Mass Fusion Splicing of Optical Ribbon Fiber: Manufacturing Process Development

by

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Bachelor of Mechanical Engineering, Georgia Institute of Technology

Submitted to the Department of Mechanical Engineering and the Sloan School of Management
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Mechanical Engineering
and
Master of Science in Management

in Conjunction with the Leaders for Manufacturing Program at the
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ABSTRACT

Celestica, a global electronics manufacturing services provider specializing in high-technology products in computing and communication, has recently established a leading position in the relatively young optical networking equipment manufacturing industry. In order to solidify its leading position and identify new opportunities for growth in this area, Celestica must proactively develop new manufacturing processes to meet current or future customer demand.

This work describes the process used to identify the best available process equipment for mass fusion splicing, a process which Celestica believes will be valuable to its optical networking equipment customers. An overview of optical networking, fiber optics, measurement systems analysis, and designed experimentation is provided as project background. The design and analysis of the measurement system employed in the project is described in detail. The experimental design and data analysis leading to the final conclusions are discussed, with emphasis on the time/cost/accuracy tradeoffs inherent in the practice of designed experimentation. Finally, the project is analyzed in the context of Celestica's business strategy.

Thesis Advisors:
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Finally, I would like to thank my most trusted advisor, my best friend, and my biggest fan, my wife Michelle Chassereau Jackson. Thank you for your love, patience, caring, and support through what have been two very exciting and challenging years.

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1.0 INTRODUCTION

This work is based on a six-month internship at Celestica New England in Portsmouth, New Hampshire that began in June 2001. Celestica Incorporated is a global electronics manufacturing services (EMS) provider headquartered in Toronto, Canada. Originally formed in 1994 as a subsidiary of IBM, Celestica was purchased by its management and Onex Corporation in 1996. Since 1998, Celestica (CLS) has been publicly traded on the Toronto Stock Exchange and the New York Stock Exchange. In 2001, Celestica employed approximately 32,000 people in 40 facilities around the globe, with 2001 revenues of $USD 10.0 billion. Celestica is the third-largest EMS provider in the world.

Celestica offers design, prototyping, assembly, testing, product assurance, advanced failure analysis, supply chain management, world wide distribution, and after-sales service to original equipment manufacturers in the computing and communications industry. Celestica's historical competencies revolved around printed circuit board assembly, systems integration and test. Over the past several years, Celestica has begun offering its services and expertise to original equipment manufacturers (OEM) in the optical networking equipment (ONE) industry. This field is often referred to as opto-electronics assembly, referring to both the optical and electronic components of the equipment being manufactured. Contract manufacturing in the optical networking equipment industry requires new processes and competencies, which Celestica is building as its service offering in this industry expands.

1.1 Celestica's Opto-Electronics Assembly Strategy

As more OEM's in the ONE industry sought contract manufacturing partners to improve the cost and quality performance of their manufacturing systems, Celestica and several of its competitors moved to build competencies and skills to satisfy those customers. Celestica has articulated and implemented a clear strategy for building and sustaining a competitive advantage in the opto-electronics assembly area.

The first piece of Celestica's strategy is a Global organization of technically skilled engineers chartered with developing the required technical skills to address the unique challenges of opto-electronics assembly. . The Global Opto-Electronics Technology team is intended both to further Celestica's expertise in opto-electronics assembly and to serve as a resource to local sites, providing knowledge and best practices to capitalize on specific local opto-electronics assembly opportunities.

In addition to the organizational structure, Celestica developed a project list focused on both the technological development of the ONE industry and the manufacturing process technology development in the opto-electronics assembly field. These projects were focused around the components that typify optical networks of today and the near future which Celestica needs to begin developing knowledge and systems to manufacture. They also identified specific manufacturing processes which Celestica needed to develop to offer a full portfolio of opto-electronics assembly services. This project list serves as a guide for the Global Opto-electronics Technology organization.

1.2 Project Motivation and Objectives

The Portsmouth Photonics Lab is a part of the Global Opto-Electronics Technology team. The Photonics Lab is staffed by highly competent technical experts with concentrations in optics and photonics, optical system test development, and opto-electronics assembly processes. The Portsmouth Photonics Lab is responsible for developing and fostering a high level of opto-electronics assembly competence in the Celestica New England site staff, completing projects which build Celestica's portfolio of technologies and processes, and working with local ONE OEM's in the New England region to demonstrate Celestica's capabilities to these potential customers.

One of the specific projects is to develop a world-class manufacturing process to splice optical fibers which are presented as a ribbon. Optical networks and optical networking equipment operate by sending signals encoded on a beam of light through optical fibers. The optical fibers are made of silica, or glass, and are analogous to wires in a telephone network. In order to build a useful optical network, high-quality connections must be made between optical fibers to allow light to pass from one part of the network to other parts of the network. These connections are achieved by carefully preparing and aligning the fibers to be joined, and then melting them together. This process is known as fusion splicing, and it is a critical step in the opto-electronics assembly area. Historically, optical fibers have been spliced together one pair at a time, but there is a trend in the industry towards using optical fibers which are presented as a ribbon. These ribbon fibers have multiple (usually 2, 4, 8, or 12) optical fibers in a planar array, much like ribbon cables which are ubiquitous in personal computers. Ribbon fibers offer productivity advantages when compared to single fibers, because the number of splicing and handling steps are reduced as more fibers are routed and spliced simultaneously.

One key roadblock to continued adoption of ribbon fiber technology is that ribbon fiber presents unique challenges in the fusion splicing process. Because the fibers are joined together and are thus prevented from being individually aligned, precise 3-dimensional alignment is very difficult to achieve. The tools and techniques used to splice ribbon fiber are less refined and less robust than the state of the art fusion splicing techniques employed by Celestica in single fiber splicing. Nonetheless, optical networking OEM's are interested in migrating to ribbon fiber where possible because of the unique benefits afforded by ribbon fiber.

As a result, the Portsmouth Photonics Lab undertook a project to develop a world-class manufacturing process to overcome the challenges of ribbon fiber fusion splicing. The goal of the project is to survey the currently available equipment for mass fusion splicing to determine which equipment, if any, can form the basis of a robust, reliable manufacturing process. The deliverables of the project are the best candidate for the eventual manufacturing process, and a set of recommendations and actions that will allow the development of a robust manufacturing process at any Celestica site around the globe to satisfy potential customer demand for ribbon fiber splicing.

1.3 Project Methodology

This project was undertaken as a data-focused manufacturing process development project, incorporating best practice analytical techniques in the area of measurement system design, measurement system evaluation, and designed experimentation. Highest emphasis is placed on ensuring reliable and accurate results to allow for a robust equipment selection decision. Speed and experimental cost are also considered throughout the project.

The first step in any experimentation-oriented project is to build and verify an adequate measurement system. In this project, the measurement system evaluation is complicated by several issues. First, the behavior of light in optical fiber offers unique measurement challenges. Second, the tests required to evaluate potential process equipment are destructive in nature, and therefore do not conform well to traditional measurement system evaluation methodologies that generally require repeated testing of the same sample. Several novel techniques in measurement system design and evaluation were implemented to overcome these challenges, and this paper will discuss those techniques in detail.

Once a capable measurement system was established, the next step was to identify the possible process equipment options and design an experimental regimen to determine which option is best suited to Celestica's goals. This first requires a careful articulation of Celestica's needs and requirements for the process under development, which is developed by benchmarking similar existing processes within Celestica and by consulting with the relevant body of knowledgeable people. Then an experimental plan is formulated which can cost-effectively gather the data required to evaluate the options according to Celestica's criteria.

The experimental plan for this project consists of two phases. The first phase is a screening experiment to narrow the total set of possible equipment choices to a smaller set, with a target of two types of each part of the process equipment set. The screening phase is designed to emphasize experimental efficiency to speed the narrowing of the decision set. Once a smaller set has been identified, the second phase begins. The second phase is a more in-depth, rigorous investigation to generate enough data to recommend a final toolset.

Once the final toolset is identified, the project focuses on the required steps to move from a set of commercially available equipment to Celestica's corporate standard process. These issues include refinement and customization of the equipment to meet Celestica's specific needs, development of training, operating, and maintenance documentation to speed implementation in the plant, and identification of follow-on projects which can be completed to further Celestica's expertise in ribbon splicing.

Each of these experimental phases is accompanied by a great deal of detailed data analysis. This paper will discuss the data analysis both to highlight the results of the experiment and to discuss the analytical methods used.

The project results will be extensively discussed from an analytical and experimental perspective during the data analysis and experimentation portions of this paper. To shed additional light onto the issues relating to this project, a discussion of the results of this project will also be undertaken from a business perspective. This analysis will focus on how the mass fusion splicer evaluation criteria map to Celestica's specific goals and requirements, and on the strategic value of undertaking process development efforts such as this in the short and long term.

In addition to the process development project details, this paper will include an analysis of Celestica's Opto-Electronics Technology strategy using the Organizational Processes Three Lenses framework. The strategy and organization will be analyzed using the strategic design, political, and cultural lenses, both specifically in relationship to this project and more generally in relationship to Celestica's overall business strategy and organization.

2.0 LITERATURE REVIEW

This project deals with a number of distinct, but inter-related issues. In order to lay the foundation for the analysis and to allow for synthesizing conclusions from the experimental results, it is necessary to review the areas of the project independently. In general, this project deals with fiber optics and optical networking, fusion splicing, measurement system design and evaluation, and experimentation and data analysis.

2.1 Fiber Optics and Optical Networking

In today's world, the concept of fiber optics based communication networks is often taken for granted. The fiber optic industry has developed at a blistering pace over the past several decades, moving from laboratory experiments to a world-wide network in a very short period of time. The optical networking industry is still undergoing rapid technological change. In order to understand the state of the industry and how it impacts EMS companies like Celestica, it is necessary to discuss both the history of the development of the technology and the current state of the industry.

2.1.1 The Pre-History of Optical Communication

As telecommunications devices and networks like the telegraph and telephone were developed in the late 1800's, innovators were constantly searching for new media to carry communications signals. Alexander Graham Bell was reported to have used sunlight reflected off of a diaphragm to send voice signals over a distance of 200 meters (Senior). Experiments such as these produced variable results, and light as an information carrier was hindered by two key problems. First, no light source was available which was able to transmit modulated signals over long distances reliably. Second, no propagation medium other than open air was available, and open air transmission was severely limited by the line-of-sight requirement and by atmospheric conditions like haze or fog.

The first of these challenges was overcome by the development of the laser in the early 1960's. The laser represented a high-intensity, directional source of light which could be modulated electronically to carry an encoded signal. Unfortunately, the best innovations in optical waveguides at that time induced attenuations of approximately 1000 dB/km, which was prohibitively high for effective communication (Li).

The fundamental breakthrough in light transmission media came in 1970 when scientists at the Corning Glass Corporation reported silica-based (glass) optical fiber with attenuation below 20 dB/km (Mynbaev). This was believed to be the threshold for acceptability in developing silica-based fiber optic networks.

2.1.2 The Emergence of Fiber Optics and Optical Networking

Over the years following the breakthrough at Corning in 1970, further refinements were made to the attenuation of optical fiber. The current state of the technology is attenuation on the order of 0.2 dB/km. Continued advancement in laser technologies, and the development and refinement of equipment needed to transmit signals over optical fiber, have led to world-wide networks of optical fiber transmitting vast amounts of data. According to BusinessWeek Online, an estimated 283 million miles of optical cable has been installed since 1980 (Kharif, August 31, 2001.)

In addition to a build-out of a massive optical network, researchers have worked diligently to increase the data capacity (bandwidth) of a single optical fiber. Faster modulation techniques for the laser source allowed for higher bandwidth. Sophisticated multiplexing techniques have been employed to permit sending multiple signals simultaneously down the same fiber, which can be demultiplexed and routed separately at the other end. The result is two fold: data networks with massive data capacity which are serving the growing data transmission needs of the telecommunications industry, and the development of very sophisticated equipment to transmit, receive, multiplex, demultiplex, route, and switch the signals on the optical network. As optical networking equipment (ONE) manufacturers such as Lucent, Alcatel, Nortel Networks, and Sycamore Networks have grown and continued to focus on newer, more advanced products, the need for sophisticated manufacturing techniques and systems to build the equipment has grown.

2.1.3 Optical Networking Equipment Manufacturing

As large ONE companies developed new products, they built manufacturing and distribution systems to produce, test, and deliver their equipment. Over time, however, many of these firms observed the rise of the electronics manufacturing services (EMS) industry and sought to take advantage of the capabilities and services offered by EMS companies. EMS companies such as Celestica, SCI Systems, and Solectron have worked to build capabilities in the opto-electronics assembly field to serve the needs of the ONE industry.

Opto-electronics assembly offers unique challenges when compared with more traditional electronics manufacturing. First, the technology continues to evolve at a very rapid rate. Optical components suppliers and ONE companies are focused on integrating the latest technology into their products, which can lead to components which are unreliable. The rapidly changing technology also places a burden on EMS providers to continually develop new manufacturing processes to stay abreast of the state of the technology. Second, transitioning to opto-electronics assembly requires an understanding of the physics of photonics and how fiber handling, routing, and interconnection can impact the operation of the system. This area of science is relatively new and still somewhat developmental, and the relevant skills take time and energy to acquire. For a much more thorough analysis of the unique challenges of opto-electronics assembly at Celestica and the ONE industry in general, see "Optical Networking Equipment Manufacturing" by Jason Holman, MIT 2001.

2.2 Fusion Splicing

One of the specific manufacturing challenges in opto-electronics assembly is how to connect two optical fibers reliably to allow for clear data transmission. There are several solutions to this problem, but in a manufacturing environment this challenge has been addressed by fusion splicing, or the process of melting the two glass fibers together end-to-end to create a continuous light waveguide. Fusion splicing has traditionally been focused on joining one pair of fibers, known as single fiber fusion splicing. This project investigates the available technology for splicing multiple fiber pairs simultaneously, in a process generally known as mass fusion splicing.

2.2.1 Single Fiber Fusion Splicing

The most common type of fusion splicing is the single fiber fusion splicing, where one pair of fibers is spliced to create a connection. The process steps required for single fiber fusion splicing are very similar to those required for mass fusion splicing; it is useful to start with an examination of single fiber splicing and then discuss the additional complexities created by mass fusion. The process steps for single fiber fusion splicing are stripping, cleaning, cleaving, splicing, and protection.

Optical fiber is coated with a polymeric substance to protect the fiber from abrasion and fatigue and to minimize attenuation from a phenomenon known as microbending, where small, tight-radius bends in the fiber induce power loss (MacLean). Figure 1 shows a cross-section of a typical optical fiber.

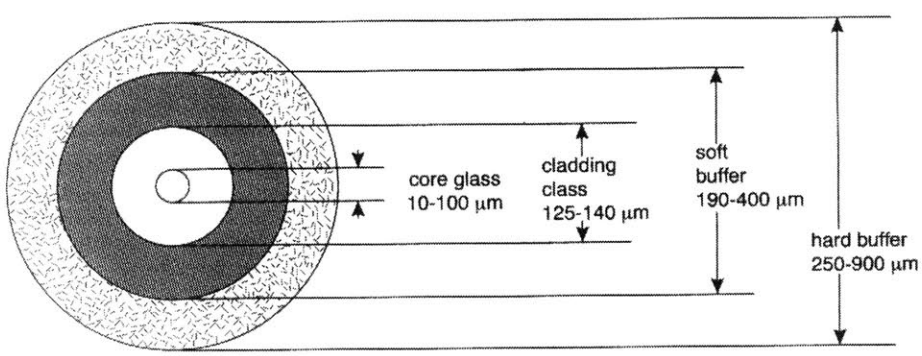

Figure 1: Cross Section of Optical Fiber (from MacLean)

For single-mode fiber, the type most commonly used in communications networks, the core diameter is approximately 9 μm with a cladding diameter of 125 μm. Light is carried in the core of the fiber. A typical buffer for single-mode fiber used in opto-electronics assembly has outside diameter of 250 μm (400 μm and 900 μm are also relatively common, depending on the application). This buffer must be stripped away prior to the splicing process.

