

# IS THAT SPLICE REALLY GOOD ENOUGH? IMPROVING FIBER OPTIC SPLICE LOSS MEASUREMENT

## NEMI Fiber Optic Splice Improvement Project

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### ABSTRACT

Initial results from a National Electronics Manufacturing Initiative (NEMI) project, formed to improve the fiber optic fusion splicing process, are reported. The focus of this paper is ultra low loss splicing for telecommunications product assembly, with typical loss of <0.05 dB per splice for standard SMF-SMF. Various project participants using different equipment and procedures performed fiber preparation, splicing, splicer loss estimation, and actual loss measurements. Sets of data spanning three loss ranges, obtained with three different loss measurement methods were compared using an industry standard gage repeatability and reproducibility (GR&R) analysis. Also discussed is a detailed review and gap analysis of available standards from Telcordia, TIA, IEC, and other organizations, relevant to fusion splicer and splice loss acceptance criteria, as well as loss test procedures and metrics. In general, current standards have inadequate specifications for low loss splicing.

Key words: optoelectronics, optical fiber, fusion, splice, loss measurement, gage R&R

### INTRODUCTION

Fusion splicing is the preferred method for optical interconnection of fiber pig-tailed components used in OE products based on the requirements for low loss, stable joints. Low-loss fiber splicing has received renewed interest in recent years because of the trend of the OEMs to out-source to electronics manufacturing service (EMS) companies, leading to wider dissemination of product performance, optical assembly and test requirements. This in turn has led to increased realization of the need for more widespread and improved industry standardization in areas such as splice acceptance criteria and optical test.

Splice loss is the most important metric, particularly for internal product splicing since the loss budget, the maximum allowed loss for proper function of the optical circuit, is usually very stringent, e.g. a loss target of <0.05 dB per splice is common. The

interdependence of the factors that cause unpredictable variation in splice loss has been previously described. [1, 2] These include fiber batch properties (mode field diameter, core/cladding concentricity), fiber preparation processes (cleaved end face condition, presence of contaminants) and splicer parameters (arc power and duration), which affect core diffusion and alignment during splicing, and thereby the optical transmission of the splice. For low loss splicing, measurement uncertainty can be a particular problem, and the repeatability and reproducibility (R&R) of the optical loss test system is rarely assessed but assumed to be adequate.

For product splicing of pig-tailed components, actual splice loss measurement is usually not possible since the free ends of the fiber are not accessible for connection to a source and detector; therefore, it is necessary to rely on the splicer’s estimate of loss. Yet, it has been observed that the loss estimation values provided by a splicer often have poor correlation to the actual splice losses. The accuracy and distribution of the estimated loss values are critical because these determine the splice loss (pass-fail) acceptance criterion. Poor estimator accuracy requires setting the loss acceptance value well below the loss budget, to ensure a small number of bad splices escape. However, this results in a low splice yield and a large fraction of splices to be reworked, as well as likely rejection of good splices.

The practical aspects of low-loss, high-yield splice loss measurement and estimator accuracy were the main drivers for forming a National Electronics Manufacturing Initiative (NEMI) member project in mid-2002, with the primary objectives of improving the product splicing process yield and thereby reducing time and costs for assembly and functional test. The project group consists of several splicer equipment suppliers, a fiber manufacturer, EMS companies, and two OEMs.

The initial tasks of the project were selected by surveying the members for topics that ranked highly in terms of potential benefit, likelihood of success and members’ enthusiasm. A secondary factor

surveyed was whether the topic had been previously investigated, either by a member company or reported in the literature. The highest ranked activities were: (1) a review and gap analysis of available standards relevant to splicing, (2) an objective assessment of the various low splice loss measurement methods and setups used by the members, (3) a comparison of the accuracy of splicer loss estimators, and (4) to qualify a splice loss test method for dissimilar fiber types such as SMF to erbium doped fiber (EDF). Initial results on the first three of these activities are reported in this paper.

## STANDARDS REVIEW

The first major activity of the project was to perform a comprehensive review and gap analysis of industry standards relating to fusion splicer and splice acceptance, splice test, reliability, and environmental test requirements. The initial effort focused on reviewing the standards readily accessible to the members, and this was extended as further standards were obtained. [Refs 3-13] Because of space limitations, only the standards most relevant to splicer and splice loss acceptance as well as insertion loss test methods and equipment are discussed here. It should also be made clear that while we attempted to be thorough in our compilation and review of the standards, the project members did not have access to copies of all potentially relevant standards, including the full range of IEC standards.. [14-16] The standards are not clear whether a splice should be considered a fiber or a passive component, and because classification as a pig-tailed component or device may sometimes be more appropriate, relevant fiber standards were also reviewed.

### Splicer and Splice Loss Acceptance Standards

The reviews of standards relating to fusion splicer and splice optical loss are summarized in Table 1. The term “passive” splicing used in Telcordia GR-1095 refers to mini, micro or ribbon splicers utilizing “cladding ” (more appropriately referred to as fixed V-groove) alignment or viscous centering, as opposed to “active” splicing used by full feature core alignment or LID (light injection and detection)

splicers. (This is somewhat confusing since “active splicing” is widely used to describe achieving a desired loss value using feedback to the splicer from an external source and power meter.) A potential conflict between the splice mean loss and loss yield requirements and objectives criteria in GR-765 is discussed in the initial list report (ILR). [7] For example, a set of 20 splices could have 19 low loss splices and a single high loss splice, and meet the yield requirement of 95% of splices  $\leq 0.10$  dB, but fail the mean loss  $\leq 0.10$  dB requirement. Telcordia also states that the splice loss estimator accuracy requirement (and objective) in GR-1095 specify limits for 90% and 100% of the population, which is practical, but conflicts with the criteria in GR-765, which applies to all splices of the set.

