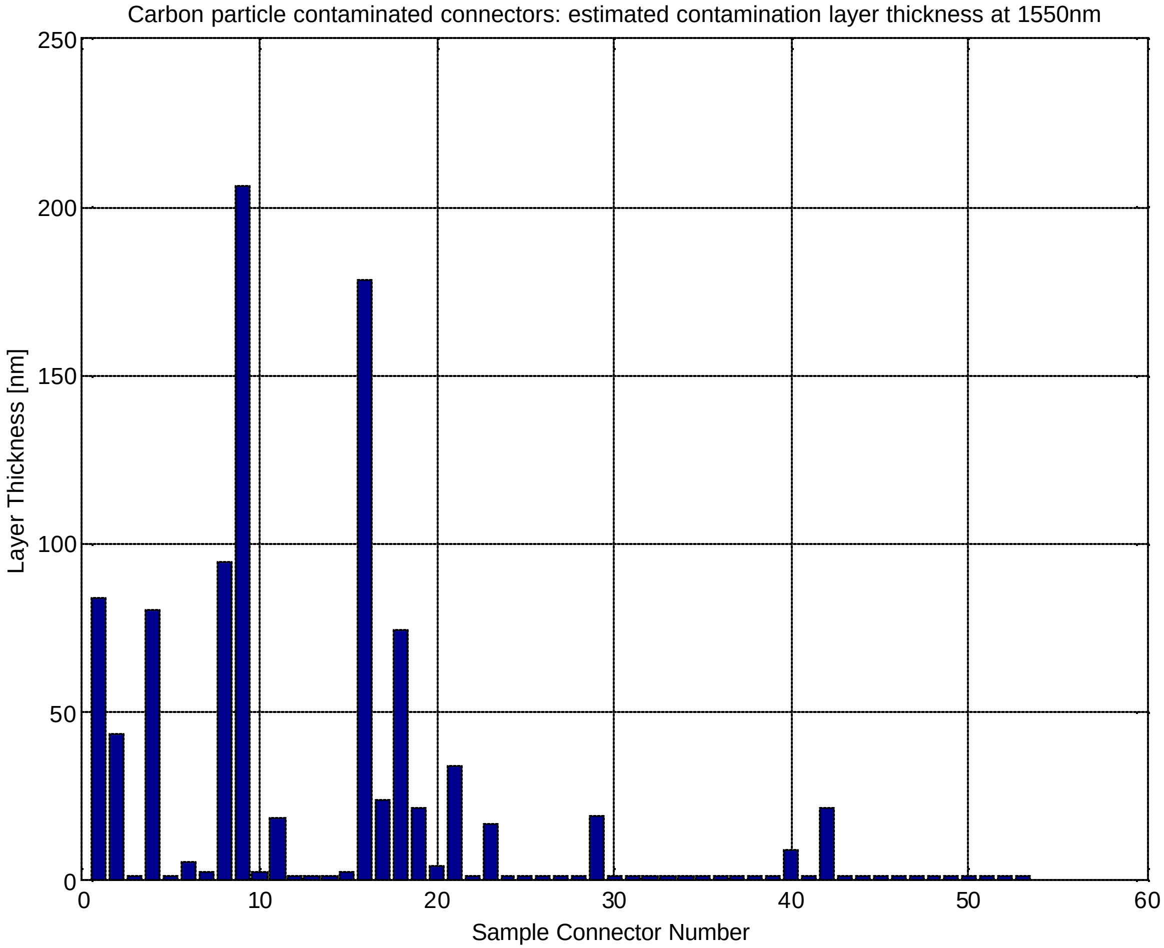


$$RL(dB) = 10\log\left[2R\left(1-\cos\left(\frac{4pn_1}{l}d\right)\right)\right]$$

$$R = (r_1^2 + r_2^2 + 2r_1r_2\cos d)\big/(1 + r_1^2r_2^2 + 2r_1r_2\cos d)$$

$$r_1 = \frac{n_0 - n_2}{n_0 + n_2}, \quad r_2 = \frac{n_2 - n_1}{n_2 + n_1}, \quad d = \frac{4p}{l}n_2h$$

