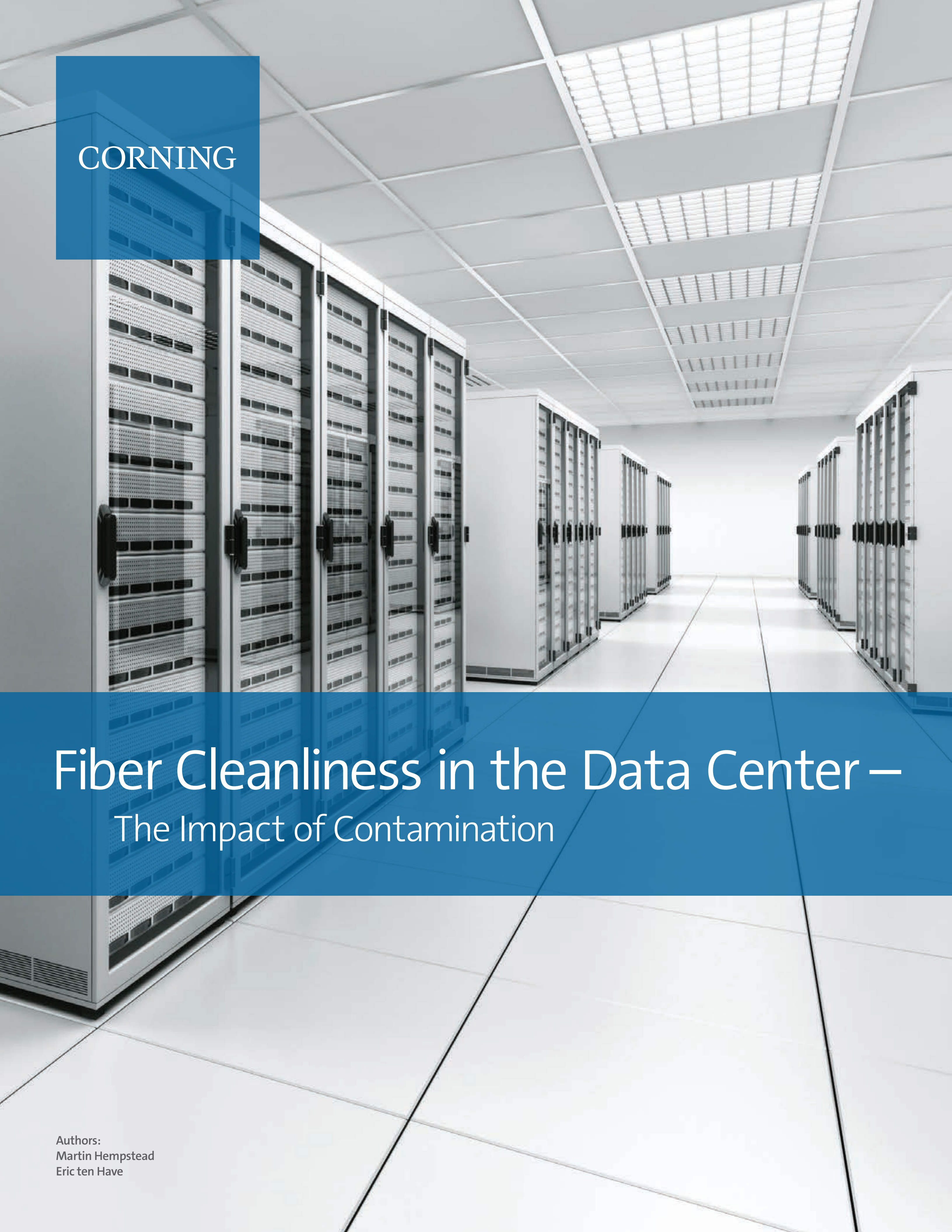

CORNING

Fiber Cleanliness in the Data Center –

The Impact of Contamination

Authors:
Martin Hempstead
Eric ten Have

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Introduction

Today's data centers demand ultra high speed and super low latency networks to support new technologies and applications being deployed around the world. The best technical solutions today are designed and deployed to transfer the exabytes of data required to support our social and professional interactions. All of this, however, can still be undone by a single piece of dirt, grease or even a skin flake on the end of a fiber connector.

This paper describes the impact of cleanliness in the data center and some of our findings in a study of debris and other contamination on optical connectors.

In this white paper, we discuss the effect of contamination on optical loss and highlight the challenges of estimating loss based on visual inspection. By investigating the nature of the contaminants and identifying contaminant reservoirs, we can study how they move to the end face. In doing so, it is also necessary to consider the challenges of reliably measuring the extent of contamination through image analysis, particularly in an instrument-independent manner. Finally, the paper concludes by looking at the impact of dust cap design and its contribution to contamination, and tests the possibility of eliminating connector end-face cleaning at the installation site while still maintaining good optical performance.

True Plug and Play – Why Cleanliness Matters in the Data Center

Corning's current recommendation is that customers clean, but don't inspect, all connectors on Corning product before installation. One key value proposition for clean connectivity is that it should allow installers to connect the equipment immediately after unpacking it, rather than first having to clean every connector, let alone inspect them, which is a common practice.

We have tested the practicality of this by measuring the insertion loss (IL) on a large number of MMF links like those that would be installed in a data center (Figure 1) using various cleaning paradigms. The results strongly suggest that products treated with an optimized cleaning process, as well as caps assembled without further cleaning (the "no cleaning in the data center" case) can perform as well as or better (in terms of IL distribution and number of IL failures) than product cleaned in the "field" just before link assembly.