The important gaps across the standards reviewed to date are summarized as follows:

- Current standards do not cover dissimilar fiber splicing, such as SMF to EDF. There is a strong need for a new standard to address dissimilar fiber splicing.
- Newer fiber types, such as 80/165  $\mu\text{m}$ , NZ-DS, LEAF, etc, are not mentioned. This is not surprising since some standards are more than six years old.
- Most of the standards concentrate on outside plant or field splicing for optical network applications and do not address module assembly applications.
- Insufficient attention is given to fiber preparation processes, which are critically important to achieve low loss and high splice yield. Default guidelines should be provided.
- Splice loss test procedures (source stability, measurement accuracy and repeatability, etc.) are generally inadequate for low loss product splicing, with typical loss requirement of  $<0.05$  dB per splice.
- Reporting requirements should include the preparation acceptance criteria and fusion splicer settings.

	<b>GR-765</b> Single Fiber SMF Splices and Splicing Systems	<b>GR-1095</b> Multi-Fiber SM Splices and Splicing Systems	<b>BT LN 469E</b> Machines Joining for Single Fiber Fusion Splicers
<b>Test fiber</b>	≤ 0.4 μm core eccentricity. TIA fiber classes IVa & IVb	Nominal geometry error, diameter 125±0.3 μm, core-cladding concentricity ≤0.4 μm	>0.4 μm core eccentricity. Fiber per CW 1505 and CW 1504
<b>Mean splice loss</b> (R = required, O = objective)	R4-85 ≤0.10 dB for fiber with nominal geometry error	R4-104, R4-110 (module) ≤0.15 dB (passive ribbon splicing)	Mean not specified
	O4-86 ≤0.05 dB	O4-105 ≤0.10 dB (passive splicing) O4-111 (within module) Std. dev. ≤0.1 dB per joint	3.1 (O) Losses follow Weibull distrbn. (shape param 1.6 & characteristic value ≈ 0.05 dB)
<b>Splice loss yield</b>	R4-89 95% of splices, ≤0.10 dB	R4-107 95% of joints have loss ≤0.20 dB	3.1 (R) 95% ≤0.10 dB and 99.8% ≤0.15 dB (implies data set n>500)
	O4-90 95% of splices ≤0.05 dB	O4-108 95% of joints have loss ≤ 0.10 dB R4-109 (within module) 100% <0.40 dB	
<b>Loss estimator accuracy</b> (CR = condition for requirement)  (CO = condition for objective)	CR4-55 Within ±0.10 dB for actual loss ≤0.40 dB. Within ±25% for actual loss >0.40 dB (n=10 splices). NB implies 100% of est. losses	CR4-62 For actual loss ≤ 0.40 dB, 90% of estimates within ±0.10 dB of actual loss, 100% within ±0.25 dB. For actual loss >0.40 dB, 90% of estimates within ±25% of actual loss, 100% within ±50%.	3.16 ±0.10 dB on fiber with known core offset ≥0.4 μm, with random orientation Mean difference between est. and actual losses ≤ 0.02 dB (n=100 splices)
	CO4-56 Within ±0.05 dB for actual loss ≤0.40 dB Within ±15% for actual loss >0.40 dB	CO4-64 For actual loss ≤0.40 dB, 90% of estimates within 0.05 dB of actual, 100% within 0.10 dB. For actual loss >0.40 dB, 90% of estimates within 15% of actual loss, 100% within 30%.	

**Table 1.** Key Standards Requirements Relating to Fusion Splicer and Splice Acceptance

### Splice Loss Test Standards

Standards relating to splice loss measurement methods and test equipment are summarized in Table 2. A number of important gaps have been identified as listed below:

- TIA 455-34A does not mention the geometry error or nominal tolerances for test fibers, e.g. core concentricity, which is specified in Telcordia GR-765 (see Table 1). Neither standard addresses other important fiber properties such as mode field diameter (MFD), core effective index and backscatter coefficient. This information may not be necessary for the in-line methods, in which a single fiber is cut and spliced. However, in the cutback or bare fiber adapter (BFA) methods, in which the two fibers are likely to be dissimilar, differences in the intrinsic characteristics of the fibers need to be considered.
- Measurement accuracy is specified in some standards. For example Telcordia GR-326 (singlemode optical connectors and jumper assemblies) calls for accuracy within ±0.05 dB (section 5.2), and TR-001196 (splice verification

sets) requires ±0.2 dB and an objective of ±0.1 dB (section 4.1.1), for losses between 0.0 and 1.0 dB. [7, 9] However, the standards do not describe how to measure accuracy. There is a need for traceable standard components (fiber splices or attenuators) in the low loss range of 0-0.05 dB, to avoid extrapolation and assumptions of linearity from the higher attenuation ranges covered by commercial instruments.