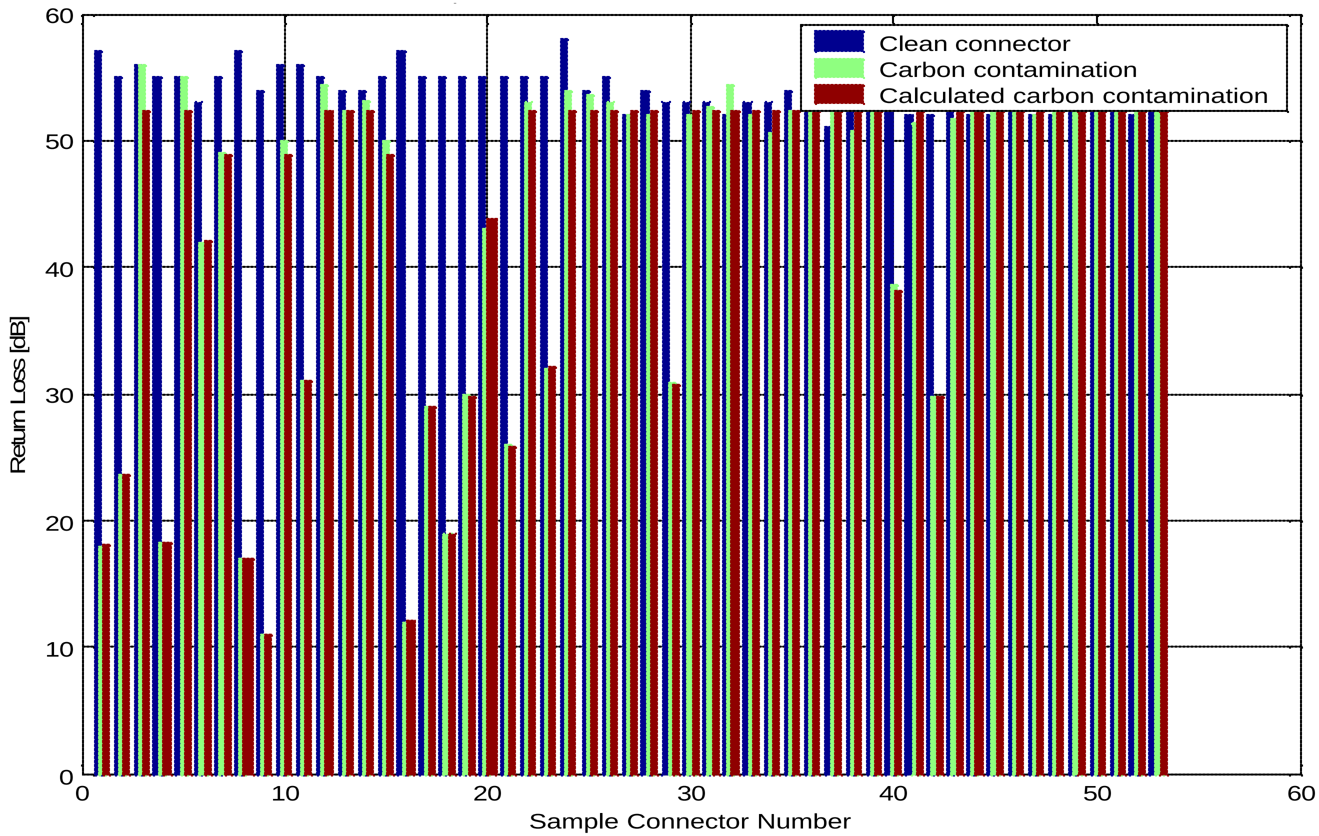
RL Modeling Data



- Particles trapped in between two endfaces result in air gap.