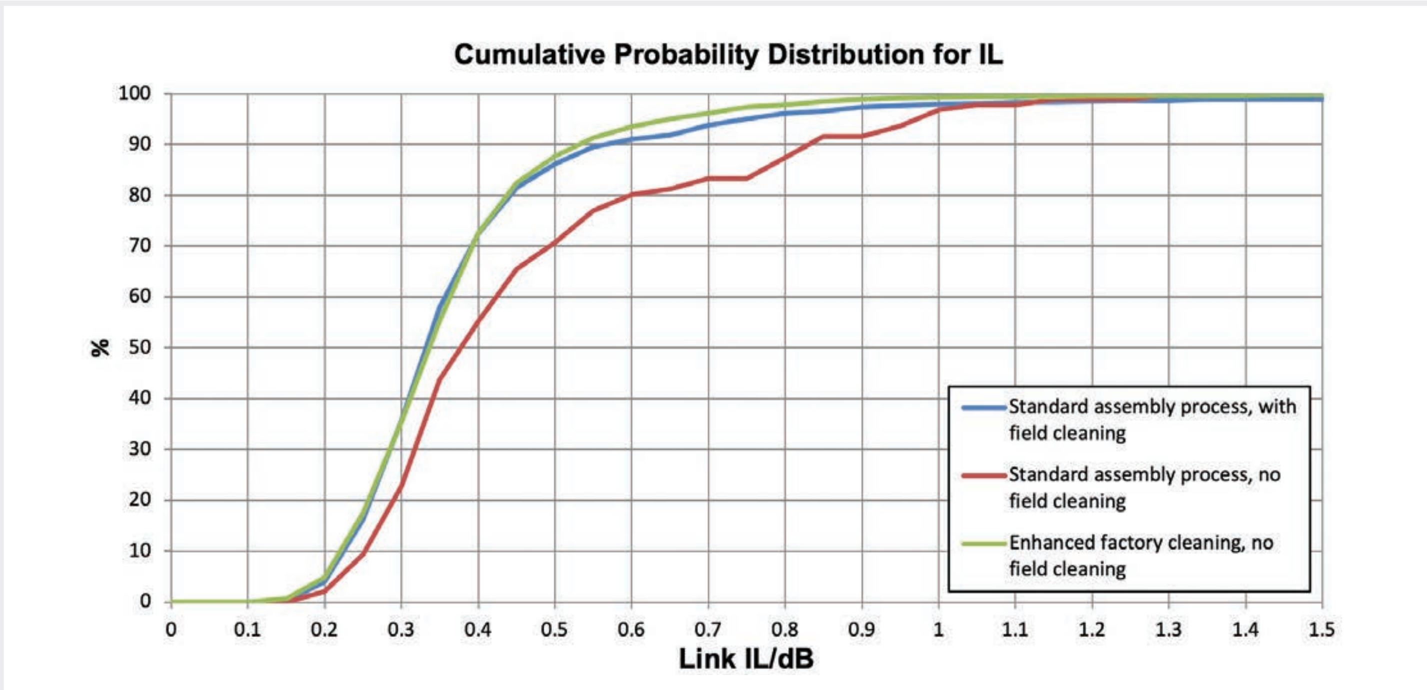

Figure 1: Comparison of IL measurements of a typical link architecture for the current process (standard assembly process with field cleaning, blue line) and the "no cleaning in the data center" case (enhanced factory cleaning without field cleaning, green line). Links consisted of two 12-LC to 1-MPO modules connected by an MPO-MPO jumper. The data shows that enhanced cleaning and the use of optimized caps assembled without field cleaning can perform equivalently or better than the current standard process. Data for standard product assembled without field cleaning (red line) is given for reference and performs worse than either of the other products.

Nature of Contaminants Found on Connector End Faces

Corning's current recommendation is that customers clean, but don't inspect, all connectors on Corning product before installation. One key value proposition for clean connectivity is that it should allow installers to connect the equipment immediately after unpacking it, rather than first having to clean every connector, let alone inspect them, which is a common practice.

We have studied the types of materials that can be found on the end faces of industry connectors using a variety of techniques, such as:

- Scanning electron microscopy (SEM) for morphological information and its associated energy-dispersive X-ray analysis (EDX) for data on the elemental composition
- Raman and IR spectroscopy for information on molecular composition

The results for single-fiber and multifiber connectors typically deployed in data centers are shown in Table 1 and Table 2, respectively. There is a very wide range of materials, many of which cannot be definitively identified, including:

- Skin flakes, identified as nitrogen-containing organic particles, which makes them indistinguishable from polyamide polymer particles from a compositional perspective
- Minerals and other inorganic debris
- Oils, and
- Many generic "organic" (carbon-containing) particles, some of which presumably derive from the injection-molded polymers used to form the connector housing components.

These were found on both single-fiber connectors with zirconia ferrules and on MPOs with glass-loaded polymer ferrules. The particle sizes and morphologies are also highly variable.

Listing of the different material compositions found on LC connector end faces.		
Polyamide (skin flake)	PET	Acrylic adhesive
Silica-reinforced epoxy resin	C/Al/salts	Cellulose
Organic	Polishing residue	CaCO3
Possible calcite	C with Fe/KCl particles	Talc
C/O particle (possible polymer)	Organic/salts	
C smear/stain	C/O/Na/Si/S/Cl/K fiber	

Table 1: Listing of the different material compositions found on LC connector end faces.

Listing of the different material compositions found on MPO connector end faces.		
Polyamide (skin flake)	NaCl particle	C/O/Si w/silica particles
C/O particle (possible polymer)	C smear/stain	Si/O particle
C/O/N particle	C/O/Si/Cl particle	Cellulose
Organic	PEI – Ultem (polyetherimide)	Delrin (acetyl resin)
LC – black plastic	SiC particle	C/N/Na/Si/Cl particle
K/Al/Si/O particle	C/Si/O particle	Organic salts
C/O/Si particle	C/N/Na particle	C/Na/Mg/Al/Si/K/Ca/Fe with KCl inclusions
Stainless steel	Microscope jig shaving	Silica
C/Na/Mg/Al/Si/Cl/K/Ca with zirconia inclusions	O/Mg/Si particle	C/O/Na/Al/Si/Cl/K/Ca particle
C/O/Na/Mg/Al/Si/S/Cl/K/Ca particle	Organic w/Al, Si and salts	
C/O/Si/N particle	C/N/Na/Cl particle	

Table 2: Listing of the different material compositions found on MPO connector end faces.