When stripping the buffer from the fiber, it is critical that the surface of the fiber not be damaged. Any surface flaws in the fiber weaken it considerably. A thorough discussion of fiber strength can be found in section 2.2.3. Several methods are currently available for single fiber stripping, varying in cost and performance. The lowest cost, lowest performance method is a hand-held stripping pliers, which resembles a traditional wire stripper. More expensive, but more reliable, processes include fully automated strippers which incorporate heating to loosen the buffer prior to stripping.

Even the best stripping process, however, leaves some residue on the surface of the fiber. This residue must be removed prior to splicing. There are two commonly used cleaning methods. The first entails using a lint-free cloth or wipe moistened with isopropyl alcohol to wipe away any remaining residue. This is a fast, cheap, and portable process, but it requires that the wipe make contact with the cladding glass. This could potentially create surface flaws or cracks which could weaken the fiber. An alternative method for cleaning fibers is to use an ultrasonically actuated bath of isopropyl alcohol. This method produces very clean fibers with a reduced chance of damage to the fiber, but is more expensive.

Once the fiber is stripped and cleaned, it must be cleaved. Cleaving has two purposes. First, it prepares the end of the fiber for splicing by creating a smooth, flat surface which is orthogonal to the longitudinal axis of the fiber. This allows two fibers that are butted up to one another to have clean, flat, parallel surfaces that will create a high quality splice. Second, cleaving ensures that the fiber to be spliced is the correct length. Single fiber fusion splicing machines have the ability to make very fine adjustment to the position of the fibers to ensure good alignment, but their range of motion is limited. Cleaving fibers to a specified, highly repeatable length ensures that the fusion splicer will have enough range of motion to align the fibers.

Cleaving is accomplished by scoring the fiber with a precision cutting tool, and then stressing the fiber such that the defect created by the cutting tool propagates into a crack that leaves a very clean face. Cleave quality is very important to both the strength and optical performance of a splice; as a result, single fiber fusion splicing equipment is designed to closely measure the cleave quality prior to splicing. As such, while a bad cleave can create a bad splice, the typical impact of a bad cleave is wasted time as fibers are rejected by the fusion splicer and must be stripped, cleaned, and cleaved again. Figure 2 shows examples of poorly cleaved fibers that can result in bad splices. A range of tools is available for cleaving single fibers. For less critical applications, inexpensive portable hand-held cleavers exist to quickly cleave fibers in the field. For highly critical applications, semi-automated cleavers with ultrasonically actuated blades are available.

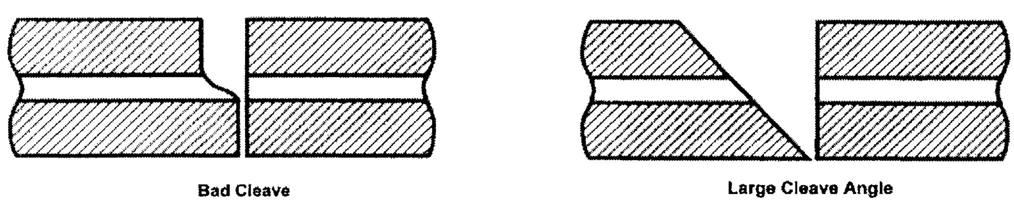

Figure 2: Examples of Poorly Cleaved Fibers (from Mynbaev)

Once the fibers have been stripped, cleaned, and cleaved, they are loaded into the fusion splicer. Fusion splicers perform several important tasks in completing the splice. First, the splicer aligns the fibers. Alignment of single fibers is typically accomplished by 3-axis translation of the chucks holding the fiber. Examples of misaligned fibers are shown in Figure 3.

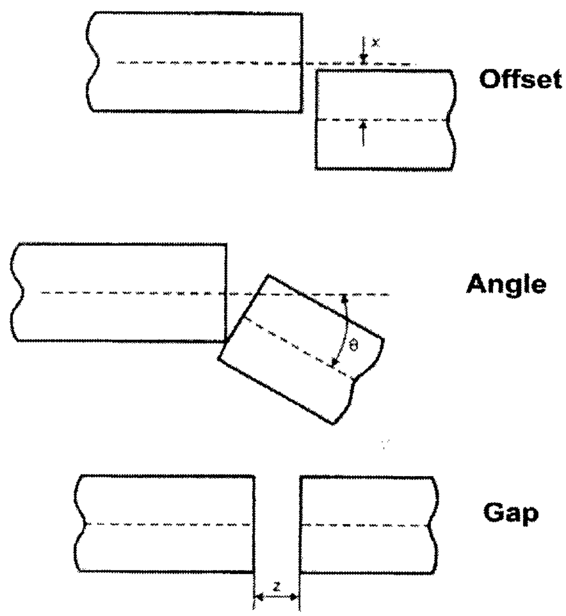

Figure 3: Examples of Alignment Errors (from Mynbaev)

There are several methods by which fiber alignment is detected by the fusion splicer. The crudest method, called passive alignment, uses a precision mechanism referred to as a v-groove. A figure showing the single fiber splicing using v-grooves is shown below.

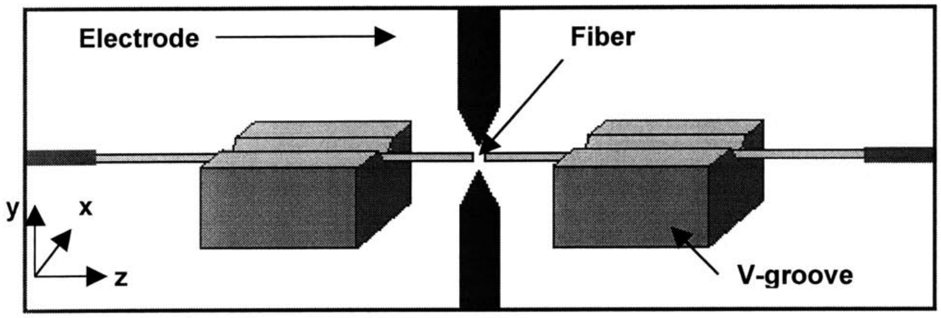

Figure 4: V-Groove Passive Alignment Splicing (from Corning Cable Systems)

Each fiber is placed in a v-groove, and the fusion splicer makes the explicit assumption that the two v-grooves are perfectly aligned in the x- and y- directions. The only actuation of the fiber is in the z-direction, or along the longitudinal axis of the fiber. In addition to assuming perfect alignment of the v-grooves, passive alignment relies on very clean fibers; any dirt on the surface of a fiber will prevent it from settling into the v-groove correctly and could result in poor alignment. Also, passive alignment uses the outside geometry of the cladding glass to locate the core of the fiber, which is where the light is actually carried. If the cladding glass and the core are not concentric, the cores could be misaligned resulting in a poor splice. Optical fiber also exhibits a property known as curl, which is a curvature of the stripped fiber caused by residual thermal stresses in the glass material. Passive alignment is not able to adjust for excessive fiber curl. Figure 5 shows misalignment due to poor core-cladding concentricity and excessive fiber curl.

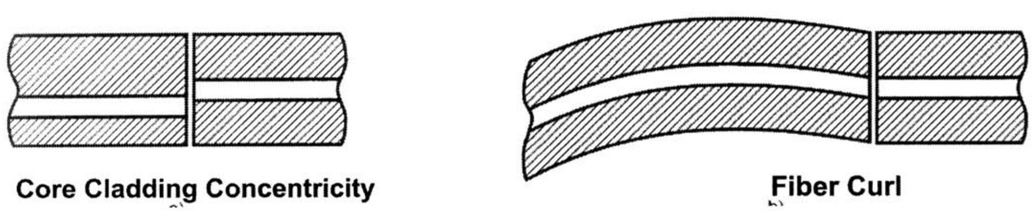

Figure 5: Examples of Splicing Problems Caused by Fiber Properties (from Mynbaev)

Active alignment is different from passive alignment in two ways. First, the fiber can be translated in all three directions to ensure alignment. Second, the fusion splicer uses one of three techniques to determine the location of the fiber cores. The fusion splicer aligns the cores, generally resulting in a better splice. It is worthwhile to understand how the fusion splicers locate the core to understand how the fusion splicer estimates the quality of the splice.

The three most common methods for detecting the core of an optical fiber in fusion splicing are profile alignment system (PAS), lens-profile alignment system (L-PAS), and local injection and detection (LID). PAS relies on a high resolution, adjustable focus camera to view light passing across the fiber, and detects a dark bands at each edge of the core of the fiber. A schematic of the PAS system is shown in Figure 6 below, from the Corning Cable Systems web site (www.corningcablesystems.com).

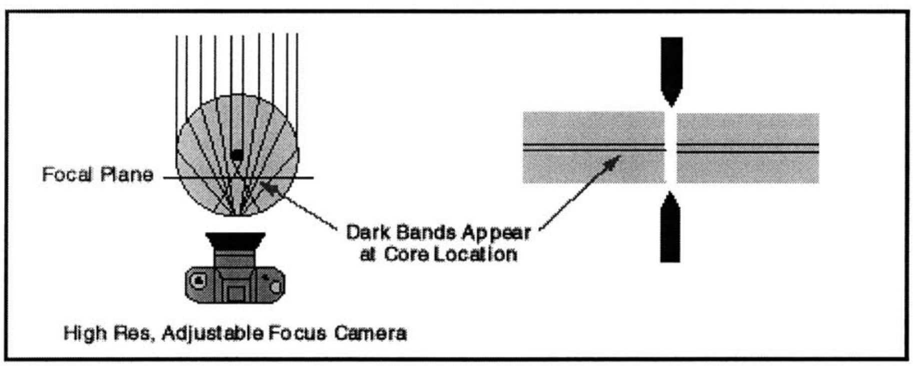

Figure 6: Profile Alignment System (PAS) Schematic (from Corning Cable Systems)

In the above figure showing the PAS system, the left image is looking down the length of the fiber. The dark spot in the center of the fiber is the core, and the lines coming from above represent the light being shined across the fiber. The fiber refracts the light such a way that the edges of the core appear as dark bands if the focal plane of the camera is adjusted to the correct location. The right image represents what the camera in a PAS system would actually detect. The two fibers are on the left and right, with the core highlighted in dark lines. The two electrodes, used to generate the arc which creates the fusion splice, are shown on the top and bottom.

Lens – profile alignment system (L-PAS) is similar to PAS, but a high intensity light source is added. The result is that the curvature of the fiber focuses the light passing through it, resulting in a "bright" line in the center of the fiber. The L-PAS system aligns the edges of the cladding and the brightness profile measured by the cameras. The following two figures show key features of the L-PAS system. Figure 7 shows how the fiber acts as a convex lens, creating a bright line in the center of the fiber. Figure 8 is a representation of what the camera would see in the L-PAS system, a profile of brightness where the light that does not pass across the fiber is bright (the edges) and the light that does pass through the fiber is focused on the center (the brightness peak). The fusion splicer aligns the two brightness profiles (one from each fiber), and then splices the fibers.

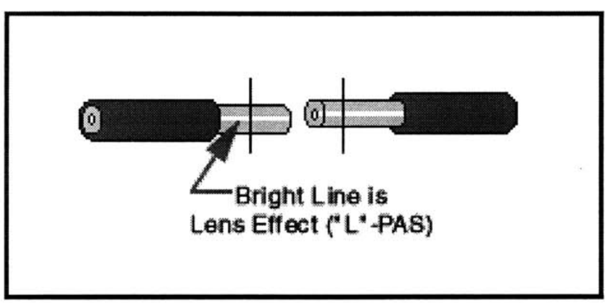

Figure 7: Bright Line Effect of L-PAS (from Corning Cable Systems)

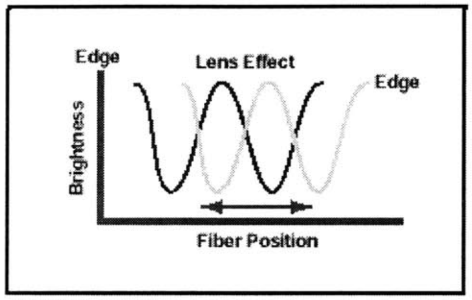

Figure 8: L-PAS Brightness Profile (from Corning Cable Systems)

Local injection and detection (LID) is fundamentally different from PAS and L-PAS. A LID system injects light into one of the fibers being spliced, and measures the light being transmitted into the other fiber. The fibers are assumed to be aligned when the power being transmitted to the downstream fiber is maximized, and then the splice is completed. A schematic of an LID system is shown in Figure 9.

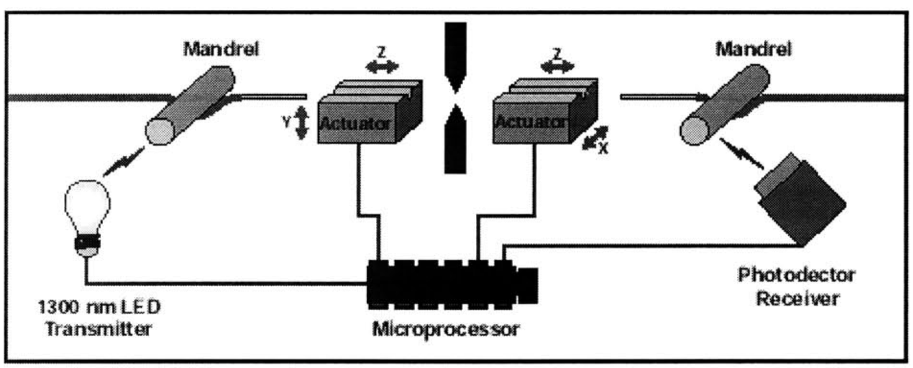

Figure 9: LID System Schematic (from Corning Cable Systems)

Alignment is critical to the completion of a high-quality, low attenuation splice. Each alignment system has strengths and weaknesses. Passive alignment generally results in higher-loss (worse) splices, but is inexpensive and the exclusion of additional mechanical actuators saves space and power consumption, which are critical to portable splicers. PAS and L-PAS improve loss performance when compared to passive alignment, but they rely heavily on optics which require cleaning and maintenance for continued operation. LID systems yield the lowest loss splices, but the LID system is more complex and expensive because it requires a source and photodetector. The proliferation of types and models of single fiber fusion splicers is driven by the specific needs of the customers of splicing equipment. For outside plant installation, where fiber optic cable is installed in buildings or along roads, portable fusion splicers are typically employed. These portable units are compact, lightweight, battery powered, and generally use passive alignment to conserve space and energy. For more quality-critical splicing applications like opto-electronics assembly, more sophisticated splicers are used. These models are designed to be used in a factory setting, and are designed to maximize the quality of the splice. They generally use one of the active alignment schemes. This proliferation of models and types of single fiber fusion splicers allows for the selection of equipment which is designed for the specific type of splicing to be performed.

In addition to aligning the fibers, the fusion splicer performs some checks to determine whether the fibers are well prepared. For example, fusion splicers measure the cleave angle, or the number of degrees between the plane of the end face and the plane perpendicular to the longitudinal axis of the fiber. The goal is a cleave angle of 0 degrees; the user has the ability to specify a limit of acceptability for their specific process.

Once the fibers are aligned and have been checked by the splicer, the fusion splicer splices the fibers. The splice is formed by heating the fibers using an electric arc passing between two electrodes positioned near the fiber ends. The fibers are subjected to very high heats and are pushed together in the molten state to facilitate a bond. The electrodes are turned off, and the spliced fiber cools. This process is carefully controlled by the fusion splicer, which controls the current of the arc, the duration of the arc, and the amount the fibers are pushed together during fusion. Some splicers incorporate other features, such as multiple stages of the arc that can be configured for different currents and durations. The output of this stage is a spliced fiber.

Once the fiber is spliced, the fusion splicer must estimate the quality of the splice. Estimation is required because actually measuring the loss of a splice to be used in the field is impossible, except in the case of LID system splicers. Splice loss can generally only be measured on splices created especially for the purpose of measuring loss. Therefore, if a manufacturer needs to know the quality of a splice made in the factory, they must rely on the estimator. In the case of the LID system, a loss measurement is made on the splice. While this is a power measurement, it is only an estimate of the actual insertion loss of the splice in service because the system assumes that a known amount of light is injected into the fiber upstream of the splice; because there is clearly room for variability in the amount of light injected, the measurement is an estimate of field performance. Other splice loss estimators (PAS and L-PAS) use the images obtained before, during, and after the splicing process by the alignment system to estimate the loss of the splice. Each fusion splicer vendor has proprietary estimation algorithms which have varying degrees of accuracy. Passive alignment splicers must also provide an estimate of splice loss. These splicers generally use the PAS or L-PAS method, but only use the data for estimation and not for fiber alignment. When choosing a fusion splicer, the accuracy of the splice loss estimator becomes very important because there is no way to verify the estimate; a manufacturer must rely on the estimator to know the quality of the process.