- A source stability of <0.01 dB (Telcordia) is barely adequate for low loss splicing in the range 0-0.05 dB, where measurement repeatability of 10% of the range requires stability of ±0.005 dB, or better. The best current data (in-line sets I-1 & I-2, see Results and Discussion section) demonstrate that short-term stability of ±0.001 dB is achievable. However, the TIA 455-34A (section 3.1.3) target of ±0.02 dB is inadequate. At the same time, TIA provides for more precise low loss measurement by including a source monitor to control source drift.
- The TIA specification for detector resolution of 0.01 dB, for losses <0.5 dB, is also inadequate for low loss measurement.

- Useful information on test set-ups, such as coupling the fiber to the detector (e.g. integrating sphere), use of fiber loops as high order mode filters, and isolators to prevent back reflections, is generally omitted. TIA 455-34A (sections 4.3 & 4.4) has the best coverage and mentions that for SMF, the fiber coating is often sufficient to function as a cladding mode stripper, fiber lengths can be as short as 2 m, and there should be no bends with radii <3 inch within the test fibers.

Both the in-line and BFA methods are covered in TIA 455-34A, although TIA refers to “cutback method” or “pigtailed devices” when describing the loss tests described in this paper as BFA. Of the various standards reviewed, TIA 455-34A comes closest toward satisfying the need for a precision loss measurement method, and with some modification and additions, it could be adopted as a standard for very precise loss measurements.

	<b>GR-765</b> Single Fiber Single-Mode Optical Splices and Splicing Systems	<b>GR-1095</b> Multi-Fiber Single-Mode Optical Splices and Splicing Systems	<b>GR-198</b> Optical Loss Test Sets	<b>TIA 455-34A</b> Interconnection Device Insertion Loss Test	<b>TIA 455-8 and 59</b> Measurement of splice or connector loss and reflection using an OTDR
Splice insertion loss test method (attenuation, transmittance)	5.1.4.1 In-line with selectable (optical switch) reference fibers, also OTDR per TIA 455-59.	5.1.4.1.1 In-line, measure continuous fiber, then break, splice and re-measure. Optical switch to select test or ref fibers. Also OTDR method.	Optical loss test sets (OLTS) used for outside plant optical network. Hand-held types with integrated optical source & power meter	1.1, 1.3, 5.1 & 5.2 SM splicing (test method B), procedures. In-line version and cut-back equivalent to “BFA”. Recommends source monitoring.	OTDR , single fiber
Source wavelengths and spectral width	1310 and 1550 nm	5.1.4.1.4 1310 ± 20nm and 1550 ± 20nm spectral width ≤ 75 nm	R4-1 Dual λ capability. At 1310 nm: LED ≤140 nm, laser ≤5 nm. At 1550 nm: LED ≤150 nm, laser ≤5 nm	3.1.1 660, 850, 1310 & 1550 nm. Center wavelength ±30 nm, spectral width <140 nm for 1310 nm (LED or laser diode)	850, 1300, and 1550, ± 20 nm
Source stability	5.1.4.1.4 <0.01 dB over measurement period	5.1.4.1.4 <0.01dB over period required to make one set of measurements	R4-2 Within ±0.5 dBm over 8 hr period at (23±2°C)	3.1.3 “Greater” of ±0.02 dB over period of test or 10% of max attenuation	Not specified
Accuracy	Not specified	Not specified	R4-17 ≤±0.5 dBm at Pin -10 dBm Optionally -25dBm	Not specified	Calibrated to ≤ 0.05 dB
Detector range, response power (RP) and linearity	5.1.4.1.4 ≥60 dB below source power Linearity not specified	5.1.4.1.4 ≥60dB below the source power Linearity not specified	R 4-11 Min RP -55 dBm Max RP +1 dBm Linearity not specified	3.4 Must measure all power emitted from output fiber. Linearity within 5% of range of power	None specified
Resolution	Not specified	Not specified	Not specified	3.6.2 Better than 0.01 dB for loss <0.5dB	Min. reportable loss of non-reflective “event” (splice) ≤0.10 dB

**Table 2.** Standards Specifications for Insertion Loss Test Methods and Equipment

## EXPERIMENTAL METHODOLOGY

To achieve a better understanding of the relevance of current standards for low loss splicing, the different optical test systems were assessed relative to the loss range of interest. For low loss splicing, an acceptable measurement discrimination of 10% of the range requires measurement precision of  $\pm 0.005$  dB. Since it was not known which, if any, of the various measurement systems used by the project members were capable of achieving this target, they were compared against the same measurement repeatability and reproducibility criteria.

### Stability Test Method

To assess the stability of optical power for each measurement system, a series of tests were conducted to monitor the drift of optical power over time. During these tests, each system was referenced and allowed to drift for a period equal to the time required to complete a set of fusion splices and loss measurements. For each measurement system, three runs were conducted with thirty data points acquired evenly over the evaluation period. The maximum deviation from the reference, across all three runs, was used as the metric for source stability.