RL Modeling Data

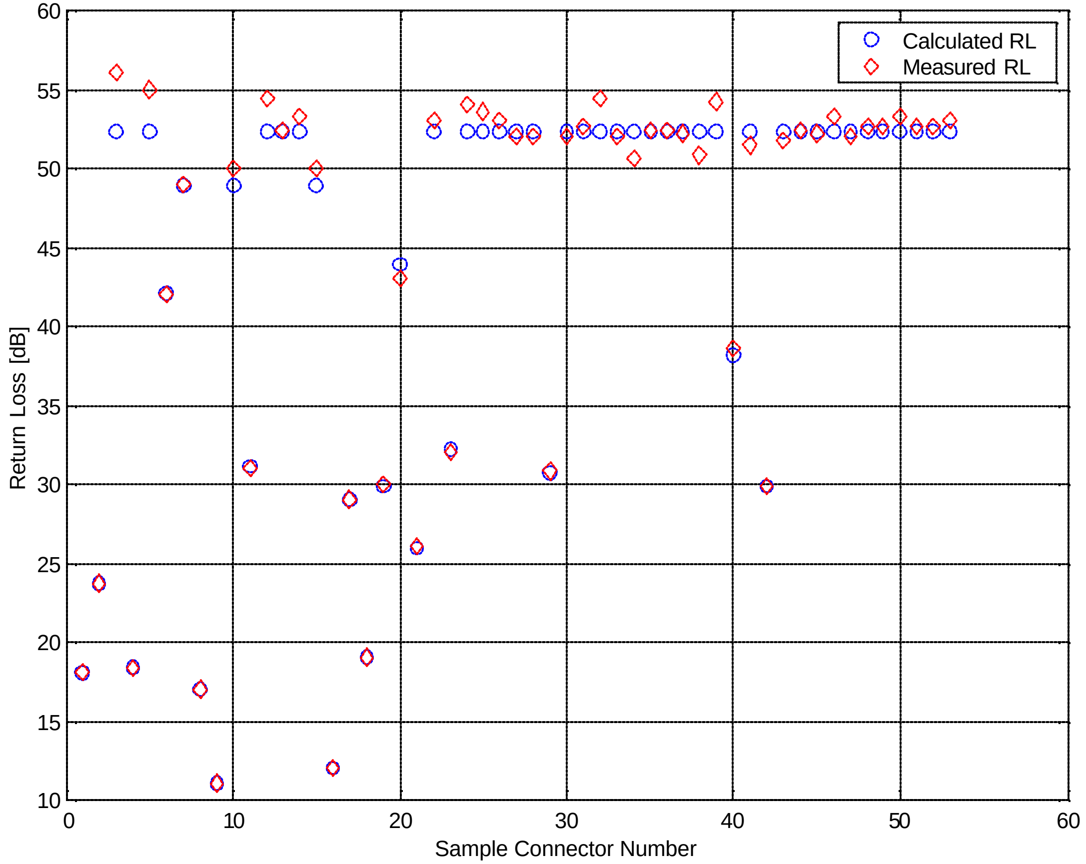
RL at 1550 nm



The air gap (contamination layer) can be estimated from RL measurements

Return Loss Modeling Data