Impact of Contaminants in Fiber Optic Connections

There are at least two potential effects of contaminants on fiber optic connections in data center applications: lost optical power as light is scattered or absorbed (insertion loss, IL), which degrades the received signal-to-noise ratio and reflected power, which can interact with the signal source in SMF (return loss, RL). These can arise from the direct optical effect of the contaminants, from air gaps imposed by rigid contaminants, and from damage to the end faces caused by the contaminants.

Since the risk of mating contaminated end faces is high, there is a lot of interest in knowing how the optical performance is likely to be affected. In response to this interest, work has been done to estimate the expected IL for a given distribution of contaminants on the polished fiber end face of a connector.

One published model uses a power-weighted occluded area approach.[1] An image of the connector end face with a distribution of contamination is used as the input data; the contamination distribution is treated as an opaque mask so that each pixel on the fiber end-face image is either transmitting (no debris, 100% of power is passed through) or occluded (debris present, 0% of power is passed through). When this mask is superimposed on the power distribution passing through the fiber, the transmitted power, and, hence the IL, can be estimated. Of course, a connection involves two surfaces, so the masking effect of the two distributions of contamination must be combined.

This model can explain part of the IL performance, as seen in Figure 2 below taken from reference 1, where a clear correlation between the measured loss and the loss estimated by this process is shown. But the best-fit polynomial prediction is very far from perfect, falling well short of what would be required to implement pass/fail criteria with low false positives or negatives. Moreover, the magnitude of the loss is not consistent with the Gaussian-weighted occluded area – for example, if 30% of the power was absorbed or blocked, the expected loss would be 1.5 dB, not the 0.6 dB shown on the best fit.

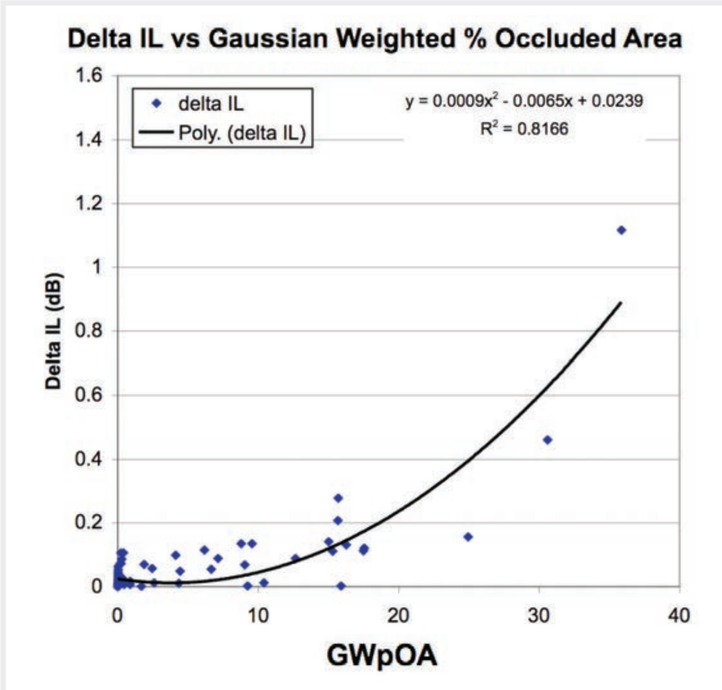

Figure 2: From reference [1]. Excess insertion loss due to debris as a function of the Gaussian-weighted occluded area (GWpOA). The data points (Delta IL) are fitted to a quadratic trendline.

This model is appealingly straightforward and easy to implement, but there are several factors not accounted for that make the predictions likely to diverge from the actual results. An accurate calculation of the loss from contaminants at the mating zone between two connectors requires the 3D distribution of contaminants, characterized by their optical properties, at the wavelength of interest after the connection is made. The contaminant distribution seen in a typical inspection scope lacks most of this information:

- The scopes typically use blue light for illumination, which is effective at giving a good spatially resolved image but does not indicate the optical properties at use for wavelengths in the near-infrared (near-IR).
- The optics in many inspection scopes seem to be designed to generate images with strong contrast; for example, this is done by picking up only light that passes directly through the end face or is scattered at only very small angles, so that most debris particles look dark. The scopes indeed reveal debris with very good contrast, but no information is available, even at blue light wavelengths, about the real and imaginary parts of the refractive index.
- The inspection scope image gives no information about the shape, material composition, or mechanical properties of the debris. Since physical contact connections involve enormous pressures, around 1,000 atmospheres in the case of an LC connector, to induce the required Hertzian contact deformation, most contaminants will be completely deformed in the connected state. The pressure will be even higher on smaller debris particles that create a gap at the interface. The optical performance of the contaminated interface will be determined by this deformed distribution of material; to know this distribution requires knowledge of the initial distribution in the unmated state and a model for the effect of the pressure on that distribution.
- For single-mode fibers, the occluded area model is even more inappropriate than for multimode fibers, since phase plays a major role in determining transmission. As an extreme example, a phase shift of one half of the fundamental mode by π radians would completely extinguish transmission, with no material absorption required at all – in this case, the light would be 100% coupled into the cladding.

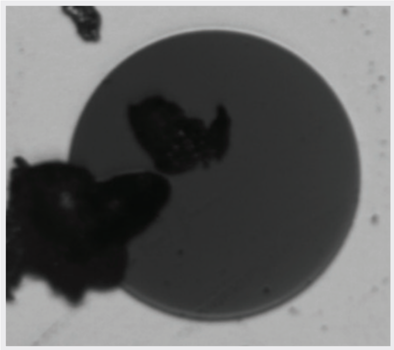

Figure 3: Skin flakes on a fiber and surrounding zirconia ferrule, as seen through a connector inspection scope. Note that the translucent skin flake appears completely dark.