Fusion splices may be placed under tension to provide an additional quality check on the splice. This function can be performed by the splicer or by a separate piece of equipment. A more thorough discussion of fiber strength can be found in section 2.2.3, but the basic idea behind tensile testing of splices in practice is to ensure that there are no gross flaws or defects in the fiber which could propagate into cracks and cause latent field failure of the splice.

The final step of single fiber fusion splicing is splice protection. This can be accomplished using a heat-shrink sleeve with an incorporated strength member, generally known as sleeves. Sleeves are fast, clean, and strong, but they are bulky and can cause problems in the routing of the spliced fiber in the equipment being assembled. An alternative method is recoating, where the splice is covered in a UV-curable resin and then cured using UV lamps. Recoated splices are unobtrusive and simplify routing processes, but the process is slower than using sleeves and requires the use of messy chemicals.

2.2.2 Mass Fusion Splicing

Mass fusion splicing is the process by which multiple fiber pairs can be spliced simultaneously. The multiple fiber pairs are typically in the form of ribbon fiber, where the fibers are presented in a planar array much like a computer ribbon cable. The process steps for mass fusion splicing are very similar to those employed in single fusion splicing, but in every step there are differences and challenges created by the application of the process to a ribbon fiber. Many of these differences arise from the needs of the historical users of mass fusion splicers, the outside plant installers who install ribbon fiber in buildings. Unlike single fiber fusion splicing, where there are a variety of types of splicers designed for different uses, mass fusion splicers are almost entirely designed for outside plant installation. Transitioning equipment optimized for portability into a manufacturing plant presents challenges which will be discussed in general here. The process steps in mass fusion splicing are the same as in single fiber splicing.

Ribbon fiber is made up of individual fibers which are joined together as a ribbon. Each individual fiber has the same buffer materials as a single-mode fiber (section 2.2.1), and in addition to this buffer material, there is a ribbon matrix material that must be removed. The matrix material is a polymeric substance that encapsulates the individual fibers and holds them in place. The properties of the matrix material create some unique challenges in ribbon fiber stripping. First, the ribbon matrix material must be heated before it can be removed. All ribbon-stripping equipment incorporates heaters to accomplish this task. If the matrix material is not heated well enough, it will not strip cleanly. If it is heated too much, it disintegrates into a powder during stripping and the fibers do not get clean.

The second problem created by stripping ribbon fiber is that the tools available to accomplish this task have been designed with portability as the primary concern. They are typically very unsophisticated, and require a lot of user skill to operate effectively. A picture of a typical thermal stripper for ribbon fiber is shown in Figure 10.

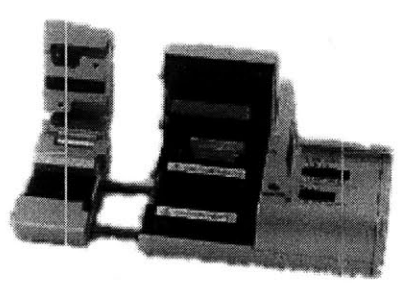

Figure 10: Typical Configuration of Ribbon Stripping Tool (from Sumitomo)

For example, the user must apply the right amount of pressure to clamp the fiber in place and to engage the blades to ensure that the material will strip. Too much pressure could damage the fiber, too little could result in not stripping the coating. The user must hold the ribbon in the stripper the precise amount of time required. If the user attempts to strip too soon, the heater will not have had time to loosen the material enough for it to strip off easily. If the user waits too long, the material will turn to powder and the fibers will come out very dirty. It is also possible to pull the fibers too quickly or too slowly, resulting in a bad strip. These strippers are small, lightweight, and generally designed for the needs of an outside installer whose tolerance for high loss splices is much higher than a manufacturer like Celestica. There are several models of strippers that are generally made with this form factor. In addition, there is one other stripper model that is automated, and is designed to be better suited to the plant environment. It is, however, a more expensive alternative than the manual strippers.

Once the fibers have been stripped, they must be cleaned. For cleaning, the processes employed are identical to single fiber; either wiping with an isopropyl-soaked wipe or using a sonicated bath. In either case, there is a new challenge. When the stripped ribbon fibers are wetted, they tend to clump together from the surface tension of the isopropyl alcohol. This must be dealt with by drying the alcohol, either by using a dry wipe or by allowing the fibers to air dry. Once they are dry, the fibers separate out into individual fibers.

The cleaving process is limited by the form factor of the ribbon. The typical form factor is shown in the Figure 11 below. The fibers are placed on supports that suspend the fibers above a sliding blade. The blade slides across the ribbon, scoring each fiber. The fiber can then be broken at the scored mark to create a cleaved end. The sliding blade mechanism lends itself well to cleaving a ribbon, because one blade can be used to score the bottom of all of the fibers with the same motion, and then the fibers can be broken. There is a problem created by cleaving ribbon fibers, namely that the lengths of fiber that have been broken off from the ribbon to be discarded must be gathered up and disposed of. This problem exists in the single fiber process as well, but picking up 12 small segments of transparent fibers the diameter of a human hair can be substantially more frustrating than picking up one. The result is that time can be lost by the operator being required to clean up after each cleave.

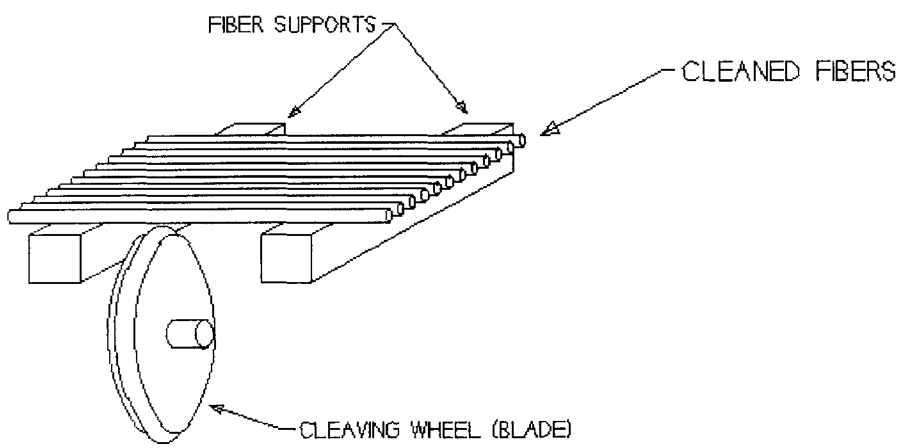

Figure 11: Typical Configuration of Ribbon Cleaver

The cleaved fibers are loaded into the mass fusion splicer. Because the ribbon fibers are joined together by the ribbon matrix, they are constrained to move together in the x- and y- axes. As a result, mass fusion splicers invariably employ passive alignment, or v-groove technology. The mass fusion splicer has multiple parallel v-grooves, one for each fiber pair, and the fibers are loaded into the v-grooves for alignment. The splicer then seeks to bring the fibers together in the z-direction, but again this is complicated by the ribbon construction. The fibers cannot be manipulated in the z-axis individually, but rather must be moved as a ribbon. If the ribbon is crooked in the splicer, the end faces of the fibers in the ribbon will not be perfectly aligned.

The cleaved fiber is placed in the splicer. The operation of the mass fusion splicer is very similar to the operation of a single fiber splicer, particularly a passive alignment single fiber splicer. The ribbons are moved together in the z-axis. The splicer performs many of the same checks as a single fiber fusion splicer. There are two one additional check critical to the success of mass fusion splicing called gap and offset. Gap refers to the z-axis gap between the left fiber and the right fiber immediately prior to splicing, typically around 10 – 20 μm. A single fiber fusion splicer can simply move the fibers closer together to overcome gap errors, but a mass fusion splicer may not be able to. For example, if 11 of the 12 fiber pairs have acceptable gap measurements and one of the fiber pairs does not, the fusion splicer cannot correct the error and the user must seek to resolve the problem. Offset is the x- and y- axis distance between the centerlines of the cores of the fiber pair, typically 0 – 4 μm. Again, a single fiber fusion splicer can move the fibers to ensure alignment, but a mass fusion splicer is not capable by virtue of its passive alignment design. The user wait for the splicer to identify a problem condition, and then intervene and resolve the problem.

When no errors are detected, the mass fusion splicer splices the ribbons together using a single pair of electrodes. The electrodes are placed above the fibers, and the placement and design of the electrodes is intended to ensure that each of the multiple fiber pairs are subjected to the same heat for the same time resulting in similar splice characteristics. However, it is obvious that this cannot be realized perfectly. The two images in Figure 12 demonstrate this challenge.

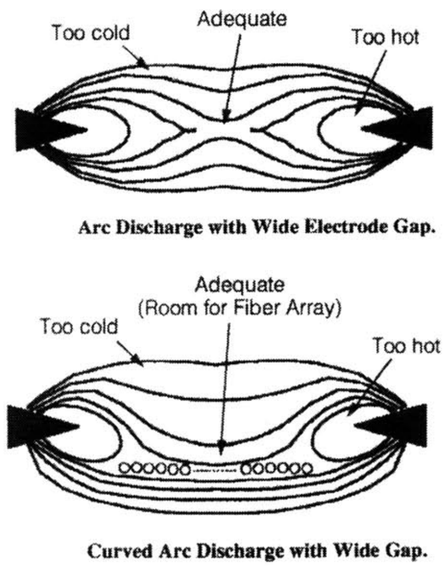

Figure 12: Temperature Contours in Arc (from Fujikura)

The top figure shows the temperature contours if the arc were discharged without modification. There is clearly no isothermal area for the ribbon fibers. The bottom figure shows the result of modifications to the arcing process that are intended to create a space where the ribbon fibers are exposed to near-isothermal conditions. In order to achieve a satisfactory splice, the fibers must be offset below the electrodes (as shown in the bottom figure) and the arc must be modified to allow for favorable temperature conditions. Even with the curved arc (bottom figure), it is clear it is very challenging to create a plane of near-isothermal conditions to minimize variability between the splice characteristics of the fibers at the edge of the ribbon to those in the center. In order to compensate for this problem, every mass fusion splicing equipment vendor has given the equipment the capability to do complicated self-calibrations designed to understand the effects of these temperature profiles. One common method for getting an indication of the temperature each fiber is exposed to is to prepare and load a pair of ribbons, discharge the electrodes without pushing the fibers together, and then measure the amount each fiber pair has "melted back". A screenshot of the fusion splicer display after this test has been completed is shown in Figure 13.

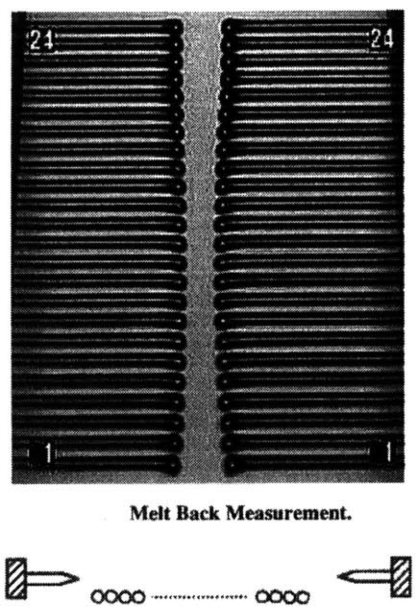

Figure 13: Ribbon Splicer Meltback Test (from Fujikura)

This image shows a melt-back measurement test from a developmental 24-fiber fusion splicer, but the test mechanics and output are very similar for the 12-fiber fusion splicers studied in this experiment. The splicer measures how much the fibers melted back as a result of the arc, and the splicer can evaluate whether there are hot or cold areas in the arc region which will affect the quality of a splice. If a problem is detected, the operator must identify and resolve the cause, which is likely to be dirt or residue on the electrodes.

After the splice is completed, the mass fusion splicer produces an estimate of the insertion loss of each splice. The techniques used to derive these estimates are identical to those in single fiber fusion splicing, with one very notable exception. Single fiber splicers are able to focus very closely on one fiber; the resulting digitized image used for estimation is relatively high resolution. Mass fusion splicers use very similar optics and light sources to simultaneously estimate the loss of 12 fibers; the image resolution for any one fiber is lower than in single fiber splicing because each fiber only occupies one twelfth of the captured image.

While mass fusion splicers often have tensile testing capabilities, they are rarely used. The testers can only put very small loads on the ribbon, which when distributed over multiple fibers amount to insignificant tensile stress. In addition, the splice protection mechanism for ribbon fibers is very sturdy, so there is no perceived need for tensile testing of mass fusion splices. The typical mass fusion splice protection sleeve is a plastic jacket with a strength member (usually quartz) and two tubes. The inner tube is a low-melting point plastic and the outer tube is a heat-shrink plastic. When the sleeve is heated, the inner tube becomes molten polymer, and the outer tube shrinks to press the molten polymer between and around the ribbon fibers. As the heat shrink outer sleeve shrinks, the molten polymer forms a seal and the ribbon is pressed flat against the quartz bar. Figure 14 shows a cross section of the ribbon splice protection sleeve before it has been heated.

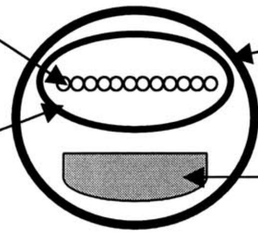

Figure 14: Ribbon Fiber Splice Protector Cross Section

Along with the specific differences at each process step, there is an overarching difference between the mass fusion splicing process and the single fiber fusion splicing process. In the single fiber fusion splicing market, there are multiple models available from each vendor to suit the needs of specific customers. For example, the single fiber fusion splicing tools used by a utility company employee at the top of a telephone pole are fundamentally different from the single fiber fusion splicing tools employed in a factory by a company engaged in opto-electronics assembly. For mass fusion splicing equipment, this market segmentation has not occurred because mass fusion splicing is just being introduced into factory settings. Therefore, any attempt to adapt the field-use mass fusion splicing equipment to a plant environment will face challenges. For example, because the field ribbon strippers are not particularly good, the ribbon fibers are not as clean as they could be even after sonication. This results in offset errors in the splicer because the fiber has debris on it that prevents it from laying in the v-groove correctly. This excess dirt and debris may also cause the splicer optics to become dirty prematurely and require cleaning. These challenges will continue to face mass fusion splicer adoption in a production setting until the manufacturers of mass fusion splicers develop products designed specifically to meet the needs of the opto-electronics assembly market. In the meantime, companies who are interested in performing mass fusion splicing in a factory setting must be clever in adapting the current equipment to their specific needs.

2.2.3 Tensile Strength as an Indicator of Splice Quality

As mentioned briefly in sections 2.2.1 and 2.2.2, tensile strength testing is often incorporated in a splicing process as a check of splice quality. In order to understand why tensile strength is a plausible surrogate measurement for splice quality, it is important to understand the failure mechanism of an optical fiber.

The theoretical ultimate tensile strength of silica-based optical fiber is approximately 1,000 – 2,000 kpsi, but in practice this strength is rarely achieved (Li). This phenomenon is attributed to the presence of defects or cracks in the surface of the fiber. When a specimen with a crack is placed under tension, the tip of the crack acts as a stress concentration point, which can reduce the local tensile strength. These cracks are assumed to be randomly distributed throughout the length of the optical fiber; an optical fiber which breaks under tension is assumed to have broken at the location of the largest flaw (Li). Over time, in the presence of moisture or cyclical loading, the cracks in a fiber will propagate into the fiber, degrading the strength of the fiber.

Tensile testing in fusion splicing is generally conducted by putting the fiber under a specified tensile stress. A typical specification for this test in single fiber fusion splicing is 100 kpsi. It is worth noticing that this is an order of magnitude below the theoretical strength of the material. If the fiber breaks, then it is obviously discarded and re-spliced. If the fiber does not break, it is assumed to be good and is kept. There are two key assumptions which lay the foundation for using tensile testing as a splice quality test. First, the fibers being spliced are subjected to harsh processes which could potentially damage the fiber. Second, if the fibers are damaged in the splicing process, this creates a potential for a latent field failure, an unacceptable possibility. Because the splice protection mechanisms are not hermetic seals, it must be assumed that every splice could be exposed to moisture at some point in its service life. Moisture accelerates the crack growth process, and could eventually lead to a fiber breaking under stresses normally encountered in the field. EMS and ONE companies are loathe to expose themselves to the costs of finding and repairing a field failure, and as a result they require a tensile test, often called a "proof test" to prove the quality of the splices.