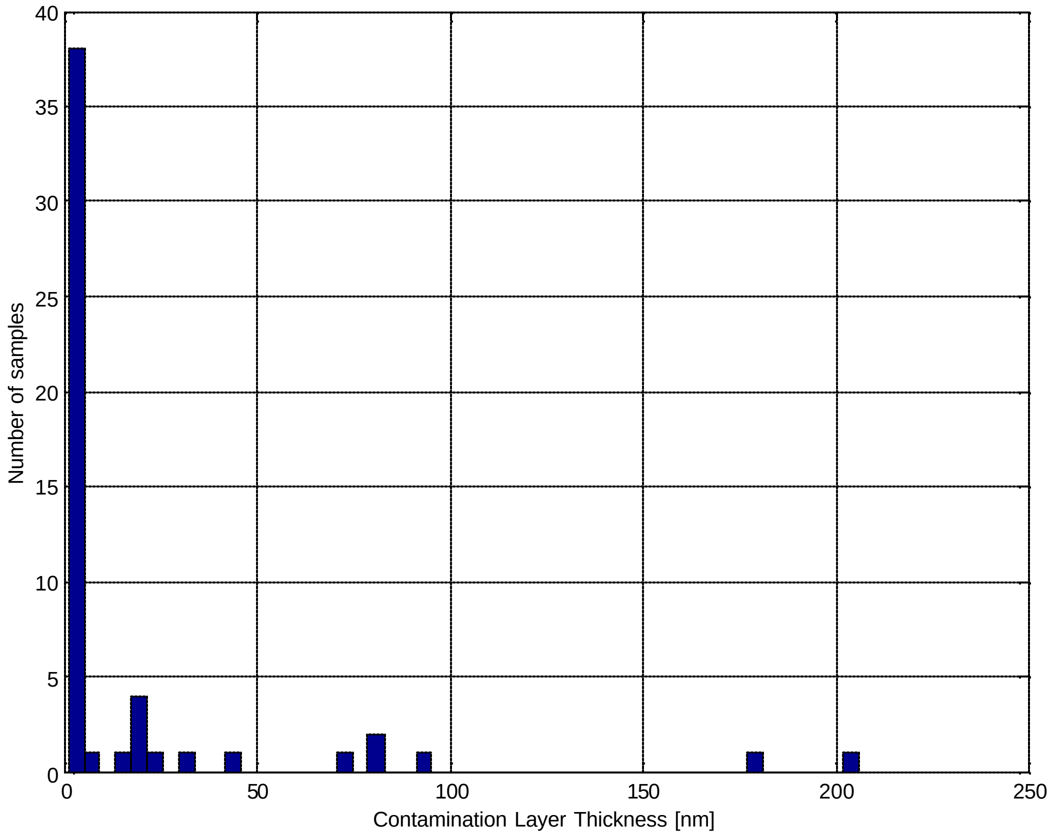
RL at 1550 nm



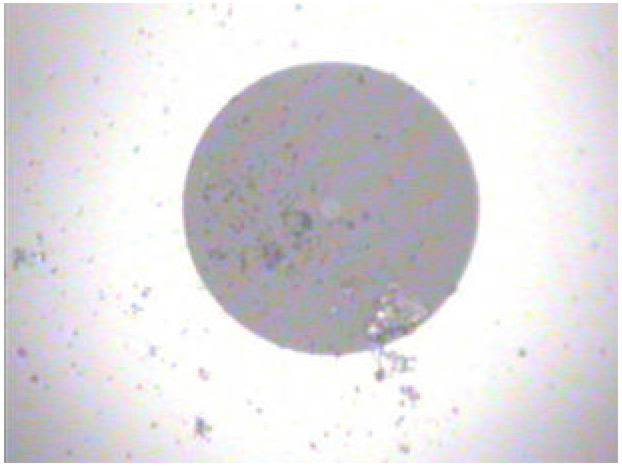
The air gap (contamination layer) can be estimated from RL measurements