### Gage R&R Test Method

To assess the repeatability of each test system, a gage repeatability and reproducibility (GR&R) study was conducted. This investigation required the production of 10 splices for each process range. The three process ranges under investigation were 0–0.05 dB, 0.05–0.15 dB and 0.15–0.30 dB. In order to obtain data points that fully span each process range, changes to arc time and arc power, as well as intentional attenuation splices, were made, as required. Each splice was measured three times, using one to three operators in a random order, resulting in three to nine measurements per splice. These repeated measurements also captured the variation resulting from fiber handling. Between each measurement, the operator moved the fiber to simulate the handling that would normally occur during splicing. Once the fiber was returned to a resting position, the splice loss was recorded. This data was then used to determine the measurement R&R by calculating the 99% spread of this distribution, taking into account both the equipment and appraiser variation represented by each data set. [17] The range based GR&R procedure determines the commonly quoted percent R&R by calculating it as a fraction of the total variation.

$$\% R \& R = 100 * \frac{R \& R}{TV} \quad (1)$$

$$R \& R = \sqrt{EV^2 + AV^2} \quad (2)$$

$$TV = \sqrt{R \& R^2 + PV^2} \quad (3)$$

Where R&R = Repeatability and Reproducibility  
EV = Equipment Variation  
AV = Appraiser Variation  
PV = Parts or Process Variation  
TV = Total Variation

In the analysis of data from this study, the total variation (TV) was replaced with the formal process range under investigation, as is done in a tolerance-based analysis. This was done to consistently calculate the repeatability of several independent data sets as a fraction of the range under investigation. Ideally, a measurement system should provide a percent R&R value of  $\leq 10\%$  for acceptable discrimination, 10-30% for marginal and  $>30\%$  GR&R for poor. [17]

$$\% R \& R = 100 \frac{R \& R}{Range} \quad (4)$$

The errors associated with stability and repeatability were combined using a root sum of squares approach that assumes the variables were independent.

### Gage R&R Test Procedure and Setups

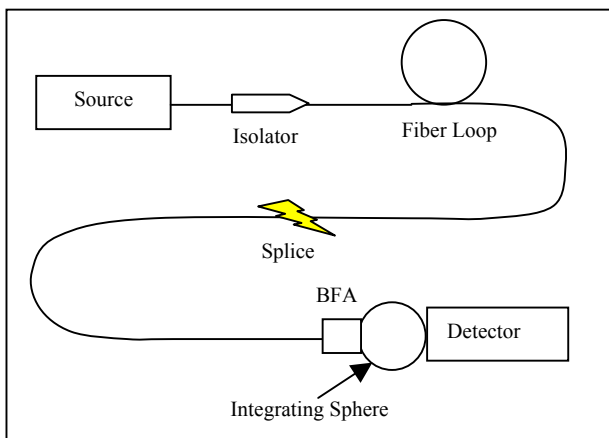
Techniques commonly used to measure splice loss usually include an optical power source and meter or an OTDR. There are many variations possible when using a power source and meter, but in general they fall into one of two categories. With the in-line method, the fiber ends remain fixed throughout the entire testing process. In the BFA method, also known as the “cutback” method, the fiber directed to the meter is reconnected for every measurement and splice. These methods begin with setting up a reference fiber, then measuring the splice loss compared to the reference. For the standard SMF used for all measurements described here, the fiber under test has negligible intrinsic loss over the length. If the fiber has significant loss, this has to be included in the splice loss calculation.

### In-line Method

The initial setup consisted of a reference fiber between a source and a meter. The source was allowed to stabilize and the meter’s wavelength was matched to the optical source. Once the setup was reasonably stable, the power meter was referenced. Then, the fiber was cut in the center and spliced back together, with the new meter reading representing the splice loss. [18] A schematic of the in-line test method is shown in Figure 1.

There are several setup variations that may make the in-line method more accurate and robust. Patchcords that attach the fiber to the power source and meter will protect the connection ports from damage and make the connections more resistant to handling or accidents. Using a length of fiber over 20 m or wrapping a shorter fiber around a mandrel several times (per TIA 455-34A) will remove light from the fiber that may be traveling in

the cladding. [11] An isolator can be used to ensure the source stability is not affected by back reflection that can cause fluctuation in laser launch power, although many sources have an internal isolator. The use of a low reflection optical connector (angled polish, APC type) at the source can also reduce the effects of back reflection. To improve mechanical integrity, the fiber sections that will not be moved during testing can be secured, preventing unnecessary movements and ensuring stable connections. An integrating sphere can also be used with a BFA at the detector. Ideally, a BFA and an integrating sphere will remove any measurement dependence on how the fiber is attached to the detector. This allows reconnecting to the power meter with reduced impact to connection repeatability. See Figure 1 for some possible variations in the setup, many of which were used for the gage R&R tests performed by the members of this project.