As a result, Celestica and much of the rest of the industry believes that tensile strength testing is a valuable indicator of the capability of the splice process, with particular emphasis on the information tensile testing can provide on the quality of the preparation process.

2.3 Measurement Systems Analysis

This project includes a great deal of experimentation to identify the best possible equipment for mass fusion splicing at Celestica. In order to gather meaningful results in any experiment, attention must be paid to the capability of the measurement process used to gather those results. In order to treat the subject of measurement systems analysis (MSA) in this context, the first step is a brief review of the basic concepts of measurement. The Gage Repeatability &

Reproducibility (Gage R&R) methodology for measurement system analysis will be discussed in detail, followed by a discussion of a special case of Gage R&R analysis where the test under study is destructive. Finally, a discussion of the challenges of measurements in the fiber optics field will be undertaken.

2.3.1 Variability in Measurement Systems

This review is summarized from Measurement Systems Analysis, a reference manual published by the Automotive Industry Action Group (AIAG):

There are six basic sources of variability or error in a measurement system. Each of them can potentially lead to the collection of misleading data, and potentially to the adoption of bad decisions based on the poor data. The first step in any data-driven decision making process should be to understand the measurement system used to gather the results under analysis, paying attention to each of the following six areas: bias, repeatability, reproducibility, stability, linearity, and discrimination.

Bias represents the difference between a measured result and the "true" or absolute value. In many situations, the absolute value is hard to obtain, and reference values are substituted. For example, the generally accepted practice for determining the bias of a digital scale is to take a "known" weight (usually certified by some independent agent) and weigh it on the scale. The difference in the result and the "known" weight is the bias. Bias is also sometimes referred to as "accuracy". In this project, the most critical measurements used for generating experimental results are relative measurements, or the difference between two measurements made by the same measurement system. In the case where the measurements are relative, bias is less important than linearity.

Repeatability is the intrinsic variability between measurements of the same part by the same operator. That is, a perfectly repeatable measurement system is one where operator A measuring part 1 will always obtain precisely the same result regardless of how many measurements are taken. A measurement system with poor repeatability would demonstrate a high degree of variability even when the same operator uses the same measurement system to measure the same part.

Reproducibility is similar to repeatability, with the difference being that reproducibility is the variability of the measurement system when operator A and operator B each use the measurement system to measure the same part. It is interesting to note that an estimate of reproducibility is not possible to obtain without some information about the repeatability of the measurement system. This is because the measurements made by operator A are always affected by the repeatability of the system, and the same is true of the measurements made by operator B. Therefore, the variability of the data collected with both operator A and operator B are subject to both repeatability variation and reproducibility variation. In general, the expectation is that the measurement system will be more variable as more operators are introduced into the system.

Stability is the variability in the measurement system over time. A stable measurement system will produce the same results tomorrow that were produced today and yesterday. A common mistake made in thinking about stability is that the source of variation is the passage of time itself. While it is possible that a measurement system is sensitive to time, stability measurements most often show the sensitivity of the measurement system to other special causes that vary with time. For example, if the temperature or humidity in the area where the measurements are being taken changes from day to day, the results would be unstable if the measurement system were sensitive to temperature or humidity.

Linearity is closely related to bias. A linear measurement system is one where the bias does not change throughout the measurement range. Linearity errors generally are one of two types: curvature, where the measurement systems can be described by polynomials of order greater than 1 or by exponentials, or slope errors, where the system is technically linear but where the slope of the system response is greater than or less than one. Slope errors are more common, and as a result are generally what is referred to as linearity errors. Because "non-linear" measurement systems are usually measurement systems that are linear with the wrong slope, the term "linearity" as used in the context of measurement system evaluation is somewhat of a misnomer. An example is useful to demonstrate the concept of linearity. Imagine one scale (scale #1) which has a non-zero bias but which is linear, and another scale (scale #2) which has zero bias but is considered non-linear due to a slope error. Scale #1's bias is +10 kg, while Scale #2's slope is 1.1 (scale #2's bias appears to be 10% of the measurement at any point in the measurement range). Now imagine that the desired measurement is the weight of a heavy object, but that the object is on a pallet. The true weight of the object is 100 kg and the true weight of the pallet is 10 kg. If a common tare-weight method is used to determine the weight of the heavy object, the results are summarized in the following table:

	Scale #1 Result	Scale #2 Result
Measure tare (pallet)	20 kg	11 kg
Measure tare + object	120 kg	121 kg
Calculate weight of object	100 kg	110 kg

This example is rather simplistic, but it shows how a "non-linear" measurement system (scale #2), a measurement system with a bias that changes throughout the measurement range, can lead to erroneous measurements, especially when relative measurements are used. Therefore, the linearity of the test system must be investigated and characterized.

The final concept in measurement systems analysis is discrimination, or resolution. Discrimination is not a source of variability in a measurement process, but it is an important consideration nonetheless. A measurement system with high discrimination will be able to detect very small changes in the process being measured, which is a desirable outcome. Discrimination, like the rest of these measurement system concepts, is relative to the system. For example, a plain stick of wood 12 inches long is a low discrimination measurement tool if the object being measured is 16.25 inches long; the same stick is relatively high resolution if the object being measured is I-95 between Boston and New York.

2.3.2 Gage R&R Methodology

One of the challenges when thinking about measurement system capability is to understand the relevance of the variability of the measurement system. If a measurement system has a variability which can be characterized by a standard deviation of 10 units, but the process being measured has a standard deviation of 100 units and specifications which are 1000 units apart, then the measurement system variability is probably insignificant. A methodology commonly used to introduce this concept into practical MSA work is called Gage R&R.

The Gage R&R is a fairly simple methodology. A typical implementation can be described as follows: three operators each measure 10 parts 3 times using the measurement system under analysis. The measurements must be randomized and ideally the operators should not know what part they are measuring or their prior results when they are making a measurement. When a study is conducted in this way, the Gage R&R methodology can be used to obtain estimates of four parameters of interest. The formulas most commonly used in the Gage R&R study can be found in Measurement System Analysis, Chapter II, Section 4.

The first estimate is the repeatability of the system, also called the equipment variation. This represents the variability observed when the same operator makes measurements of the same part over time.

The second estimate is the reproducibility of the system, also called appraiser variation. This takes into account the variation in results between operators when multiple operators measure the same part. Repeatability and reproducibility are commonly added together to formulate the R&R statistics, but these numbers represent standard deviations; variances, the square of standard deviations, can be added and then the square root of the sum of variances is the combined variability. R&R can be obtained by the following formula:

$$R\&R = (\text{Repeatability}^2 + \text{Reproducibility}^2)^{(1/2)}$$

The third estimate is the part-to-part variation, or process variation. This is the variability due to differences in the parts being measured. In conducting a Gage R&R, it is advisable to select samples that represent the range of variability normally observed in the process. This can be done by random selection if the sample size is moderately large.

The final estimate is the total system variation, which represents the variability observed between multiple operators making multiple measurements on multiple parts with the same measurement system.

The usefulness of the Gage R&R methodology is that the results are generally expressed as a percentage of the total variation. For example, the R&R statistic can be divided by the total variation to get a representation of the measurement system variation as a percentage of the total system variation. This makes it easier to judge a measurement system's capability; a measurement system with 5% R&R is obviously better suited than one with 50%. The accepted rule-of-thumb is that a measurement system is considered good if it has less than 10% R&R, and considered unacceptable if it has >30% R&R, with the range between 10% and 30% considered marginal.

Another useful feature of the Gage R&R method is that a reasonable data set is collected under controlled circumstances, and that data can be used to gain some insight into the discrimination of the measurement system. A simple but effective way to accomplish this is to count the number of distinct measurement results that were obtained. If 90 measurements were made and there were 90 different results obtained, then the measurement system has a fine discrimination. If, however, only 10 distinct measurement results were obtained the system may not have enough discrimination to be useful.

In addition, because the data was collected in a controlled manner and ideally the experimenter can account for any special causes that might impact the usefulness of the data, it may be possible to glean information about stability and/or linearity from the Gage R&R data. For example, if the part-to-part variability was higher for parts at one end of the measurement range than the other, non-linearity might be suspected. Even if the data is not conclusive, it can be helpful in directing further investigation.

2.3.3 Gage R&R with Destructive Testing

Some tests can be described as destructive, in that the act of performing the test alters or destroys the part being tested. This type of test poses a special challenge in measurement system analysis. Traditional Gage R&R methodology calls for repeatedly measuring the same parts with multiple technicians, but in the case of a destructive test this is clearly impossible.

There are several methods to compensate for destructive testing. The simplest method is to carefully select parts such that the variability between the parts is expected to be higher than the variability of the measurement process. By selecting samples in this manner, the part-to-part variation is assured to be high relative to the process specifications, and this high part-to-part variation can be used as a reference point to compare R&R. If R&R is much lower than the part variation, the test system can be deemed acceptable. If R&R is close in magnitude to the part-to-part variation, the test system requires improvement. There are other methods for evaluating the variability of a destructive test, such as using a nested design Gage R&R. For this experiment, the first method relating to the selection of samples was used.

2.3.4 Measurement Challenges in Fiber Optics

Fiber optics offers some unique measurement challenges which require special consideration. Primary among these is variability due to the polarization of light in the fiber. Fiber optics testing and measurement equipment can also exhibit instability, and this must be considered in test design.

Polarization can be a source of variation in optical measurements. Some components of a measurement system in fiber optic systems behave slightly differently depending on the polarization state of the light being transmitted. Optical power detectors, for example, can exhibit a range of observed power measurements of up to +/- 0.5 dB depending on the polarization of the incoming light. Switches, splitters, and couplers also exhibit a dependency on polarization. In general, if the polarization state does not change, the behavior of these devices is constant. Unfortunately, the polarization state of light traveling in a standard single mode optical fiber is changed whenever the fiber is moved. As a result, the polarization state of the light in any practical experiment is always changing. In an experiment where the fiber does not need to be moved, this can be compensated for to some degree by immobilizing the fiber in the test setup. In a splicing experiment where the fiber must be moved, a depolarizer must be added to the test setup. There are several types of depolarizers available, but the goal of all depolarizers is to reduce the degree of polarization of the light in the system, thereby minimizing polarization dependent loss.

Stability of optical test systems are also a potential source of concern. The primary source of instability in an optical measurement system is temperature and/or humidity fluctuations. For example, optical source devices such as Fabry-Perot lasers have typical stability specifications of +/- 0.005 dBm over short periods of time and +/- 0.03 dBm over 24 hours, and these specifications typically assume a tightly controlled temperature environment of ΔT +/- 1 °C (from Agilent 8165x technical specifications). It is possible to see fluctuations in output power of a typical laser of up to 1 dBm due to temperature changes in a less controlled environment (www.kingfisher.com). This instability is large relative to the typical insertion losses specified for mass fusion splices (typically 0.05 dB), and as a result must be thoughtfully handled in order to assemble a capable measurement system.

Another consideration in fiber optics measurements is units. Optical power is generally measured in watts (W), but it is conventional to express the power readings in dBm, or power in decibels referenced to 1 mW. The formula for dBm is:

$$\text{dBm} = 10 \log \frac{\text{actual power } (P_2)}{.001 \text{ watt } (P_1)}$$

Attenuation measurements, including splice insertion loss measurements, are found by subtracting the post-splice power reading in dBm from the initial power reading in dBm, and the result is expressed in decibels (dB) due to the cancellation of the 1 mW reference power from logarithm algebra.

2.4 Designed Experimentation Overview

Designed experimentation is a broad field of study engaged in understanding how best to characterize and optimize a system. For a system with multiple inputs and one or more important outputs, carefully designed experimentation provides an efficient and speedy methodology to understand how each of inputs impacts the outputs, and often how interactions between the inputs affect the output. For a thorough discussion of designed experimentation, two good references are Design and Analysis of Experiments by Montgomery and Improving Quality Through Planned Experimentation by Moen, Nolan, and Provost. This discussion will only cover a very brief review of this field to offer a jumping off point for the experimentation and analysis discussed in Chapters 4 and 5.

The first step in solving a problem is to clearly define the problem, ideally through identifying specific goals to be accomplished and means by which progress towards those goals can be measured. The measurement system(s) to be employed must be analyzed and validated, as discussing in Section 2.3. Once the problem is clearly defined and the measurement system is validated, the project moves into the experimentation phase.

There are almost always multiple ways to achieve an objective. In experimentation, for example, one way to investigate a process is to vary one factor while carefully holding all others constant , and then cycle through all inputs one at a time to develop relationships between each input and the output variables of interest. This is sometimes called one-factor-at-a-time or OFAT experimentation. OFAT experimentation is relatively easy to plan, conduct, and analyze, but it can be inefficient if there are a large number of factors and no information about possible interactions between inputs can be obtained. Another possible method is a factorial experiment, where an experimental plan is drawn up calling for the various inputs to be changed simultaneously. Factorial experimentation generally requires fewer experiments because each of the inputs is being varied in each trial, and information about the interactions between inputs can be observed. Factorial experimentation, however, takes longer to plan, and can be more complicated to conduct and analyze.

Understanding these and other choices in how to conduct experimentation to gain insight into the relationships between process inputs and process outputs is the domain of designed experimentation. The experimenter must understand what information is required to answer the question at hand, and how best to conduct and analyze experiments to get that information taking into account cost, time, and the reliability of the results, among other things.

In this project, several experimental methodologies are implemented. Each will be discussed more thoroughly as a part of the analysis of the results, but briefly the basic types of experimentation conducted in this project are: blocked-design screening experiments, full factorial experiments, and fractional factorial experiments. In each case, a tradeoff was made between the amount of information content delivered from the experiments and the amount of effort and time invested in conducting the experiments. The details of these methods and the trade-offs considered will be discussed as a part of the data analysis.

3.0 MEASUREMENT SYSTEM ASSEMBLY AND ANALYSIS

This project was undertaken to develop a manufacturing process for mass fusion splicing of optical ribbon fiber for Celestica's opto-electronics assembly process. There were three main stages of the project, 1.) measurement system assembly and analysis, 2.) screening experimentation and data analysis, and 3.) final experimentation and analysis. The methodologies employed in each case were unique to the challenges faced in each stage, and as a result will be discussed individually.

The two main response variables of interest in this project that require the assembly and verification of a measurement system are optical insertion loss and tensile strength. Optical insertion loss, also called splice loss, is the attenuation caused by the insertion of a splice in the system. Splice loss is measured in decibels (dB), and the goal of the experiment is to achieve very low splice loss with a very low variability of splice loss. Tensile strength is the strength of the fiber when stressed to failure in tension, measured in thousands of pounds per square inch (kpsi). The two measurement systems are completely separate, and were assembled and analyzed independently.

3.1 Splice Loss Measurement System Analysis

A schematic for the test system assembled for measuring splice loss is shown in Figure 14 below. The system was designed and assembled with several constraints and guiding principles in mind. First, only one source was to be used to maintain consistency. Second, a depolarizer was incorporated to minimize the polarization dependent loss of the components in the test system; the fiber between the source and the depolarizer was completely immobilized throughout the entire experiment. All single-fiber connectors used in the test system were FC Angled Polished Connector (FC/APC). The light from the laser source is split by the use of a precision 1x2 splitter. One of the outputs of the splitter is used to measure the power through the splice, while the other is used as a reference signal to detect any drift in the test system over time. The output of the 1x2 splitter to be passed through the splice must be able to be routed to each of the 12 fibers in the ribbon being spliced.

A 1x12 high performance splitter was used to split the source into 12 light paths. These light paths were connected into the ribbon by the use of a fan connector, taking 12 FC/APC connectors and combining the 12 fibers into an MTP ribbon connector. The fan connector and all MTP connections in the system were immobilized. In order to ensure that any light transmitted into the cladding glass was properly dissipated, a minimum of 200 meters of ribbon fiber was inserted on either side of the splice point. A second fan connector was used to connect the MTP connector at the end of the ribbon to the FC/APC connections on the switch. 12 on-off switches, one for each lightpath, were inserted into the system. The outputs of the switches were passed through a 12x1 high performance coupler, and the output of the coupler was connected to an optical power meter. The second output of the 1x2 splitter is connected directly to an optical head with an integrating sphere, to be used as a reference signal to correct for drift. An integrating sphere is a polarization-insensitive device which allows for quick, reliable, and accurate measurement of optical power.