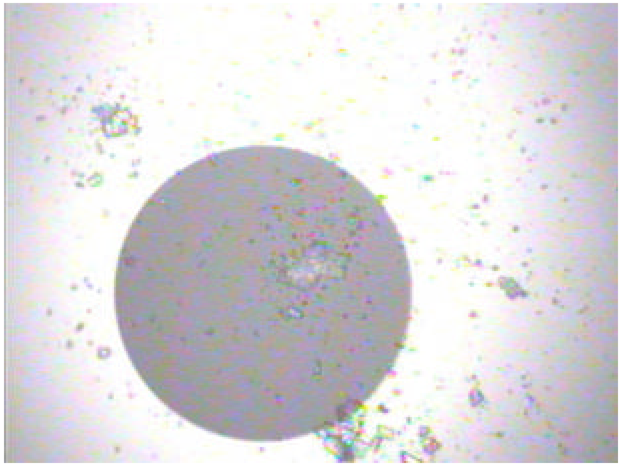
Return Loss Modeling Data

Histogram of the contamination layer thickness



Air Gap Calculation

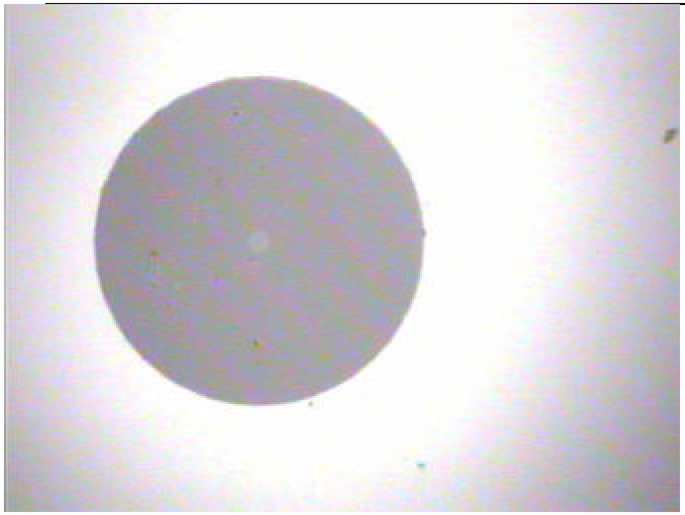




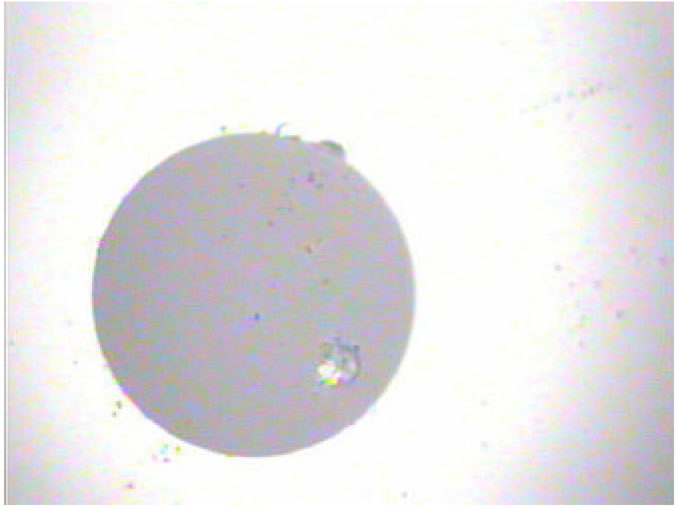
Test Connector #1B **Reference Connector**

The average IL clean=0.1 dB, RL clean=57 dB, IL contaminated =0.36 dB, and RL contaminated= 12dB. The thickness of the air gap was approximately 180 nm

Air Gap Calculation



Connector #19B



Reference Connector

An average IL clean=0.02dB, RL clean=55dB, IL contaminated=0.03 dB, RL contaminated=24dB. The calculated thickness of the air gap was ~80 nm.