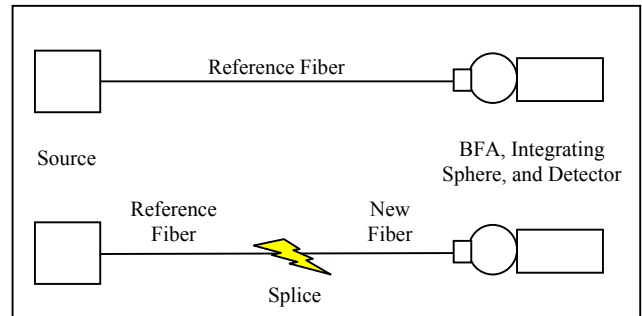


**Figure 1.** In-line Method Setup. A simple setup only requires a source, detector and fiber.

### BFA Method

In the BFA method, one end of the fiber remains fixed in the source, while the end directed to the power meter is constantly changing to a new fiber for each sample. Due to the changing fiber end face, it is important to have a BFA receptacle on the detector, or BFA-integrating sphere, to minimize the variability of the connection. As with the in-line method, the BFA method began by waiting for the source to stabilize and matching the source and detector wavelength settings. The fiber end directed to the power meter was prepared and inserted into the BFA. The BFA was then inserted into the detector or integrating sphere, as shown in Figure 2. Once the system stabilized, the power meter was referenced. Next, the fiber was removed from the BFA. A new piece of fiber was cut, prepared at one end and inserted into the BFA. The other end of the fiber was spliced to the reference fiber. The new reading on the meter indicated the splice loss (assuming the fiber added had negligible loss). Subsequent measurements on a single splice were made by removing the fiber from the BFA, re-preparing the end and reinserting the fiber into the BFA. Further samples were made by cutting out the additional fiber, re-zeroing

the reference fiber, and inserting a new fiber between the reference fiber and the BFA as with the first sample. Many of the same setup variations can be made for the BFA method as for the in-line method.



**Figure 2.** BFA Method Setup: Before and After the Splice is Made

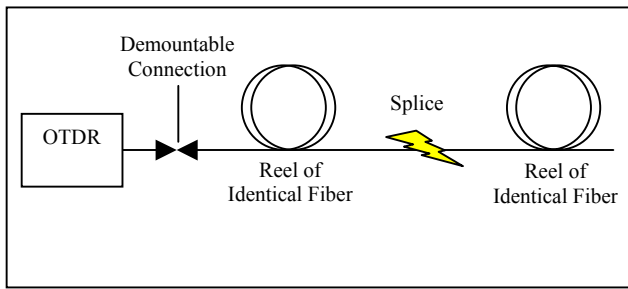
### OTDR Method

The Optical Time Domain Reflectometer, or OTDR, has been in use for fiber optic installation, testing, and repair for more than 20 years. [19, 20] The instrument launches a powerful pulse of light into a fiber, then monitors the light coming back up the fiber. By constructing a chart of received signal versus time, and converting “time” to distance by knowing the speed of light in the fiber ( $c/n$ ), the OTDR creates a chart of all measurable attenuation effects in the fiber, such as splices and connectors, versus their distance from the meter. In this case, it was of interest to evaluate the potential of the latest OTDR’s for accurate measurement of very low loss fusion splices.

The use of an OTDR for fusion splice and splicer evaluation is described in Telcordia GR-765-CORE and particularly detailed in TIA/EIA fiber optic test procedures (FOTP) 455-8 and 455-59. [12, 13] However, the splice loss values described in these procedures are relatively high compared to the typical values desired in manufacturing, and it was not known whether it is practical to extend these methods consistently within the loss regime below 0.05 dB.

The gage R&R method was used to evaluate the OTDR for the measurement of low loss splices in Corning SMF fiber. Unlike the in-line and BFA methods, it was decided that neither source stability nor the linearity test was relevant. Since the OTDR is continuously self-referencing, all backscattered readings are relative to each launch pulse, the stability of the optical source over a period longer than pulse return time is irrelevant.

The OTDR test method is shown in Figure 3. The meter was connected to a 2.2 km reel of SMF fiber through a short connectorized jumper. The test splices were made between this reel and a second 2.2 km reel of SMF fiber certified identical by the manufacturer.



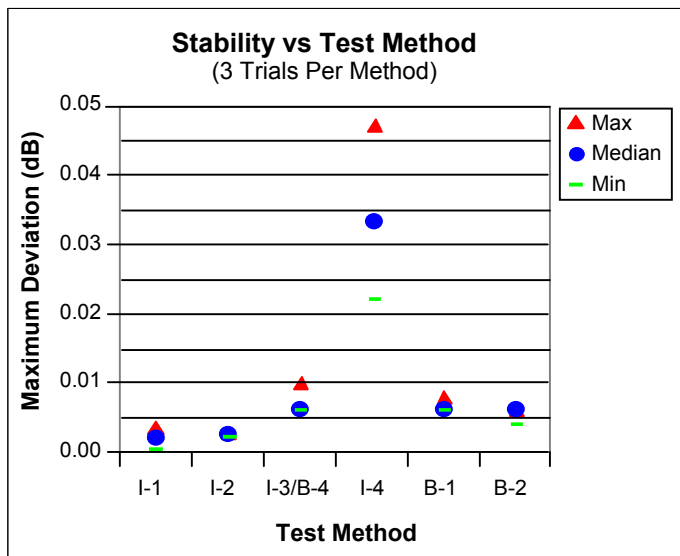
**Figure 3.** Schematic Diagram of OTDR Test Setup for Splice Loss Measurement

Thirty splices were made and tested as outlined in the Gage R&R test method. Care was taken to select OTDR settings, particularly pulse width (long) and averaging time (at least 30 seconds), to optimize its loss calculation accuracy. The 4-point linear slope analysis (LSA) method was used automatically by the OTDR for loss calculation of non-reflective events.