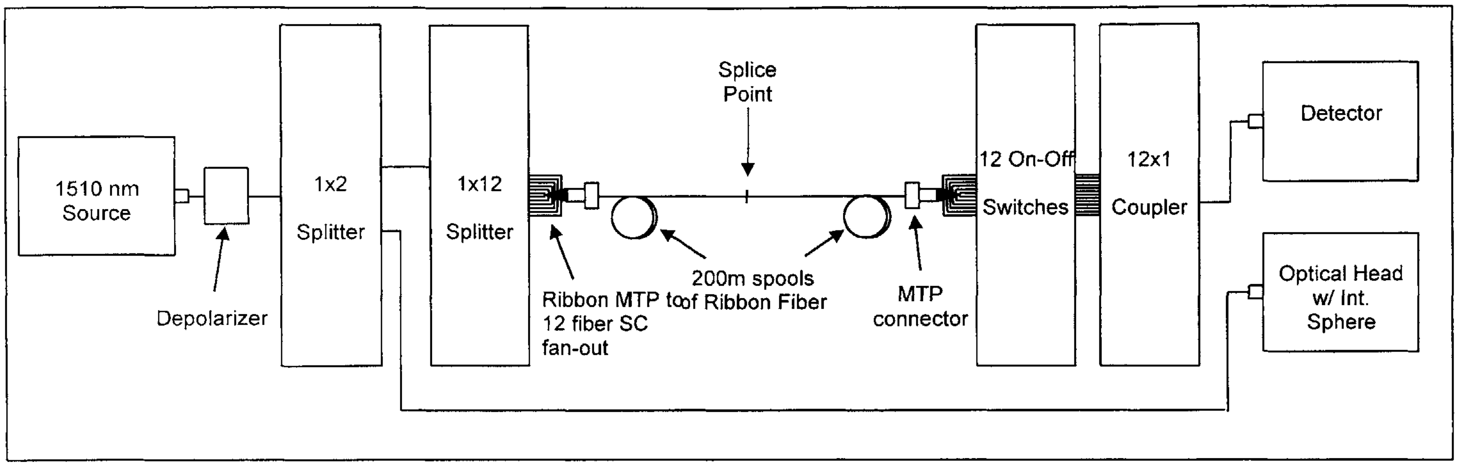

Figure 14: Splice Loss Measurement System

3.1.1 Splice Loss Measurement System Stability

The test system was assembled according to the schematic, and measurement system analysis began. The first step in the measurement system analysis was to understand the stability of the 1510 nm laser source. The laser source, optical power meter, and optical head with integrating sphere are all connected to a control device called an optical mainframe. The operating software for the optical mainframe contains an application which logs data over time to allow for automated collection of stability data. The procedure for conducting a stability test was:

Procedure for Measurement of Optical Source Stability

1. Connect optical source to detector
2. Turn on optical source and wait 1 hour
3. Set up Stability application on optical mainframe with the following parameters:
    - Total Time: 23hrs 59mins 59secs (maximum)
    - Averaging Time: 100 ms
    - Data Points: 4000 (maximum)
    - Both power meters (optical power meter and integrating sphere) logging data
4. Run stability application
5. Save results to floppy on mainframe, and analyze results.

The resulting data is a series of 4000 data points which detail the power recorded by both power meters spaced evenly over a 24 hour period, or every 21.6 seconds. Each data point represents the average power observed for 100 milliseconds. The power measurement from the integrating sphere was used to remove drift from the test system over time, in the following way:

$$\text{Adjusted Power}_{t=T} = \text{Power Meter Reading}_{t=T} - (\text{Int. Sphere}_{t=T} - \text{Int. Sphere}_{t=0})$$

Power Meter Reading = Power measurement for light transmitted through ribbon (in dBm)
Int. Sphere = power measurement of reference signal, taken using an integrating sphere (in dBm)

This equation is designed to remove any drift in the power emitted from the source from the power readings taken at any time = T. The assumption here is that any drift in source output power will be reflected identically in the measurements of both the optical power meter and the integrating sphere. Every power measurement made in this project was adjusted using this same adjustment technique.

The verification of measurement system stability was an iterative process, where sources of instability were identified and resolved, and the test was run again until the system was adequately stable. Specifically, electrical noise was found to be a source of instability in this system. The power supply for the optical source was wired to the same circuit as the laboratory air conditioner, resulting in wild instabilities in the system when the thermostat turned on the air conditioner. Because the Portsmouth Photonics Lab was still very new, this problem had not been discovered. The air conditioner was moved to a separate circuit, eliminating this electrical noise problem. The results of the final stability check are shown in Figure 15.

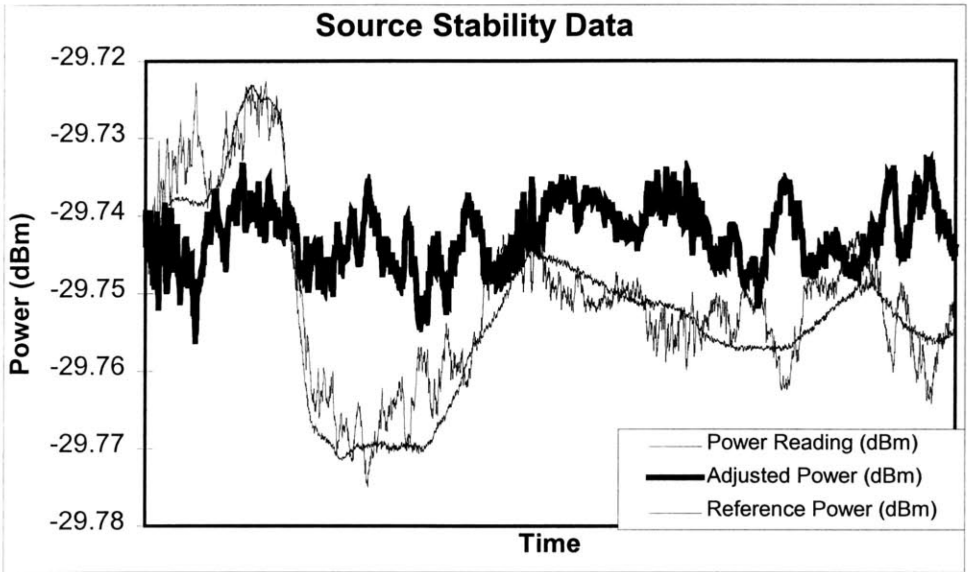

Figure 15: Stability Test Results for Splice Loss Measurement System

The stability test showed that the adjusted power varies by +/- 0.01 dBm over the time period (14 hours for this chart). This chart also demonstrates the effectiveness of the adjusted power calculations devised to improve the stability of the system. The two thin lines represent the power readings from the optical power meter and the integrating sphere. It is clear from this chart that these two measurements are highly correlated. Comparing the adjusted power reading (**bold** line) to the raw power readings (thin lines) gives a visual indication of the improved long-term stability of the test system when the adjustment is made.

3.1.2 Splice Loss Measurement System Linearity

Once the stability of the system was verified, the next step was to verify the linearity of the detector. The setup for verifying the linearity of the detector is shown below in Figure 16.

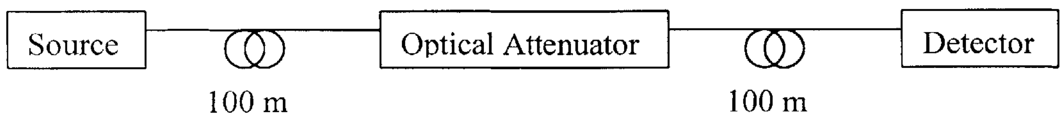

Figure 16: Setup for Measurement of Detector Linearity

The procedure for measuring detector linearity was:

Procedure for Measurement of Detector Linearity

1. Set up experiment as shown above
2. Set attenuator to 0.00 dB and record output at detector
3. Increase attenuation by 0.01 dB and record new output at detector
4. Repeat step 3 until attenuation = 0.1 dB
5. Increase attenuation by 0.1 dB and record new output at detector
6. Repeat step 5 until attenuation = 0.5 dB
7. Compare output at detector to expected output given attenuation

This experiment makes the explicit assumption that there is very low variation in the optical attenuator and that the optical attenuator is linear. The data obtained from this test was regressed using simple linear regression to check for linearity. The regression plot is shown in Figure 17.

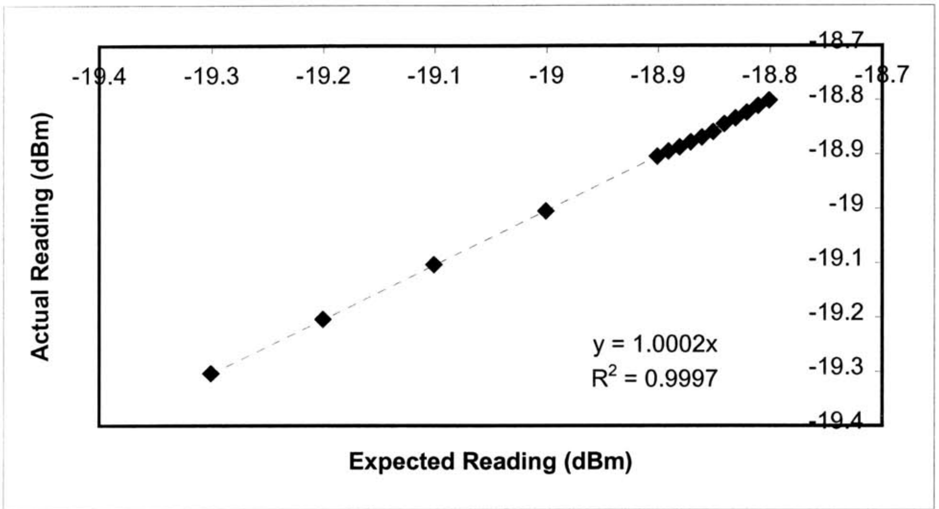

Figure 17: Linearity Check for Splice Loss Measurement System

3.1.3 Splice Loss Gage R&R Study

With stability and linearity verified, the next step was a Gage R&R study. The test system was comprised of one source and one receiver, with 12 individual measurement paths. As such, each of the measurement paths was an independent measurement system; the lightpaths in the splitters and switch were assumed to be independent. It is possible, for example, that one of the on/off switches could be less repeatable than the other switches for some reason. In order to accommodate this possibility, each lightpath was evaluated as an individual measurement system. The setup for the Gage R&R was slightly different than the actual test setup, in that the 1x12 splitter was connected directly to the switch, without any optical ribbon fiber in between. The switch was then connected to the coupler, and the output of the coupler was routed through an FC/APC barrel, and then to the optical power meter. The FC/APC connector/barrel serves as a surrogate for the splice loss; repeatedly connecting and re-connecting an FC/APC connector yields very similar insertion losses to the expected mass fusion splicing losses, but the process is much faster than completing a fusion splice. A single fusion splicer was not used in this system because Celestica's single fiber fusion splicing process produces splices which are consistently lower in loss and lower in variability of loss than the expected performance of the mass fusion splicers. The Gage R&R test setup is shown in Figure 18.

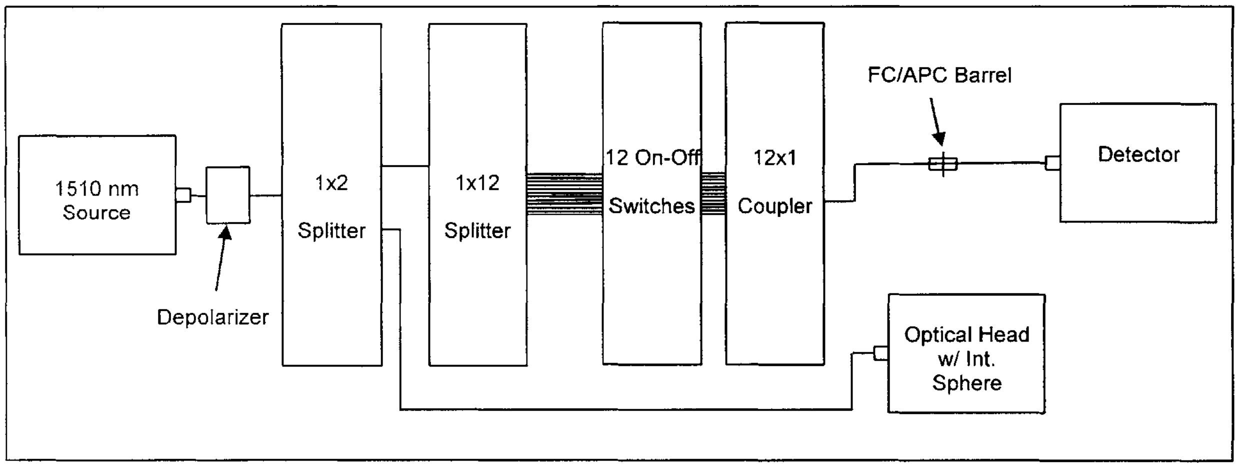

Figure 18: Gage R&R Experimental Setup

Destructive testing was discussed in Section 2.2.3. In this experiment, once a fiber has been zeroed, broken, and then spliced, there is no way to "re-zero" the fiber and measure the same splice again. This destructive nature of the test introduces a challenge when evaluating the measurement system, because a traditional Gage R&R would require multiple operators to measure the loss of the same part multiple times, but the measurement can only be taken once. Because measuring a splice insertion loss is a destructive test, adjustments to the traditional Gage R&R methodology must be made to accommodate the measurement system. The procedure for the Gage R&R is as follows:

Gage R&R Procedure

1. Set up experiment as shown above.
2. Turn on source and allow warming up for at least 1 hour.
3. Take power measurement on each channel (12 total) to be used as reference. Each of the operators should take their measurements simultaneously but independently.
4. Disconnect FC/APC connector from barrel, and reconnect.
5. Cycle through the twelve channels randomly recording the power measurement at each channel three times. Each time a new channel is selected, each operator makes one measurement. Each of the operators should take their measurements simultaneously but independently. Each operator should record 3 readings for each of the 12 channels, for a total of 36 readings per operator.
6. Repeat steps 4 and 5 nine times, for a total of 10 disconnect/reconnect cycles of the FC/APC connector.
7. Analyze data for each channel individually, with each operator making three readings of 10 parts for each channel.

The data was analyzed according to the traditional Gage R&R framework. The results of the Gage R&R analysis, as discussed in Section 2.3.2, can be summarized by two statistics, %R&R and the number of measurement levels detected. The table below shows the Gage R&R results for the Splice Loss measurement system:

Channel	% R&R	Measurement Levels
1	2.00%	49
2	2.30%	44
3	1.80%	55
4	1.70%	59
5	2.00%	51
6	1.80%	55
7	1.50%	65
8	2.00%	51
9	3.30%	31
10	4.10%	24
11	2.80%	35
12	2.00%	49

It is often useful in data analysis to use graphical techniques to demonstrate the results in a more tangible method. For the Gage R&R methodology, a good graphical technique is a chart known as a variation plot, which elegantly summarizes the relative magnitudes of the different components of variation. The variation chart for channel 3 in this Gage R&R analysis is shown in Figure 19.