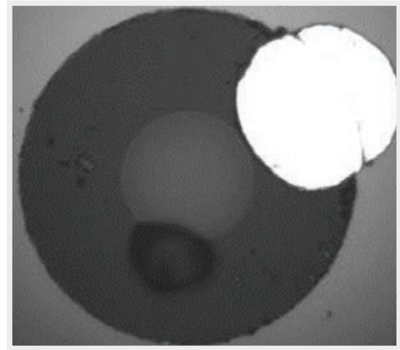

Figure 4: Image of the end face of a single-fiber connector with a steel disc (white) that has been crushed from a spherical shape by the connector mating forces.

Figure 3 above shows the appearance of a skin flake on an LC end face as seen through a benchtop connector inspection scope. The skin flake is completely dark, suggesting it is strongly opaque; however, skin flakes transmit quite well in the blue, although the light will typically be deflected by the irregular shape of the flake's surface. Note that the occluded area model would predict that a skin flake that completely covered the fiber would have a 100% loss, or IL of ∞ dB.

Figure 4 dramatically illustrates the enormous pressures acting at the optical interface in a physical contact connection. The white disc is actually a crushed steel ball, which was flattened when the connection was made. In this case, the ball was hard enough to damage the glass of the optical fiber. Consider the possible effects on something as soft as a skin flake.

To investigate insertion loss effects experimentally, we developed a technique to place particles on the fiber in single-fiber connectors. Particles were scattered on a thin glass sheet, and a microscope on one side of the sheet was used to guide a connector on the other side to make contact with and pick up one of the particles. The same microscope was used to image the particle on the connector after the glass sheet was removed.

Figure 5 below shows the appearance of particles of 3 different materials on the connector end face, after mating with a clean connector.

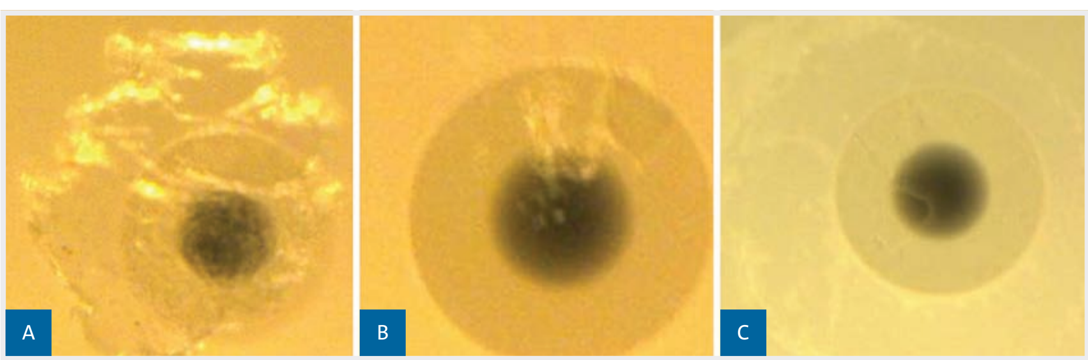

Figure 5: Particles deliberately placed over fibers in LC connectors to study effect of occlusion on IL: (a) Delrin®, (b) Ultem®, (c) skin flake.

Table 3 below gives the measured IL for each case. Note that since these images are taken with a normal lab microscope with a large numerical aperture, the appearance is quite different (and a color image can be produced because white light illumination is used). The losses cover a wide range and do not seem to be well-correlated with the degree of coverage seen in Figure 5. In particular, a skin flake that covers the entire core shows very little loss on mating – contrast this with the 100% loss that would be expected based on the appearance in inspection scopes (Figure 3).
This should not be taken to imply that debris cannot degrade IL, but that estimating the effect accurately requires far more data than provided by a simple inspection image.

Measured insertion loss for occluded connectors shown in Figure 5 above.	
Material	IL
Connection 1: Delrin®	0.08 dB
Connection 2: Ultem®	0.48 dB
Connection 3: Skin flake	0.01 dB

Table 3: Measured insertion loss for occluded connectors shown in Figure 5 above.

Imaging and Measuring Contamination on Connector End Faces

To really understand the effect of contamination and cleaning, we had to develop methods for assessing the contamination load on ferrule end faces. Current industry imaging systems and image analysis software are designed to deliver pass/fail judgments on end-face appearance, according to user-defined criteria. Generally, the criteria in the existing IEC standard 61300-3-35 are a popular choice, although these criteria really apply to surface damage rather than contamination. In fact, the IEC document calls for all loose debris to be removed before inspection – the term “loose debris” is defined as “particulate and debris that can be removed by cleaning;” from our point of view this is rather circular (we note that the IEC standard is under active review, which may impact some of the discussion and conclusions of this section). Under the influence of this standard, the software packages attend to the IEC inspection zones, a 250 µm diameter circle centered on the fiber core for single-fiber connectors, and just the fiber itself for MPO-type connectors. Some routines will even stop when the contamination level exceeds some threshold beyond an IEC failure. Thus, a clicker-cleaned end face could have an IEC pass while showing substantial contamination outside a central cleaned area, as in Figure 6 below. For our work, we needed software that would examine the entire end face and identify all the debris and other contamination on the end face and, just as importantly, accurately indicate the effect of a cleaning intervention, showing what features were removed – or added. This was particularly challenging for the MPO-type ferrules.

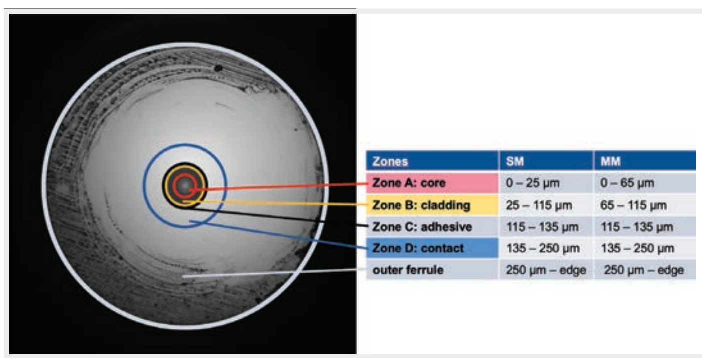

Figure 6: IEC inspection zones for a multimode LC connector (end face after deliberate contamination with oily material then cleaning with “clicker” cleaner stick).