Ferrule Contact Diameter Calculation

- **Contact diameter calculations for mated connector pairs**
  - **Minimum contact diameter 146 µm, 0.5 kgf, 5 mm end face radii**
  - **Maximum contact diameter 195 µm, 0.9 kgf, 30 mm end face radii**
  - **Estimated contact diameter range for test connectors, 156 – 185 µm**

- **Contact diameter equations**
  - **Ferrule end face deformation *h* at 0.5 kgf and 0.9 contact force**

$$h_{0.5}(R) = 1918 \cdot R^{-0.795} \qquad h_{0.9}(R) = 2368 \cdot R^{-0.795}$$

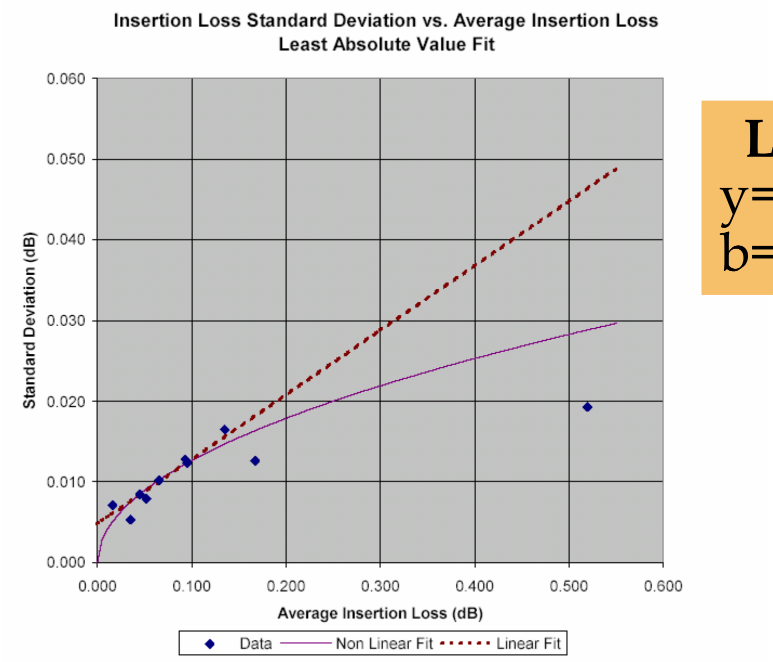
  - **Contact Diameter equation**

$$d_{contact}(R_1, R_2) = \sqrt{2 \cdot h(R_1) \cdot R_1 - h(R_1)^2} + \sqrt{2 \cdot h(R_2) \cdot R_2 - h(R_2)^2}$$

Insertion Loss Analysis

Non-linear model:

• y=2*aSqrt(4.343*x)/4.65, a=0.0446



Linear model:

y=a+b*x, a=0.0048, b=0.0800

- For SM connectors where the primary loss mechanism is lateral offset, over repeated matings the standard deviation of insertion loss is proportional to the mean of the insertion loss