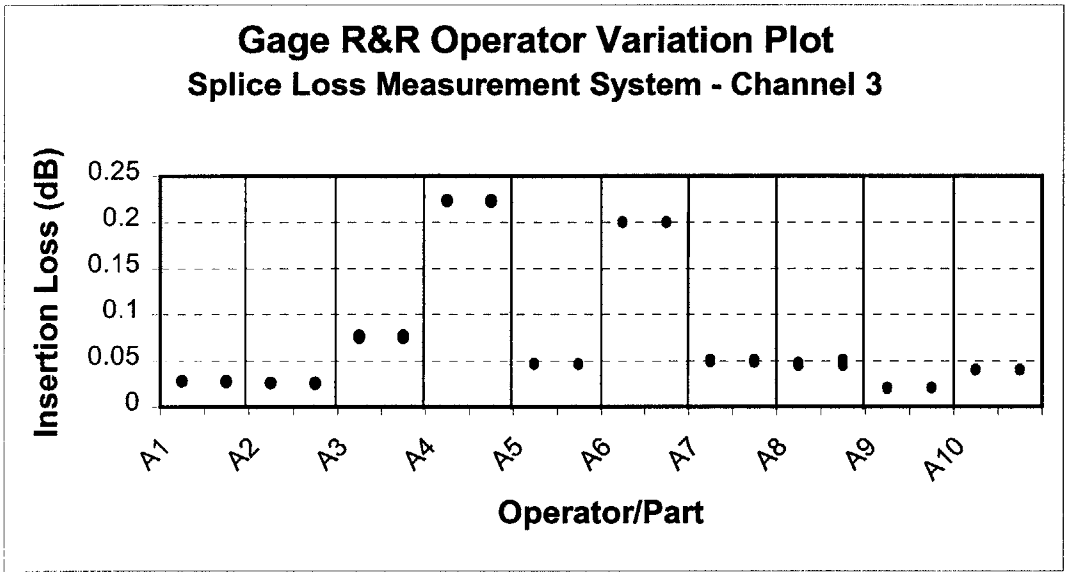

Figure 19: Example of Operator Variation Plot

Each grouping of data points on the plot represents the multiple measurements made by the same operator on the same plot. In this example, there are three data points in every grouping, but they are so similar that they often appear to be one data point. Looking at two adjacent data sets within a set of vertical lines (A1 and B1, for example) shows the variation between the groups of measurements made on Part 1 by operators A and B. The variation between the sets of vertical lines represents the part variation. Looking at this plot, it is clear that the within operator variation (the dispersion of the data points in each group) and the between operator variation (from A1 to B1, for example) are very small when compared to the part variation. Looking at the calculations from the previous table, this intuition is verified. The %R&R for Channel 3 was 1.8%, representing a remarkably repeatable measurement system.

3.2 Tensile Strength Measurement System Analysis

Tensile testing was included as a response variable in this experiment because it is an indicator of the defects and flaws in the spliced fiber. Tensile strength can, then, give some information about the damage done to the fibers being spliced by the preparation and fusion splicing processes.

For this experiment, tensile testing was done on a Vytran Rotary Pull tester. Ideally, the test system for tensile strength would be investigated using Gage Study techniques. However, the tensile strength is a truly destructive test, making it impossible to test the same sample more than once. In order to perform a Gage R&R study on the tensile testing measurement system, samples would have to be selected carefully to ensure that the variation between samples is relatively large. In the case of optical fiber, there is no practical way to control the sample with the required precision; the defects that cause crack propagation are very small and impossible to detect with common laboratory instrumentation. Given this difficulty, and also given that tensile strength is a response variable which is of secondary importance in this evaluation, the pull tester was carefully calibrated prior to experimentation, and all tensile testing was performed by the same operator to minimize any between-operator variation. No further evaluation was performed.

3.3 Measurement System Automation

This project required the collection of a very large amount of data. For the insertion loss of a single ribbon splice to be measured, a reference splice must be performed to zero out the system. Measuring the loss of a reference splice requires recording both the optical power meter and integrating sphere measurements for each of the 12 channels for a total of 24 measurements. When the splice to be measured is completed, 24 more measurements must be made and recorded. In order to measure multiple splices with multiple operators on multiple sets of equipment, the data collection system needed to allow for very fast collection of a large amount of data.

To solve this problem, a computer program was written using the LabView programming environment. The program interfaced with the laser source, switches, optical power meter, and integrating sphere to cycle through the channels and record both the optical power meter reading and the integrating sphere reading. The gathered data was saved to a file for later analysis. The development of the LabView program greatly increased the speed of experimentation and allowed the operators in the experiments to concentrate on conducting the experiment rather than cataloguing data.

4.0 EXPERIMENTATION AND ANALYSIS

Once the measurement systems were assembled and verified, the experimentation process to select the best equipment for mass fusion splicing could begin. Experimental procedures were developed to help ensure consistent use of the tools between splicers and between operators. The experimentation and analysis were undertaken in two distinct phases: a screening phase and a final selection phase.

4.1 Experimental Procedures

The experimental procedures used in the mass fusion splicer evaluation were designed with several considerations in mind. The test system was designed to ensure the accuracy of the data collected. The test procedure was designed to increase the speed of experimentation without introducing causes of variability. New reference splices were taken every five splices, to ensure that the intrinsic attenuation of the fiber did not bias the results of the experiment. The typical attenuation of optical fiber is 0.2 dB/km. In five splices, the maximum amount of fiber used is 5 meters, giving a loss of 0.001 dB. Re-referencing the system every five splices is a conservative procedure, but it ensures the quality of the data. Also, the tensile testing was separate from the splicing to allow for a single operator to do all pull testing. This required that the splices be cut out and saved for pull testing.

Procedure for Insertion Loss Test

1. Connect equipment as shown above, with continuous ribbon fiber
2. Turn on source and leave on for 1 hour
3. Use computer program to take reference reading on fiber 1
4. Use computer program to switch output to fiber 2
5. Use computer program to take reference reading on fiber 2

6. Repeat steps 3-5 for fibers 3-12
7. Cut ribbon fiber in center (splice point on diagram)
8. Strip and clean ribbon fiber
9. Cleave ribbon fiber ends
10. Fusion splice ribbon fiber ends back together
11. Gently remove spliced ribbon fiber from fusion splicer
12. Record machine's estimated loss value(s)
13. Use computer program to take output reading on fiber 1
14. Use computer program to switch output to fiber 2
15. Use computer program to take output reading on fiber 2
16. Repeat steps 12-14 for fibers 3-12
17. Cut ribbon fiber approximately 24" away from the splice on each side.
18. Store spliced fiber for rotary pull testing.
19. Repeat steps 8-18 four times, for a total of five splices stored for pull testing.
20. When five splices have been made, put a splice protection sleeve over one of the cut ends of fiber.
21. Strip and clean ribbon fiber
22. Cleave ribbon fiber ends
23. Fusion splice ribbon fiber ends back together
24. Carefully remove spliced fiber from fusion splicer.
25. Slide splice protection sleeve over exposed fibers.
26. Put sleeve and fiber into heating oven and shrink sleeve onto fiber.
27. Repeat steps 3-26 until all splices have been completed

Procedure for Tensile Testing

1. Remove the clear matrix material from the ribbon.
2. Carefully remove fiber 1 from the ribbon.
3. Place fiber 1 on the rotary pull tester.
4. Test the fiber, recording the results on the datasheet.
5. Repeat steps 2-4 for fibers 2-12.

These procedures were documented, and the experimental operators were trained to complete these procedures throughout the experimentation.

4.2 Screening Experimentation and Analysis

At the start of the project, a set of potential process equipment was identified which formed the decision set for the experimentation. This decision set included five (5) mass fusion splicers, four (4) ribbon fiber cleavers, and four (4) ribbon fiber strippers. In addition, the experiments needed to utilize multiple operators to be able to estimate how sensitive each set of equipment was to operator interaction. A full factorial experiment with such a large number of factors and levels would have been extremely time consuming to conduct. In order to simplify the experimentation process, a screening experiment was conducted to narrow down the decision set to a smaller set of choices which are more likely to be the best option.

Two simplifying assumptions were made to guide the planning of the screening experiment. First, each mass fusion splicer manufacturer provided Celestica with a complete tool set for mass fusion splicing, including the splicer, a cleaver, a stripper, and occasionally a cleaning system. The screening experiment was conducted by only using the tools that the splicer vendor provided with that splicer. This assumption ignores the possibility, perhaps even the likelihood, that the same splicer manufacturer did not supply the best splicer, cleaver, and stripper. Conducting the experiment in this manner confounds the effects of the splicer, cleaver, and stripper, and the result is that the data is only useful for comparing between toolsets. The second simplifying assumption was that the experiment would not be randomized. The experimentation for a single mass fusion splicing toolset took approximately 1-2 weeks to complete, and the mass fusion splicer manufacturers were lending their equipment to Celestica for experimentation. To randomize the screening experiment for the splicers, all five splicing toolsets would have been required to be at Celestica's site for the duration of the experimentation. In addition, the experimental set-up was designed to accommodate one splicer at a time, or at most two fusion splicers simultaneously. Attempting to randomize splicers under this space constraint would inevitably have led to excessive set-ups of the splicers, which would not be indicative of the environment they would see in the manufacturing process and which could introduce additional variability into the experiment which could skew the results. For these reasons, the experiment was not randomized for splicer; the splicers were experimented with one at a time during the screening experiment.

The design of the screening experiment was as follows:

- Five fusion splicing toolsets (A,B,C,D, and E)
- Three operators (A, B, and C)
- 10 ribbon splices per operator per toolset
- A total of 150 ribbon splices performed

The response variables, or output variables, of the screening experiment were:

- Actual Insertion Loss (dB)
- Estimated Insertion Loss (dB)
- Tensile strength (kpsi)
- Cycle time (minutes: seconds)
- Splice yield (%)

The most important response variable is actual insertion loss. The results for the screening phase for actual insertion loss are shown in the Figure 20.

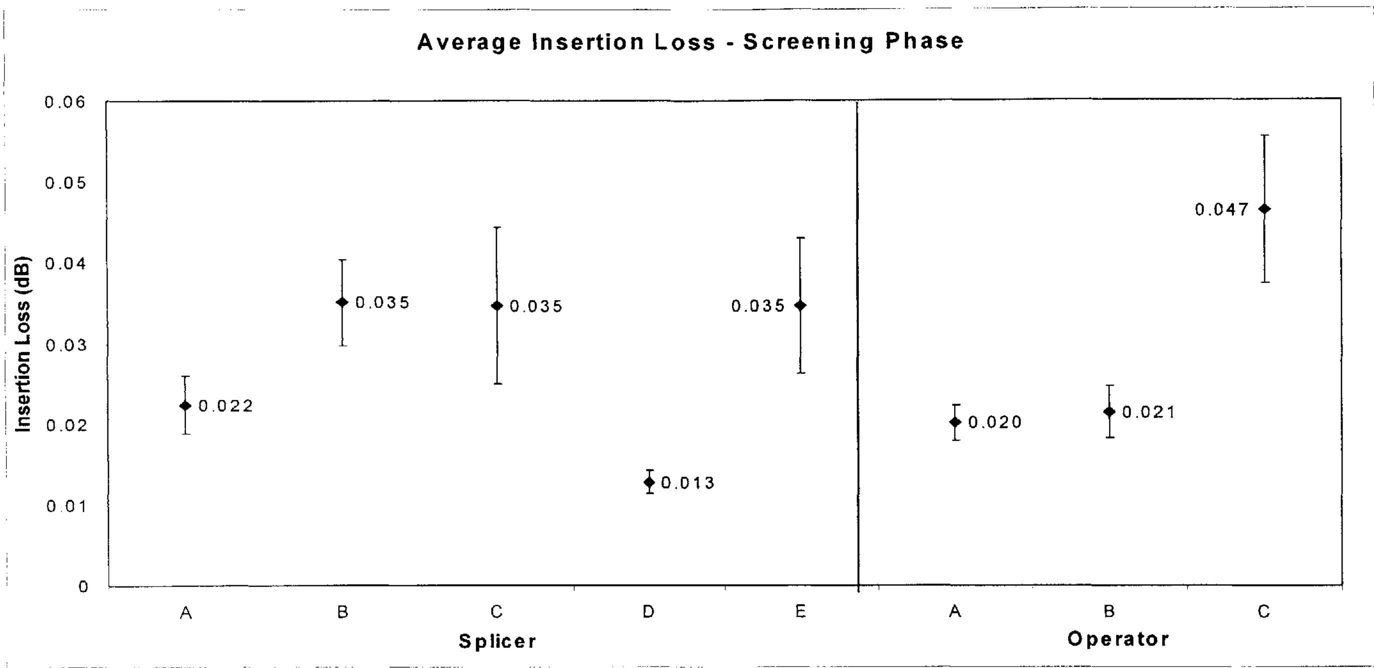

Figure 20: Screening Phase Insertion Loss

This chart is the average insertion loss observed in the screening experiment. The error bars represent the upper and lower 95% confidence interval for the average insertion loss. In general, the data sets are close in size, so the length of the error bars is representative primarily of the variability of the insertion loss. It is obvious from this chart that splicer D consistently produces lower insertion loss, which is desirable. Splicer A is second to splicer D, while splicers B, C, and E are very similar in their performance. It is also clear that there is an operator dependence problem with insertion loss; the insertion loss of operator C's splices are both higher and more variable than operator A or B.

A typical method to analyze the statistical significance of these populations of data is to use analysis of variance (ANOVA) methods or two-sample t-tests with unequal variances, or some other similar analytical technique to indicate statistical significance. This can often be a useful tool, but in this particular case not much emphasis is placed on these models. The data sets are very large, with each set containing approximately 300 data points. This large amount of data can lead to conclusions of statistical significance in situations where there is no practical significance to the analysis. For example, a two-sample t-test with alpha = 0.10 indicates that splicers C and E have mean insertion losses which are statistically significantly different. While this may be true in some mathematical sense, looking at the means of the data in the above chart shows that this fact is not particularly meaningful; for any practical definition of significance, splicers C and E have the same mean. As a result, graphical methods were considered generally effective for understanding the results of the screening experiments.

Looking back at the insertion loss results, it is clear that splicers D and A were the best performers, but the operator dependence of the system was perplexing. Further investigation to the interaction between the splicers and the operators revealed a useful insight: splicers D and A were less sensitive to operator variability than the other splicers. This is demonstrated in Figure 21.

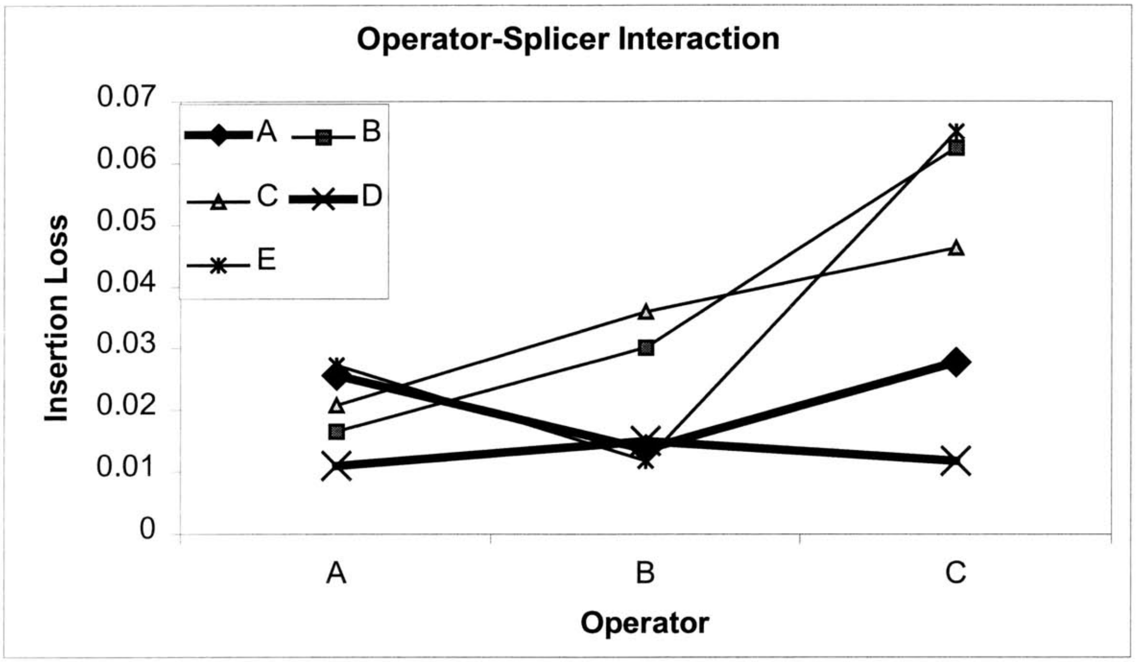

Figure 21: Screening Phase Operator-Splicer Interaction Plot

The interaction chart shows that splicers D and A are less impacted by operator C than the other splicers. The reason for this difference was not identified in the experimental analysis, but it supports the conclusion that splicers D and A performed better than their peers in actual insertion loss.