The current IEC standard provides loose definitions for the qualification of the equipment itself using inspection artifacts. However, we have found that reliable debris detection depends upon several factors, none of which are defined in the standard:

- The effective resolution of the optical system – this is affected by the optics and working wavelength and incorporates the imaging chip pixel size and dynamic range.
- The precision of the focus (which may be an autofocus), particularly the focus repeatability. This affects the resolution which, in turn, affects image contrast.
- The illumination system – the wavelength, intensity, stability, and angular distribution.
- The mechanical stability of the apparatus – vibration of the image will reduce the contrast of debris particles and increase the apparent area, to the point where a particle may not be visible.

We used off-the-shelf imaging systems but wrote our own image-analysis software for each of the systems and connector types we worked with – LC, SC and MPO.

Typical results from imaging and image analysis are shown in Figure 7 and Figure 8 below.

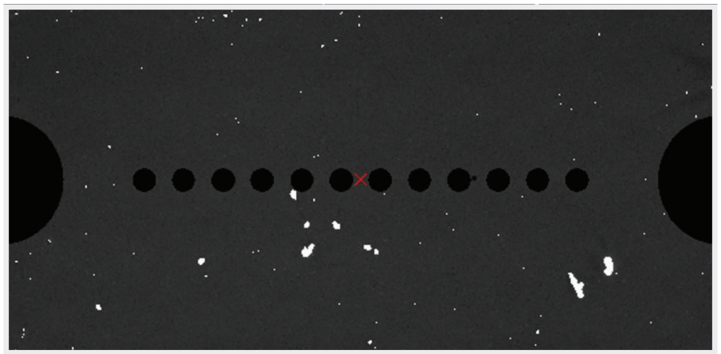

Figure 7: MPO end face after imaging and image analysis; identified debris particles are shown as white areas.

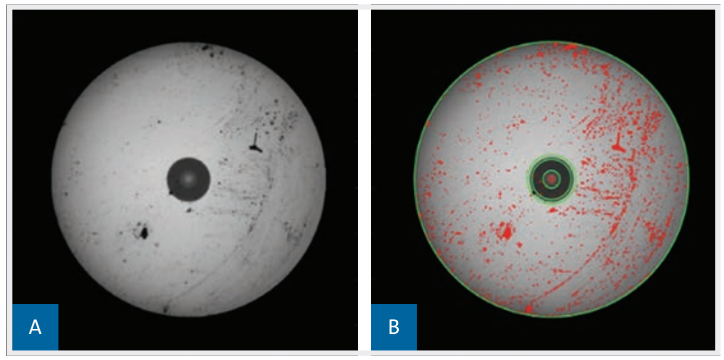

Figure 8: LC connector end face image, raw (a) and analyzed (b) -- identified debris shown in red.

Sources and Mechanisms of Contamination

The wide range of compositions found on connectors listed in Tables 2 and 3 is unsurprising, since the connectors are produced in a normal industrial production environment, and with varying manufacturing conditions. They experience a lot of processing and handling as they are made: the end faces are polished, capped and uncapped, and inserted into tight-fitting metal fixtures for inspection and measurement. Furthermore, the connectors are exposed to the processing and assembly of cable materials and housing parts.

A number of these sources are found not only in the manufacturing environment but also in installation environments where connectors are required to be uncapped and handled to be inspected and installed.

Polishing:

The polishing processes, whether carried out by lapping on wet polishing film or using abrasive slurries, produce liquid residues that contain particles abraded from the fiber and ferrules, as well as the abrasives. These residues, if allowed to dry, form a resistant film that is challenging to remove; signs of this type of contamination are strongly bonded streaks or smears on the end face. Polishing residues that dry on parts of the housing or cable jacket can later generate particulates that represent another source of debris.

Deposition of dust from the air onto exposed end faces:

While this does occur, it is at a very slow rate, and will typically result in loosely adhered debris that is easily removed. Figure 9 below shows some initially clean connector end faces that were mounted facing vertically upwards and exposed to air in a typical non-cleanroom environment for about one week. Clearly the rate of dust arrival is very slow, which is borne out by the fact that it is not common – although neither is it extremely rare – to see particles arrive on an end face while it is being inspected. The arrival rate and adhesion forces probably both depend on the state of the electrostatic charge of the end face. We have measured significant voltages (in some instances with magnitudes around 500 V) on end faces and even higher on other surfaces such as parts bags; the level of static charging is presumably influenced by humidity, by handling, and by friction during capping/uncapping.

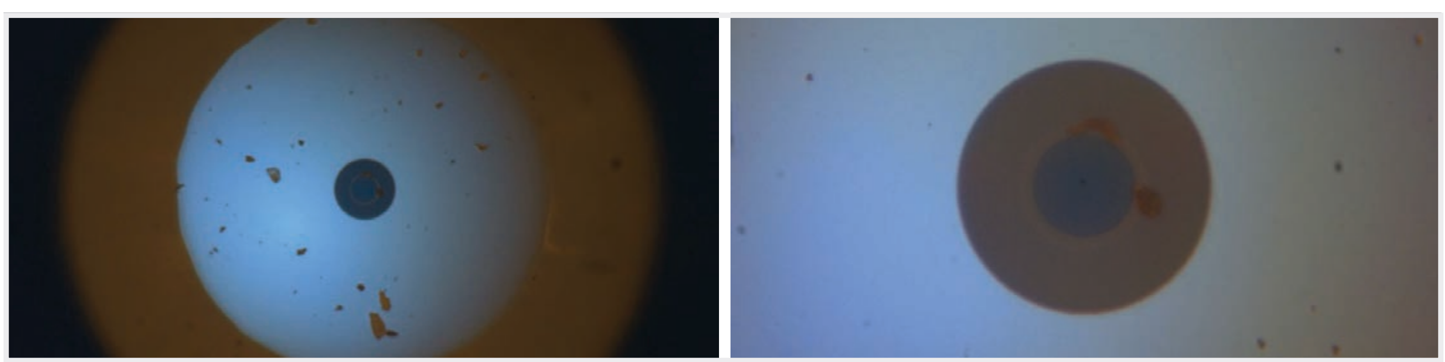

Figure 9: Results of exposure of initially clean LC connector, with end face up, to ambient air over approximately one week. Left: Full end-face field of view. Right: Expanded fiber area.