## RESULTS AND DISCUSSION

### Stability Test Results

The results shown in Figure 4 and Table 3 summarize the stability data for each test system. Maximum drift values were found to vary from 0.0028 to 0.0472 dB across test systems. While the accuracy impact of these values will depend on the magnitude and range of losses being measured, even the largest range under investigation would be significantly affected by the worst case stability, as it accounts for 30% of the process range. Although the key factors influencing stability are not discussed in this paper, the results emphasize the need for verification of test methods, even when using standard industry equipment in relatively simple applications.



**Figure 4.** Stability of the Different Test Methods

	I-1	I-2	I-3/ B-4	I-4	B-1	B-2
<b>Max Drift (dB)</b>	0.0034	0.0028	0.0100	0.0472	0.0080	0.0060
<b>Median Drift (dB)</b>	0.0020	0.0026	0.0060	0.0332	0.0060	0.0060
<b>Min Drift (dB)</b>	0.0004	0.0020	0.0060	0.0222	0.0060	0.0040
<b>Max/Low Range (%)</b>	6.8	5.6	20.0	94.4	16.0	12.0
<b>Max/Mid Range (%)</b>	3.4	2.8	10.0	47.2	8.0	6.0
<b>Max/High Range (%)</b>	2.3	1.9	6.7	31.5	5.3	4.0

**Table 3.** Stability Test Data (Two-sided Values are Shown)

### GR&R Test Results

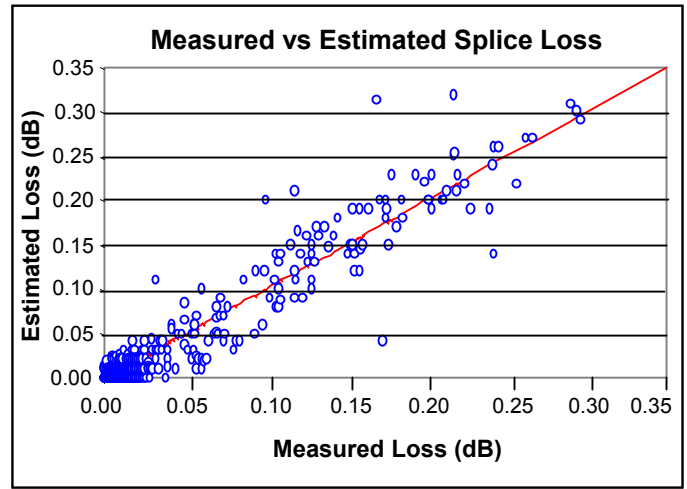
The data in Figure 5 and Table 4 provides a summary of the variation due to measurement repeatability and stability across the lowest range investigated (0-0.05 dB), a range frequently encountered during the manufacture of optical assemblies. Four groups used the in-line method (I-x), four used the BFA method (B-x), and one used the OTDR method (O-1). Considering only the % R&R data, it is interesting to note that only 5 of the 9 methods were able to meet the 10% threshold and obtain a rating of “adequate”. The addition of the stability results further degraded the performance with only two of the methods now meeting the 10% threshold.

It is also interesting to note that significant levels of variation could be found both across and within each test method. For example, even within the in-line test method, results varied by a factor of three or more. The percentage of repeatability and reproducibility over the total process variation ranged from 2.4% to 16.1%. Similar results are shown for the BFA method. Group B-3 obtained a very high value, which is indicative of a faulty gage.

The results of the study indicate that many of the commonly used methods for assessing optical power loss need careful implementation and assessment to achieve trustworthy and meaningful results. Also, the data did not suggest that any one method (in-line, BFA, OTDR) was consistently superior. Perhaps more detailed factors, such as splice and test equipment, testing environment, and whether or not an isolator is used, play a bigger role than anticipated. These findings further emphasize the need for standards that detail splice loss test methodologies. The current detail available in the standards reviewed is insufficient to achieve acceptable R&R for low loss measurement.

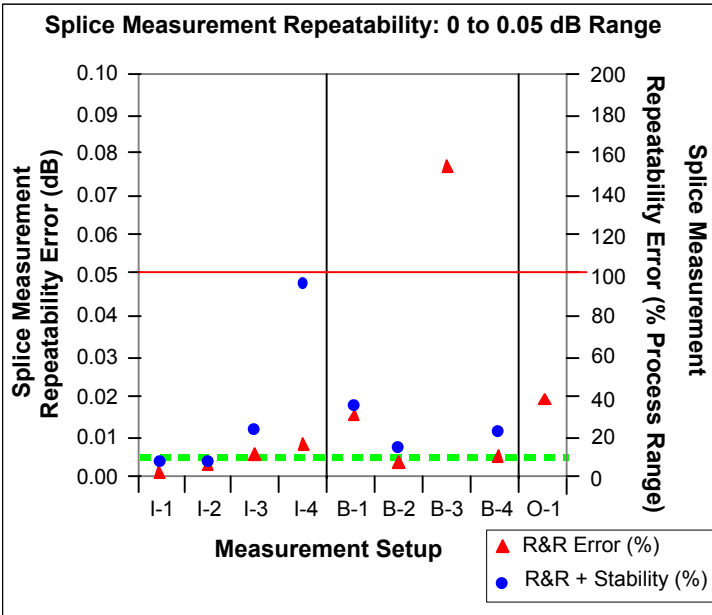
	R&R (dB)	% R&R (%)	Stability (dB)	% R&R + Stability (%)
I-1	0.0012	2.4	0.0034	7.2
1-2	0.0026	5.3	0.0028	7.7
1-3	0.0054	10.9	0.0100	22.8
1-4	0.0080	16.1	0.0472	95.8
B-1	0.0154	30.7	0.008	34.6
B-2	0.0036	7.2	0.006	14.0
B-3	0.0769	153.8	---	---
B-4	0.0052	10.3	0.010	22.5
O-1	0.0190	38.1	---	38.1