The tensile strength testing results from the screening phase were not entirely conclusive. Splicer B's splices were very strong relative to the rest of the population, and splicer A's splices were very weak. Several issues could contribute to this difference. Splicer A was the first splicer tested, so it is possible that some learning effect took place in either the splicing process or the tensile testing process. Any learning effect should have been evidenced by residuals analysis; no learning effect was found. Also, the preparation equipment was believed to be the primary contributor to tensile strength, so the strength results helped to narrow down the selection of preparation equipment for the final selection experiment. The results are shown in the Figure 22.

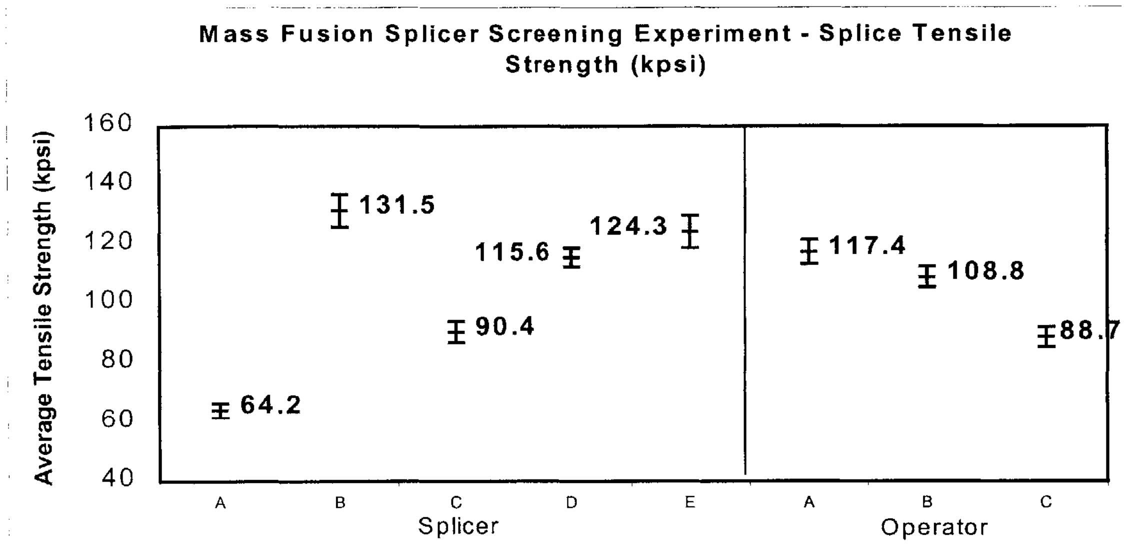

Figure 22: Screening Phase Tensile Strength Results

The accuracy of the splice loss estimators was a strong differentiator between the splicers. The Splicer D estimator is substantially more accurate than any of its peers, with Splicer A's estimator performing as a distant second. The data is hard to summarize, but the most useful statistic is to examine the percentage of splices where the estimate is wrong by more than a specified amount. Using 0.05 dB as the error-tolerance threshold, Splicer D outperformed its peers substantially, as shown Figure 23. Further analysis indicated that Splicer D's estimator outperformed the field at all possible values of the error-tolerance threshold.

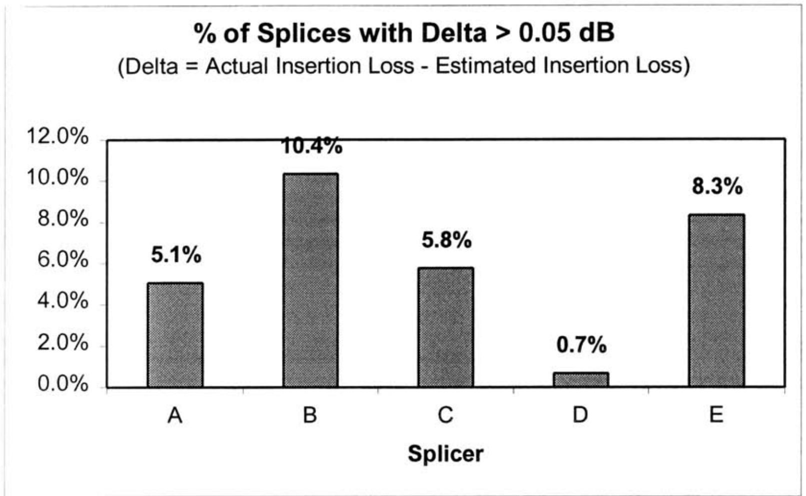

Figure 23: Screening Phase Splice Loss Estimator Performance

Splice yield was a critical criterion in this evaluation because a bad splice requires rework and slows down the cycle time of the splicing process. Defective splices were defined as those splices with any single fiber having an estimated insertion loss greater than 0.10 dB. In data analysis, these splices were eliminated from the data set for the screening experimentation results. Considering these splices in the data analysis for actual insertion loss, for example, could double-count the effect of the bad splice. If a splicer indicates that a splice is bad, the splicer's yield will be impacted. If that splice were then included in the data set for actual insertion loss and it was indeed a defective splice, then the actual insertion loss data would be tainted by a splice that would have been reworked in the manufacturing process. As a result, this experiment was basically evaluated in two stages: 1.) the percentage of the splices completed by these splicers were "good" (no estimated insertion losses > 0.10 dB), and 2.) the performance characteristics of those "good" splices. In practice, yield was a strong differentiator among splicers, in that Splicer E produced a "bad" splice 24% of the time, whereas Splicer D never produced a "bad" splice. This does not mean that Splicer D is incapable of producing bad splices, but rather that it did not produce and detect any bad splices during the experiment. The yield results are shown in Figure 24.

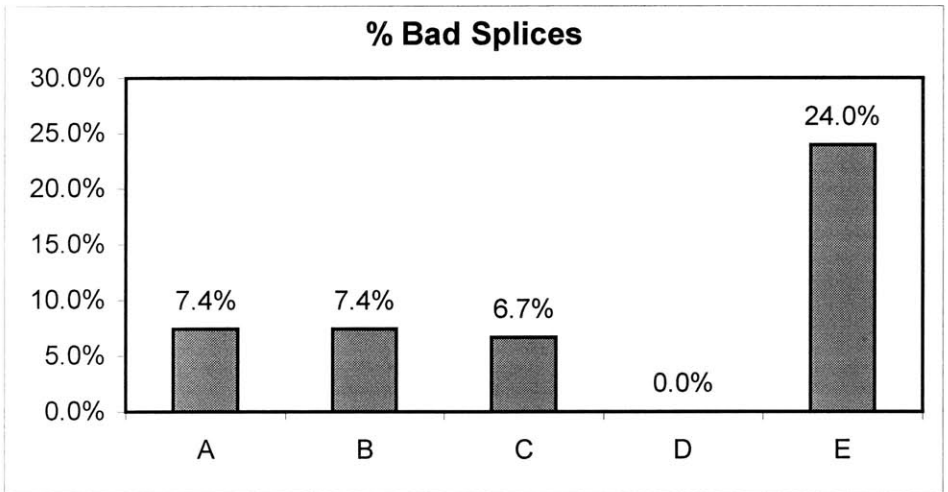

Figure 24: Screening Phase Splice Yield

The data was analyzed to attempt to estimate the cycle time of each splicer, but the data as collected was not particularly instructive. The issue with cycle time in mass fusion splicing was that almost the entire cycle was consumed by preparation activities. In the case where everything worked as planned, the preparation time was approximately 8-9 minutes regardless of the toolset used. The splicer took an additional 1-2 minutes to make the splice. The time required to complete a splice was about 11 minutes in the best case, but could often be much longer. If the fibers were not completely clean and free of debris, they would not settle into the splicer V-grooves, resulting in poor alignment. The splicer checked this alignment prior to splicing, and if an error was detected the splicer alerted the operator. Resolving this problem can be very fast, for instance by removing the fibers and re-loading them into the splicer. The resolution can be much more time consuming, requiring recleaning the cleaved fibers, repreparing the fiber ends completely, or even a thorough cleaning of the V-grooves. As a result, the cycle time information provided more information about the preparation process effectiveness than about the actual time required to complete a specific task, and the data was too variable to be conclusive. One of the key goals of the final selection phase of experimentation was to understand the impact of the preparation tools on the process, including an in-depth look at cycle time.

The operators' subjective evaluations of the splicers were an additional factor in the screening evaluation. After each operator used each splicer, they recorded their likes, dislikes, suggestions for improvement, and general feel for the unit. This information was not very useful in differentiating between splicers, primarily because the touch-and-feel characteristics of several of the different splicers were very similar. Splicers A, C, and D were extremely similar in their appearance and in their use, but produced very different results. The analytical data provided opportunities to discriminate between them, but the subjective data was very limited. Splicer A was generally seen as having a good operator interface, this may have been due to the some of the experimental operators having prior experience with a very similar operator interface. Splicer C's fiber holders were not very easy to put in the precise location required for splicing; there was a depression in the holder which was intended to fit over a raised area on the unit, but the locating mechanism was not as seamless as on other units. Splicer D was well liked for its performance and speed, and also won praise for having a clever mechanism for allowing the fibers to be jostled slightly without having to reopen the canopy, which saved time in resolving minor alignment problems (although other splicers had very similar features.) Splicer B was designed differently than the other splicers, with major differences in operator interface and fiber handling accessories; in general was not well received by the operators. The operators felt that the interface was not at all intuitive, and that some of the fiber accessories were unnecessarily complex and cumbersome. Splicer E was also very unique, and was not well liked by the operators. This is likely due to the extreme care and diligence required to get even a single successful splice from the unit, which caused nearly every facet of the splicer to be scrutinized and criticized. Splicer E did incorporate some novel fiber handling mechanisms which were considered clever and helpful. As a result, the subjective data indicates that splicers A, C, and D employed a similar concept which is intuitive and was well received, while splicers B and E were generally not well regarded.

The final analysis of the screening design arose from the availability of a stripping device which was not included in any toolset from any splicer vendor. The stripper was automated and easily controllable, and appeared to be much more user friendly and operator-robust than the other strippers in the experiment. The new stripper was loaned to Celestica for a short period of time to allow for the gathering of some quick data to evaluate the stripper. This stripper was inserted into the design by having operator A perform one-half of his splices on Splicer D with the new stripper, and the other half of his Splicer D splices on the stripper provided with Splicer D. This was considered a reasonable method to get some feel for the new stripper primarily because the stripper provided with Splicer D was identical to a stripper provided with an earlier splicer; this stripper had already been used enough to get a feel for its performance. The hypothesis was that the new stripper would increase the strength of the splices by providing a more repeatable, more controllable, less operator-sensitive method of removing the ribbon fiber coating. The strength data is shown in the Figure 25.

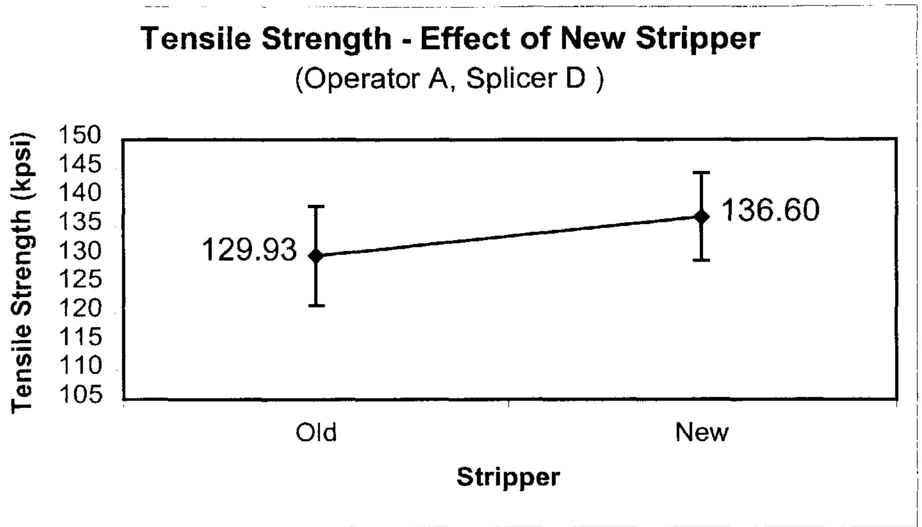

Figure 25: Tensile Strength Effect of Automatic Stripper

This brief experiment shows that the new splicer does improve strength somewhat. This difference was not statistically significant (p-value = 0.2556 for alpha = 0.05). The subjective evaluation of this new stripper was very positive, because the stripper resolved the ergonomics issues of the other stripping mechanism as well as removed the burden for the operator to be very precise with pressure, time, pull speed, etc. As a result, this stripper was selected to be further studied in the final selection experiment.

When the screening experimentation and analysis was completed, the need to conduct a final screening experiment was even more evident than at the start of the project. This was motivated from several primary concerns:

- The assumption that a splicer and its toolset would be evaluated together needed further examination. Some of the best preparation tools were provided by vendors with poor splicer performance.
- The effect of preparation equipment was not well understood, and needed to be studied more carefully.

- The high optical performance of the Splicers D and A needed to be verified with further experimentation.
- The factors that impact tensile strength needed to be more clearly understood. Of particular concern was the very low strength observed from the splicer A in the screening experiments.

4.3 Final Selection Experimentation and Analysis

After a review of the screening phase results, a decision set was selected for further experimentation in the final experimentation. The splicers included in the final experimentation were Splicers A and D. There were two strippers considered: a manual strippers from the screening phase (Stripper 1) and the automatic stripper identified in the screening phase (Stripper 2). Two cleavers were selected from the screening experiment as well, Cleavers 1 and 2.

The design for the final selection experimentation was a 2^4 full-factorial design with 3 replicates, for a total of 64 splices. The four factors to be considered were:

- Operator (Operators A, D)
- Splicer (Splicers A, D)
- Stripper (Strippers 1, 2)
- Cleaver (Cleavers 1, 2)

It is important to note that a new operator was introduced to the experimentation prior to the final selection experiments. Operator A is the same operator A from the screening experiments, but operator D did not participate in the screening experiments. The design was blocked for operator, and randomized for all other factors. The response variables, or decision criteria, were identical to the response variables for the screening experimentation.

Figure 26 shows the Main Effects Plot for Actual Insertion Loss. Each of the frames within the chart is summarizing the entire data set, so for example the left-most frame shows the average actual insertion loss for the experiment by splicer, with the bars around each data point representing the upper and lower 95% confidence intervals for the mean. These main effects plots are useful because they plot results versus the experimental factors on the same y-axis, and as such allow for very quick discrimination between the factors to determine which are most important. The factor whose line is most steeply sloped (least horizontal) is the most significant factor, and in this chart the most significant factor is splicer.

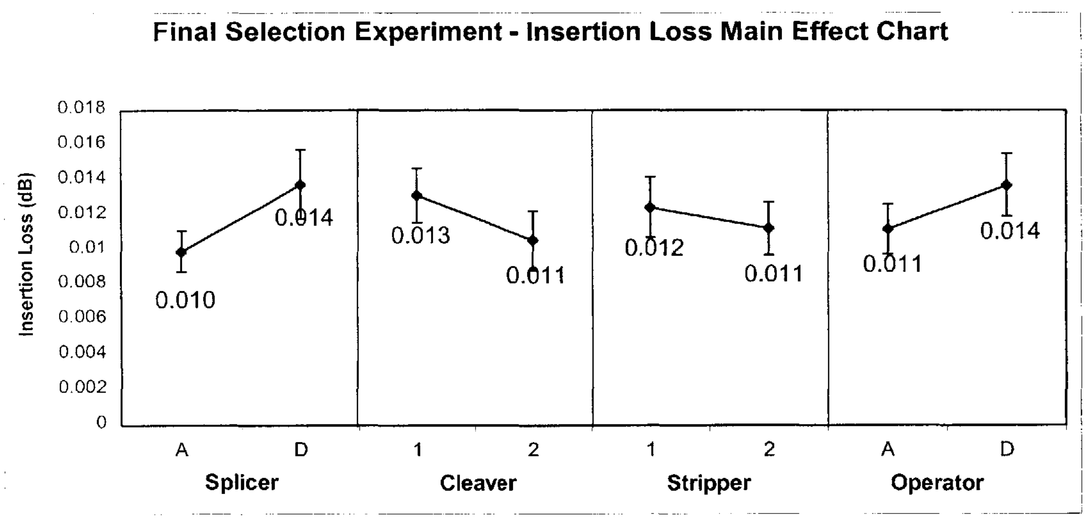

Figure 26: Final Experiment Insertion Loss Main Effects Chart

The key takeaway from Figure 26 is that although there do appear to be effects from each of the factors, the magnitude of the effects is miniscule. In fact, ANOVA analysis indicates that several of these differences are statistically significant (Splicer p-value = 0.0012, Operator p-value = 0.0277), but again the tension between statistical significance and practical significance is relevant. The difference in splicer insertion loss is 0.004 dB, a difference so operationally insignificant that statistical significance is of no interest. The key conclusion is that both splicers can produce very low loss splices, and that the other factors do not significantly affect the loss of the splices.