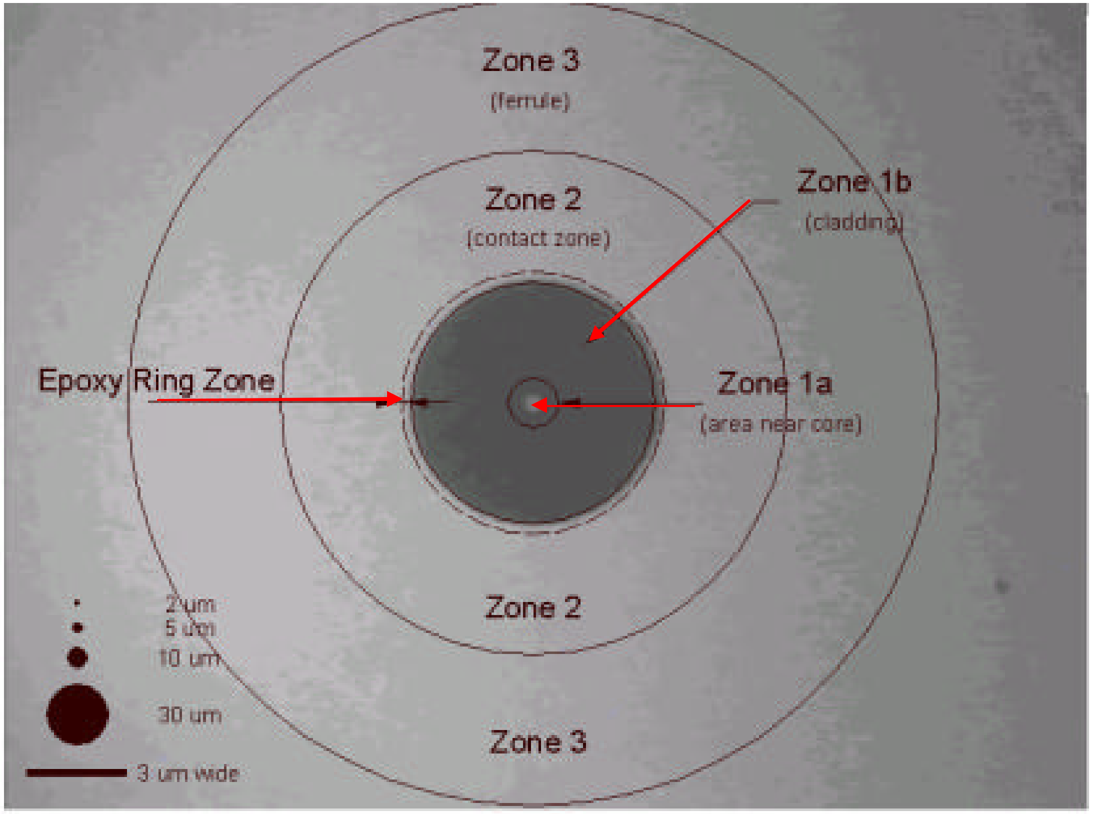
Inspection Criteria for SMF Pigtail and Patchcord Connectors

			Allowable Visible Contamination [1,2,3]	
Zone	**Description**	**Diameter**	**Non-Removables** [4]	**Scratch Width** [5]
1a	Area Near Core	< 25 um	None	None
1b	Cladding	25 um to 120 um	NRs < 2 um are Acceptable Total of 5 NRs < 5um None > 5um	None > 5 um
--	Epoxy Ring Zone	120 um to 130 um	Any	Any
2	Contact Diameter	130 um to 250 um	None > 10 um	None > 10 um
3	Ferrule Diameter	250 um to 400 um	None > 30 um	Any

Inspection Criteria Proposal

- Note 1: Any contaminants that are removable must be cleaned from the endface.
- Note 2: Any contaminants that fall across multiple zones are subject to the most stringent criteria.
- Note 3: Always use the largest (major) diameter when measuring the size of contaminants.
- Note 4: Non-Removable contaminants (NRs) are defined as "permanent non-linear features". This is equivalent to the IEC definition of "pits".
- Note 5: Scratches are defined as "permanent linear surface features".

Inspection Criteria Proposal



Ideal SMF SC UPC ceramic-ferrule endface

Conclusions

- The influence of Arizona road dust particles of 1-5 um and 6-25 um on the optical performance of single mode SC connectors was investigated
- Contamination of zone 1a near the core, (diameter of 25 um), with Arizona dust resulted in increase of an increase of IL up to 1.8 dB
- The contamination of zone 1a near the core, (diameter 25 um), along with the presence of clusters of particles with a diameter of more than 30um in the cladding layer may result in catastrophic changes of RL with changes of 10-40 dB
- It was shown that Arizona road dust of 1-5 um and 6-25 um on the cladding outside the 25 um zone 1a and the ferrule did not produce any performance degradation.
- Contamination with particles can prevent direct physical contact creating an air gap between two end-faces. The thickness of the air gap was calculated based on the RL data and was between 1nm and 200 nm.
- The acceptance of an industry standard for SM connectors will result in significant cost savings to fiber optics industry due to the elimination of insufficient cleaning and over cleaning and the reduction of contaminated non-conformance material.
- Further research will focus on the development of a cleanliness specification for MM connectors and receptacle modules.