**Table 4.** Gage R&R Test Results (Two-sided Values Shown). Note: Stability assessment was not made for method B-3 and was not required for the OTDR method O-1.



**Figure 6.** Measured vs. Estimated Splice Loss, 0.00 to 0.30 dB Range

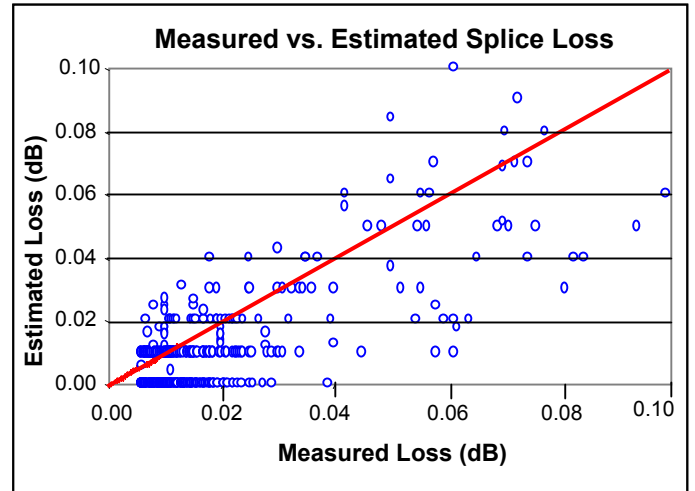
While the estimations shown in Figure 6 appear to provide reasonable agreement with measured values, this is partially due to the large splice range used in the scatter plot. When the range is reduced to below 0.1 dB, as shown in Figure 7, the degree of scatter becomes significant relative to the loss values. Poor correlation in the low loss region is an important concern for product splicing with standard SMF.



**Figure 5.** Splice Measurement Repeatability over the Low Range for All Test Methods

### Splice Loss Estimation

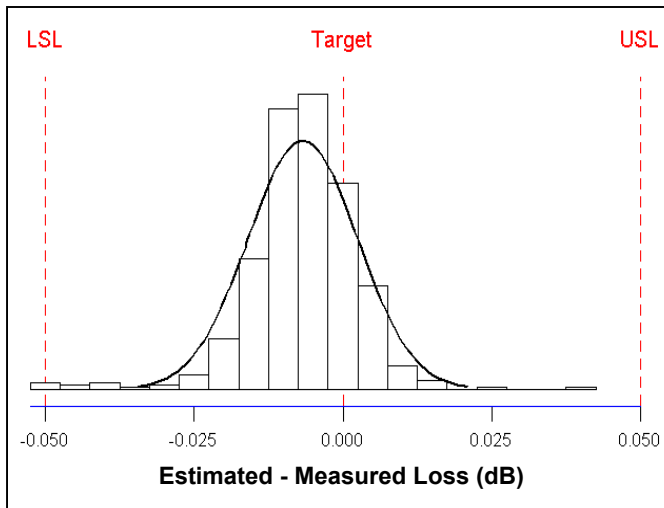
During the assembly of fiber optic products, it is not always possible to directly measure splice loss or control the splicing process using an optical source and power meter. Under these circumstances, the splice loss estimator is essential for monitoring and controlling loss and ultimately product quality. However, the data in Figure 6 illustrates that estimation systems are by no means perfect. Ideally, each point of estimation would fall on the 45° line. In practice, considerable scatter can be seen about the 45° line.



**Figure 7.** Measured vs. Estimated Splice Loss: 0.00 to 0.10 dB Range

The use of loss estimators, at this performance level, could certainly cause incorrect assignment of completed splices. Labeling a “good” splice as “bad” will often result in unnecessary rework at the splice station. However, labeling “bad” splices as “good” may result in a product continuing through the assembly process only to fail during test at a later date. This can become quite costly as performing the required failure analysis and associated repair can be very time consuming when dealing with complex and fully assembled optical products.

In order to refine the discussion of estimators, it is useful to consider what metrics could help define and quantify performance. This would facilitate defining estimation requirements and simplify the comparison of several estimators. There are several approaches to assess estimator capability, for example see Refs 1, 2 and 21. Generally, there is a desire to analyze the difference between the estimated loss and the actual loss, which is assumed here to be the measured loss for simplicity. Additionally, it would be convenient to consider both the mean offset and the distribution width of these delta (estimate – measured) values with a single metric. One metric, which satisfies both these requirements, is the process capability index (Cpk value). [22]



**Figure 8.** Process Capability Analysis on Deltas (Estimate - Measured)

The plot shown in Figure 8 demonstrates how the estimation error can be analyzed using this technique. In this case, arbitrary limits of 0.05 dB and -0.05 dB were used with a data set of 474 samples to achieve a Cpk value of 1.56. Furthermore, applying the three standard deviation limits around the mean of the deltas would provide a method for quantifying the extent of the process width of the estimator error. Applying these techniques to data acquired with several different estimation systems, provided the results shown in Table 5. As expected, the Cpk value identified Estimator 1, which had both the smallest mean and standard deviation, as the best performer.