Cross-contamination from inspection fixtures:

Inspection scopes are used both in manufacturing and installation settings to examine end faces to assess compliance with requirements – absence of scratches, digs, and contamination. In these scopes, the connector ferrules are held tightly by mechanical fixtures to provide quick-and-easy alignment to the optical axis of the instrument. These fixtures have the potential to pick up debris and transfer it between connectors, as well as to generate further debris by mechanical abrasion. Such transfers can occur by mechanical contact or by the action of electrostatic forces. The steel ball seen crushed in Figure 4 was the result of just such a transfer, the steel ball originating from artificial "dirt" that had been applied to another connector examined in the same fixture (and note that the fixture had been cleaned and moved between labs after the contaminated connector was examined but before the image in Figure 4 was collected). The images in Figure 10 and Figure 11 below are stills from a video taken with a drilled-out commercially available scope fixture, showing the result of particles jumping under the influence of electrostatic fields.

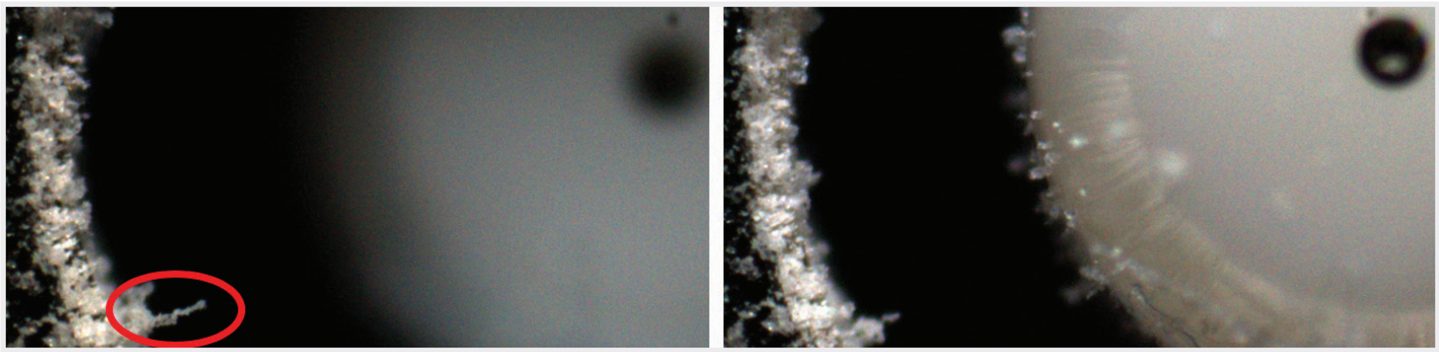

Figure 10: As an LC ferrule approaches a drilled-out metal fixture, a dust particle on the fixture (left) is pulled to the fixture by electrostatic forces (right). Both ferrule and fixture were deliberately and heavily contaminated to show the effect more easily.

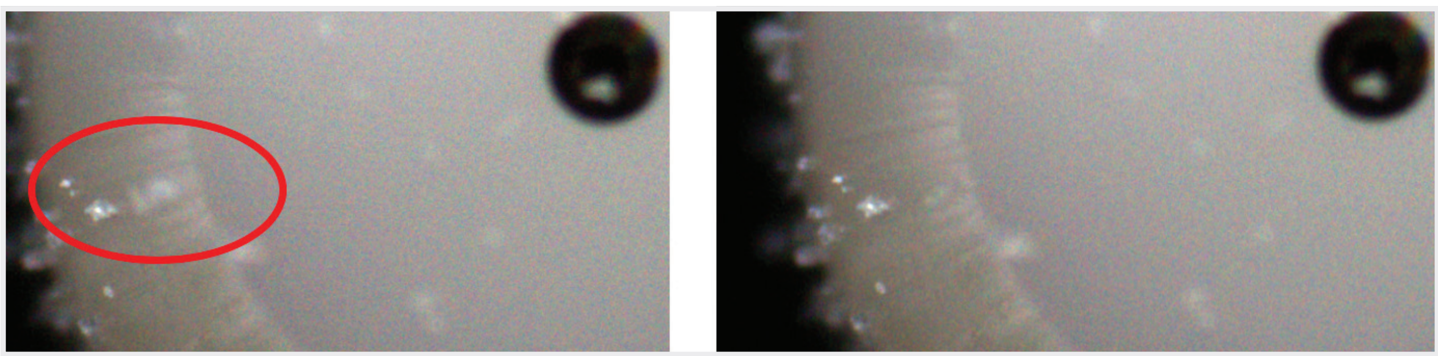

Figure 11: Shortly after the images in Figure 10 were collected, a dust particle on the ferrule (left) jumped from it, presumably again under the influence of electrostatic forces.

Handling:

In some manufacturing or installation settings, operators may or may not wear gloves or finger cots, so there is a risk that the connector end faces will pick up fingerprints or make contact with other areas of the skin. Some contaminants picked up from skin contact are surprisingly hard to remove, requiring abrasion with a solid wiper. Different areas of the body cause contamination of varying resistance to cleaning – nose oil is, as its name suggests, very oily and it is easily cleaned off, whereas contamination from the back of the arm is resistant to removal and requires a solid wipe. Fingerprints seem to fall somewhere in between – note that even the use of gloves does not avoid cross-contamination.

Contamination from dust caps:

Dust caps can carry particulate debris from the injection molding process. They can pick it up from the air, from surfaces they touch or from contact with other caps, and further debris can be generated by abrasive contact with extraneous surfaces (including ferrule end faces) or other caps. Such contaminants can be transferred to the end faces by known vectors: mechanical contact, mechanical shock (e.g., stick-slip motion when the cap is being pushed onto the connector), electrostatic forces or perhaps even air currents.

We have noted that debris on the end faces of single-fiber connectors, specifically those with beveled zirconia ferrules, tends to be located on the boundary between the central polished face and the rougher, beveled outer region. This suggests a combination of mechanical abrasion at that boundary, working against cap materials or fixtures if ferrule contact occurs during insertion, and cleaning action that is more effective in the center of the polished region.

In-process caps, used to protect the end faces as the connectors are being made, are often formed from PVC. PVC is compliant and flexible, but contains oily compounds, typically phthalates, to provide that flexibility. These compounds sometimes end up on the connectors as oily drops, which can form droplet rings around the contact region if the connector is mated.

Given the wide variety of material types and possible routes of contamination, including inherently dirty processes such as polishing, even assembling the connectors in a tightly controlled clean environment will probably not deliver acceptable end-product without a final cleaning step.

Even after the connector is fully assembled and capped, there are opportunities for it to pick up contamination before it is finally mated at the customer site.

In principle, although we haven't demonstrated this, storage under conditions of varying air pressure, temperature, humidity and/or in the presence of vibration might cause end-face contamination from particles or outgassed films.

Exposure to ambient air and inspection fixtures in installation environments carries a risk of contamination, just as it does in the assembly process, and no inspection regime will be able to avoid a final blind period when the connector is moved from the scope fixture through the air into an adapter for mating.

Through such studies, we have been able to map out some of the routes whereby particulates move onto the end face of the connector from the numerous debris reservoirs in the connector housing or the environment. One of these maps is shown in Figure 12 below.

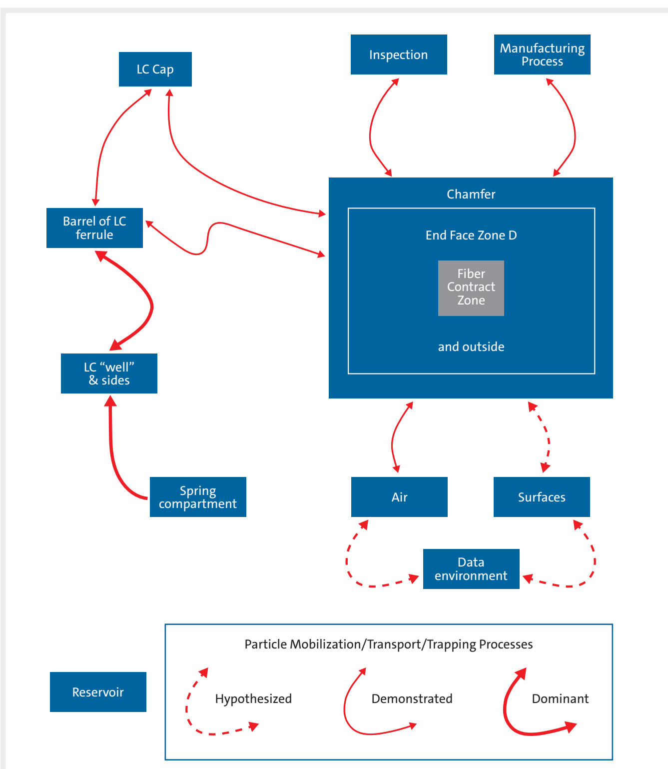

Figure 12: Map of debris reservoirs and debris transfer pathways for an LC connector.

Particle Migration

Particle migration from the outside onto the connector surface is referred to as a contamination event and was discussed in the previous section. However, particle migration may also occur within the surface area of the connector end face. No additional debris is added, but particles from the edge of the ferrule, where they do not interfere with optical transmission, may move into the core or cladding zones of the fiber, where they can cause issues with IL or RL.

Figure 13 shows a connector end face deliberately contaminated and cleaned with a clicker cleaner stick. This connector passes inspection by the IEC standard as the contamination is located outside the inspected area (zone D in Figure 6). If the contamination is only loosely bound, it can travel from the edge of the end face to the fiber area through handling or capping even without direct physical contact. We have observed instances of contamination moving through electrostatic forces or air movement during repeated cap/uncap cycles.

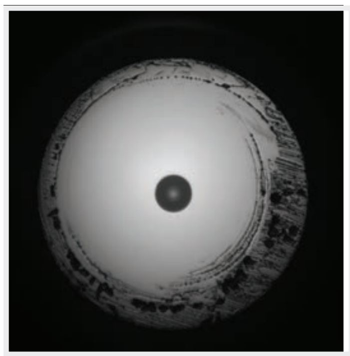

Figure 13: End face after contamination with oily material and cleaning with "clicker" cleaner stick.

During the connection process itself, the end face may also pick up debris from the other connector end face. Figure 14 below shows the transfer of contamination when a clean MPO connector is mated to a dirty one, presumably by mechanical contact.