As previously stated, the limits used in this analysis were somewhat arbitrary. However, these could easily be defined in relation to the acceptable error, e.g. 10 to 30% of the process range. This would allow the Cpk to provide ranking between estimator systems as well as an indication of performance in more absolute terms. For example, tolerance limits of  $\pm 0.05$  dB may be acceptable for a high loss range. However, limits in the order of  $\pm 0.01$  dB would likely be more informative for the low loss range.

Estimator / Splicer	Loss Range	Sample Size	Mean	Std Dev	Mean + 3 Std Dev	Mean - 3 Std Dev	Cpk
1	Low	10	-0.001	0.006	0.019	-0.020	2.55
2	Low / Mid	21	0.002	0.015	0.046	-0.042	1.08
3	Low / Mid	474	-0.007	0.009	0.021	-0.034	1.56
4	Low / Mid	38	-0.005	0.018	0.050	-0.059	0.83
5	Low / Mid	20	0.013	0.030	0.102	-0.077	0.42
6	Low / Mid	20	-0.011	0.019	0.046	-0.068	0.68
7	Low / Mid	33	0.011	0.023	0.081	-0.059	0.55

**Table 5:** Analysis of Splicer Estimation Error for Low and Mid Loss Ranges

While this analysis was useful in illustrating one method of quantifying estimator performance, a more comprehensive study is recommended to produce Cpk values in which all variables except the estimation systems are controlled. For example, the data sets in this study used various splicing techniques to “artificially” produce a wide range of values. However, these splicing techniques were not randomized across all estimation systems. Since each estimation system may have varying performance, which is dependent on the loss mechanism, the results in Table 5 may be biased.

This raises the issue from a both a comparison and application standpoint of how best to test loss estimation accuracy. It also highlights what might be some of the fundamental limitations of loss estimation that need to be kept in mind when developing loss budgets and acceptance criteria based on loss estimation. Artificially induced high loss or attenuation splices may not be indicative of typical loss mechanisms encountered in a production environment. They may also have been induced by a mechanism that is difficult to detect by loss estimation techniques. The most common methods of splice loss estimation are based on a visual inspection of the fiber cores at and around the splice point. While visual inspection may be very accurate at identifying and estimating loss due to core misalignments, it may not be sensitive to excess loss due to “overheating” of the splice, which can locally alter the mode field diameter due to core dopant diffusion. While “overheating” may have a significant impact on splice loss, it has very little effect on the visual appearance of the splice and therefore could be “overlooked” by visual loss estimation. While other methods of estimation, such as LID, may be better suited to detecting this type of loss mechanism, each method will have different limitations that need to be kept in mind when developing acceptance criteria.

With an understanding of the limitations of loss estimation and the development of a method for statistically quantifying loss estimator errors, system designers will be better able to establish loss estimation acceptance criteria that are “Designed for Manufacturability”. If for example, it is known that visual loss estimation techniques are not able to accurately detect losses due to MFD mismatches, then a separate allowance can be given to the statistical variation of this fiber parameter and its potential contribution to the loss budget. Similarly, if fusion splice manufacturers can gain a better understanding of the performance metric that is important from a manufacturing / loss budget standpoint, then they can work towards improving the methods and techniques used to estimate splice loss.

### CONCLUSIONS AND FUTURE ACTIVITIES

The review and gap analysis of current standards for splice loss acceptance criteria and loss test methods, showed that they are inadequate for low loss splicing. The most significant gaps are in the areas of fiber preparation, loss test procedures, measurement accuracy, source stability, and detector resolution. Of the standards, reviewed, TIA 455-34A comes closest to meeting the requirements for a precision loss measurement method. A possible follow-on project activity is to develop a capable loss test method for dissimilar splices, such as SMF-to-EDF, which may lead to development of a new standard to address this important gap.

Of the three insertion loss methods evaluated, the in-line method gives the best precision for the low loss range of 0-0.05 dB; however, when source stability is included, only two of the users achieved the acceptance target of 10% of the range. While the causes of measurement variability are not discussed in this paper, the results emphasize the need for improved definition of insertion loss test methods and systematic verification of test equipment and results, even when using standard industry equipment in relatively simple applications. This is particularly important for the BFA or cutback method, since this may be the most suitable method for loss measurement of dissimilar fiber splices.

The relative process capability index,  $C_{pk}$  appears to be a useful parameter for comparing splicer loss estimator systems, although the magnitude depends on the choice of specification limits. In the present study, there are probably too many possible contributors to variability, including fiber batch, splicer parameter settings, techniques used to achieve high loss splices and errors in the loss measurements obtained with different methods, to make conclusions about the accuracy of the splicer estimators. A possible future activity will be to investigate the performance of different splicer estimators when some of these variables are controlled.

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