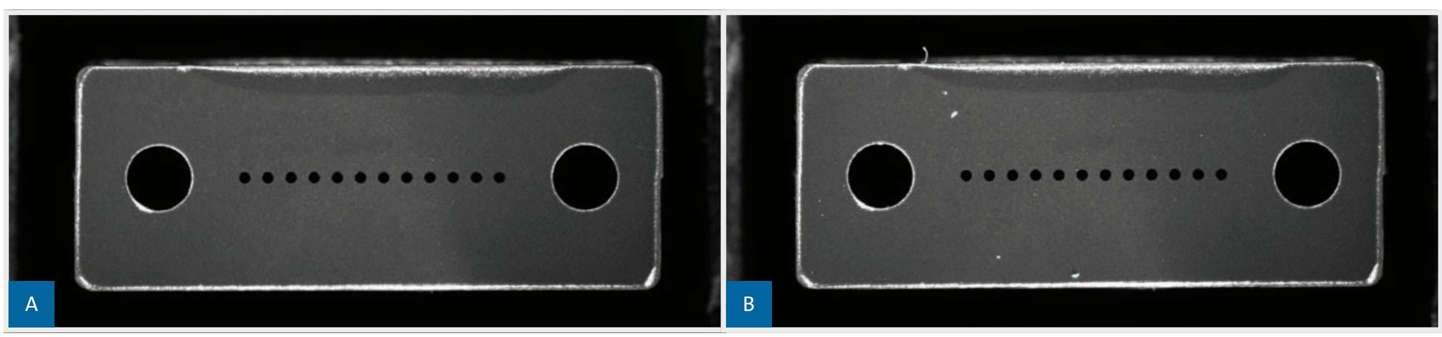

Figure 14: MPO connector after cleaning (a) and after mating with a dirtied connector (b), showing apparent transfer of contamination from one connector to the other.

It is thus of utmost importance to clean the entire end face to prevent debris from moving into a critical location after the final inspection. This will help deliver good IL performance of connections in the data center even without field cleaning (Figure 1).

Impact of Cap Design

We identified a need to design optimized caps, to address the risk of contamination and the migration of debris. Figure 15 shows a cutaway of a standard cap to illustrate this point.

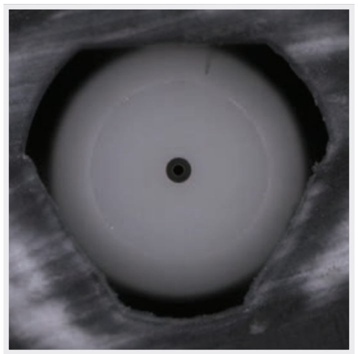

Figure 15: Cutaway of standard cap illustrating the high risk of introducing contamination.

In the course of this work we tried a number of standard and optimized cap designs and measured the effect of each on end-face contamination after capping/uncapping, in some cases with the connectors being shipped before uncapping and inspection. As shown in Figure 16 below, we found that only the standard caps added any contamination to the connector end face.

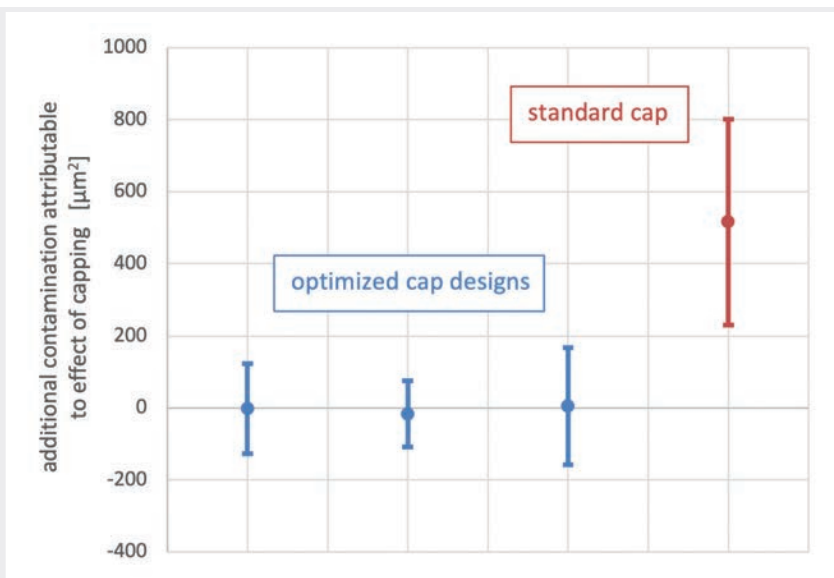

Figure 16: Final minus initial debris area after capping and uncapping clean LC connectors (with 95% confidence level error bars) for four different cap designs, three optimized designs, and one standard design.

We also tried different cap materials, including anti-electrostatic compositions, which were expected to perform better, but we did not see any advantage. There was a hint that the variation in cleanliness induced by capping then uncapping might be better for anti-static materials than for other compositions, but the statistics were weak, and this would have to be further investigated. Careful consideration is required before using these anti-static materials as they contain additives that might themselves cause contamination.

Conclusion

In this white paper we have reviewed work exploring debris and other contamination on optical connectors in the data center. We showed that evaluating the impact on optical loss using a high-contrast contamination field image is impractical and subject to large uncertainty because most of the information required to model optical loss is unavailable. Our studies about the nature of the contaminants revealed a wide range of chemical compositions and material classes. We discussed the numerous sources of these contaminants and the many paths whereby they make their way to the optical end face of a connector.

We touched on the challenges of reliably measuring the extent of contamination through image analysis, particularly in an instrument-independent manner, in the context of the IEC end-face inspection and end-face quality requirements. We also pointed out the risk of cross-contamination with the use of contacting fixtures during inspection, as the contamination of one dirty connector may spread and contaminate an initially clean population of subsequently measured connectors.

We looked at the impact of caps, specifically the advantages of optimized caps and the risk for standard caps to introduce additional contamination.

Finally, we pointed out the possibility of eliminating connector end-face cleaning at the installation site while still maintaining good optical performance through an enhanced factory cleaning that targets the entire connector end face.

Reference

[1] T. Berdinskikh, A. Ho, J. Garcia, C. Gleason, S. Huang, J. Kilmer, S. Lytle, T. Mitcheltree, B. J. Roche, H. Tkalec, D. H. Wilson and F. (Y.) Zhang, "Development of Cleanliness Specifications for Single-Mode Connectors with 1.25 and 2.5 mm ferrules," in Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference, Technical Digest (CD) (Optical Society of America, 2006), paper JThB85.

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Corning Optical Communications LLC • PO Box 489 • Hickory, NC 28603-0489 USA
800-743-2675 • FAX: 828-325-5060 • International: +1-828-901-5000 • www.corning.com/opcomm