As in the screening phase, the accuracy of the splice loss estimators continued to be a differentiator. In the screening phase, the data was summarized by the percentage of splices with an absolute error (delta) greater than 0.05 dB. Using this metric, Splicer D had 0.7% failure in the screening phase and 2.03% failure in the final selection phase. Splicer A had 5.1% failure in the screening phase and 13.54% failure in the final experimentation phase. Another way to illustrate the difference in the estimators is to examine the histograms of the deltas, or the differences between the actual insertion loss and the estimated insertion loss. The two histograms are shown in Figure 27.

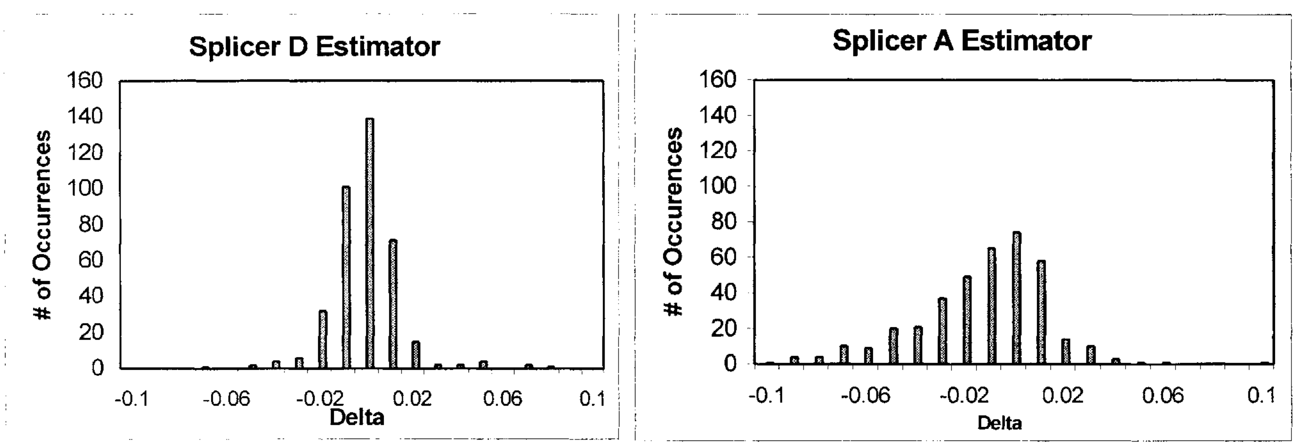

Figure 27: Final Experiment Splice Loss Estimator Error Histograms

These two graphs are plotted on the same x and y axes to give a visual indication of the probability distribution of the error. The same number of observations make up each chart, so the relative height and width of the peaks in the histograms represent the variability of the data. The Splicer D estimator is clearly superior to the Splicer A estimator when the data is shown in this way. The Splicer D histogram is much more densely grouped around a delta of 0 dB (0 dB =

perfect estimation). The Splicer A histogram, on the other hand, has a fairly wide distribution indicating a large variability in delta.

Tensile strength was a major concern entering into the final selection experimentation. In the screening experiments, Splicer A performed very poorly on this metric. Also, the working hypothesis was that the primary determinant of tensile strength is the quality of the preparation tools. The tensile strength data is presented in the main effects plot format in Figure 28.

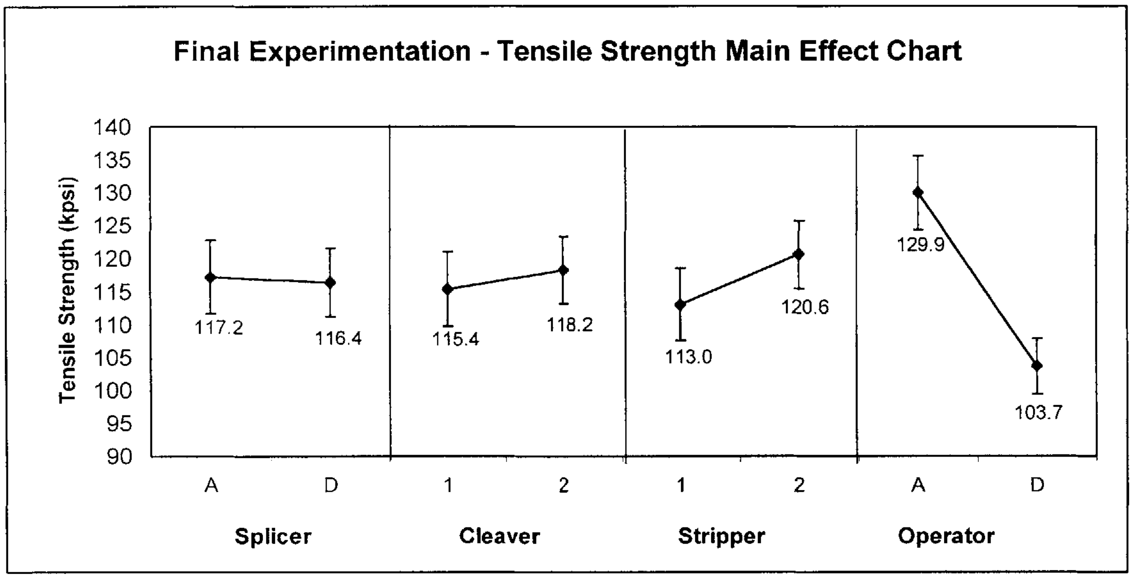

Figure 28: Final Experiment Tensile Strength Main Effects Plot

The main effects plot shows that there was very little impact on tensile strength due to the splicer or the cleaver. This resolves the concerns about strength of the splices created with Splicer A. There was a relatively small effect due to the stripper, with Stripper 2 (120.6 kpsi) outperforming Stripper 1 (113.0 kpsi). The key factor that impacted splice strength was operator. Operator A's splices (129.9 kpsi) were substantially stronger than Operator D's (103.7 kpsi). This effect is almost certainly due to a cumulative learning effect; operator A participated in the screening phase, and was able to complete many splices prior to the start of the final experimentation.

Operator D, on the other hand, was relatively new to mass fusion splicing at the start of final experimentation phase, and only performed enough splices to get familiar with the equipment prior to the final experimentation.

This learning effect is perplexing. It is in conflict with the conclusion from Phase I, which indicated that there was no cumulative learning effect evident in the residuals of the models used to fit the data. If there were some benefit to having completed more splices, then it should have been evident throughout the experiment. The most plausible explanation for the differences seen between Operator A and Operator D relates to meticulous care about the cleanliness of the splicing equipment. Operator A would have had more experience creating bad splices due to preventable causes such as dirty splicing equipment, and would have learned to detect and proactively resolve those problems before they translated to inferior splicing performance. Operator D, on the other hand, was probably still learning how to detect these conditions prior to creating bad splices, and would have allowed more problem conditions to exist. This situation can be overcome by careful training and process documentation to give operators the tools and expertise to recognize these problem conditions quickly.

Regardless of the cause of the operator effect, there are two interesting features about the operator dependency of the system. First, and most important, the actual insertion loss was not heavily dependent on operator. Given Celestica's goals and criteria in manufacturing, actual insertion loss is clearly the most important factor in the choice of a splicing toolset. This experiment indicates that cumulative experience, while it may make for stronger splices and faster splices, is not required to make splices with very high optical performance. Second, the operator effect was unrelated to the stripper effect. One hypothesis that could have emerged in the data analysis was that the manual stripper (Stripper 1) would be more sensitive to operator variability than the automatic stripper (Stripper 2). This hypothesis was not supported by the data, as there was very little interaction between operator and stripper in tensile strength. This is evidenced by the interaction chart in Figure 29. In this chart, each data point represents the average tensile strength of 1/4 of the entire data set. For example, the data point labeled 134.90 is the average tensile strength of splices made by operator A using Stripper 2. If the two lines on an interaction plot are nearly parallel, as they are in this example, there is very little or no interaction between the two factors. If there were a significant interaction, the lines would be either intersecting or far from parallel. The interpretation of this chart is that there is not a significant interaction between operator and tensile strength.

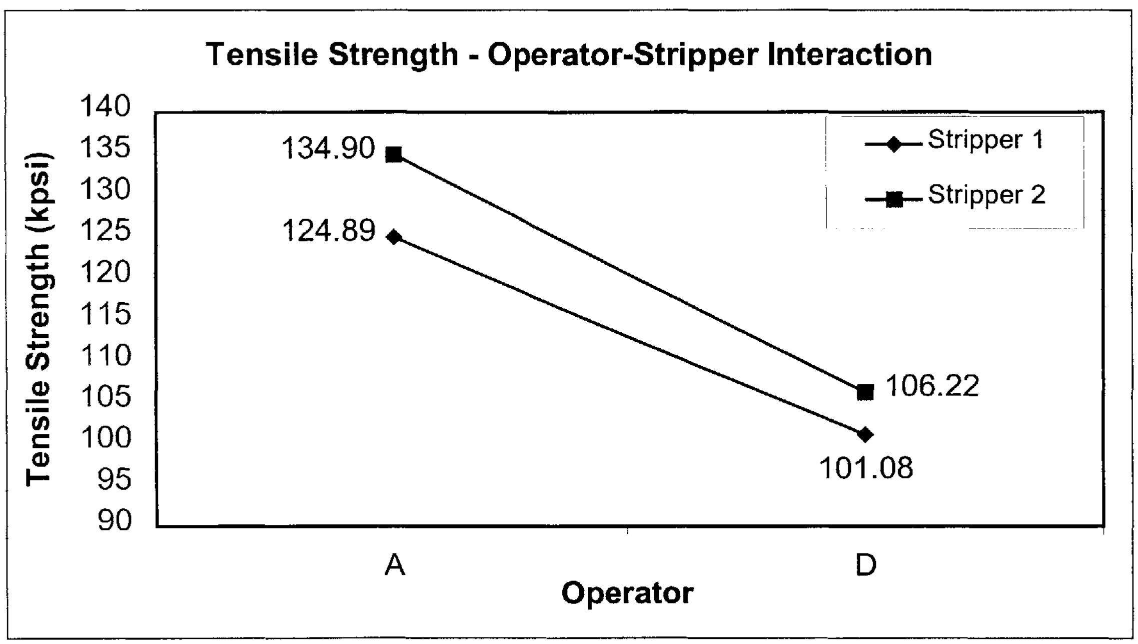

Figure 29: Final Experiment Tensile Strength Operator-Stripper Interaction Plot

As in the screening phase, splice yield continued to be a differentiator. In the final selection experimentation, only 1 out of 33 splices performed with Splicer D was "bad" according to the estimator. Splicer A produced 11 "bad" splices out of 43 attempts. Several of these were considered bad splices for "fat fiber" errors rather than for high estimated losses. The actual insertion losses of the "fat fiber" splices were quite low when measured, but the policy of excluding splices with error messages excluded these splices from the data set.

Along with further understanding of the tensile strength issues uncovered in the screening phase, one of the major goals in final selection experimentation was to learn as much as possible about cycle time of the toolsets in order to make some estimate of how long the process will take in production. Figure 30 is a main effects plot showing the cycle time data collected in the final selection experimentation.

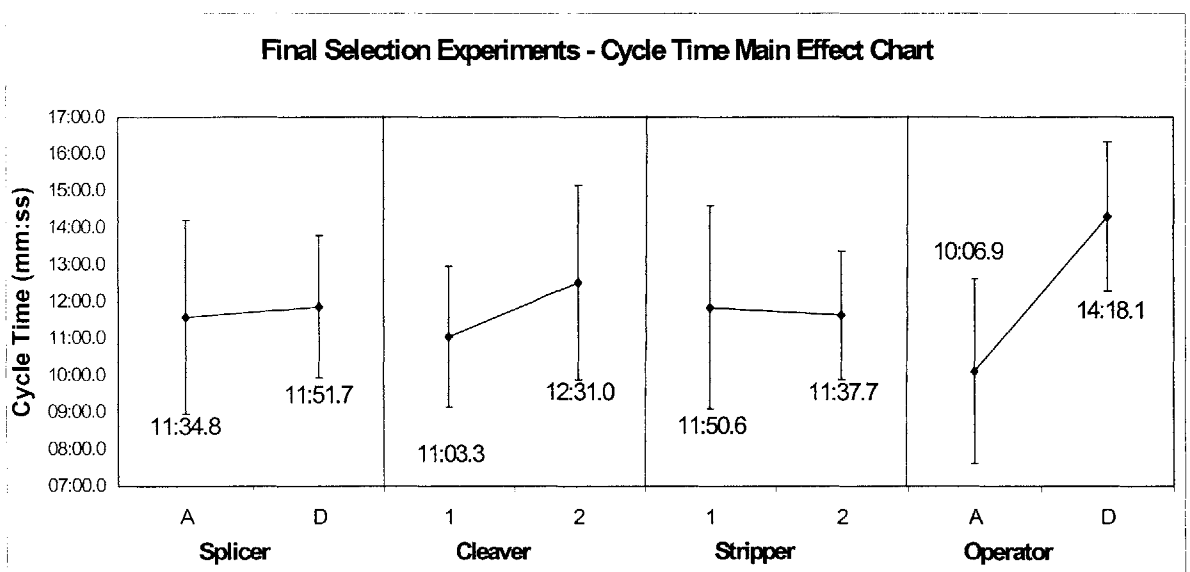

Figure 30: Final Experiment Cycle Time Main Effects Plot

At first glance, the conclusion would be drawn that only impact on cycle time was the operator. While it is true that the operator did impact cycle time, and that the likely explanation for this gap was the cumulative experience of operator A, this data also shows some very interesting other pieces of information upon closer examination. First, there was essentially no effect of the splicer on cycle time, which is consistent with the observations during the screening phase that the splicer time was a relatively small part of the process time.

Cleaver 1 appears to have outperformed Cleaver 2 by about 90 seconds per splice, a significant amount of time when compared to the 11 – 12 minute cycle time. There was no obvious reason for this difference on the surface; the operation of the two cleavers was very similar and indistinguishable in time. The key issue with the cleaver effect was that Cleaver 1 has incorporated a unique innovation which automatically collected the discarded fiber ends left over from the cleave into a bin. Cleaver 2, and all other cleavers tested, relied on the operator to manually collect 12 short glass fibers and deposit them into the waste receptacle for each ribbon prepared, or 24 per splice. This was the key to the cycle time advantage of Cleaver 1, and is an important reason why Cleaver 1 was ultimately deemed superior to Cleaver 2.

The stripper cycle time data was also very interesting. Stripper 2 appeared to take slightly less time, but given the variability of the data there was no conclusive difference. Upon further investigation, Stripper 2 began to demonstrate its worth. Because the Stripper 2 unit evaluated in the experiment was a demonstration unit, the fiber holders for the splicers were not compatible with the clamp on the stripper. For every ribbon to be stripped, the operator was required to put the fiber in the clamp supplied with Stripper 2, load the fiber in Stripper 2, wait for the completion of the automatic stripping process, and then carefully remove the ribbon from the Stripper 2 clamp without damaging the fibers, put the ribbon in the appropriate splicer clamp, and then load the splicer. This transfer of ribbon from one holder to another easily added 30-45 seconds to each splice, and this time would be eliminated by modifying Stripper 2 to allow the splicer fiber holders to be used during stripping. When the 30-45 seconds is added to the 13 seconds advantage already seen by Stripper 2, the automatic method outpaced the manual method by nearly a minute. One interesting point in this discussion is that Stripper 2 actually takes LONGER to strip the fiber (roughly 15 seconds per strip or 30 seconds per splice vs. 2-3 seconds per strip or 5-6 seconds per splice for the manual stripper). The fact that the overall process was made FASTER by using a stripping process which was inherently SLOWER indicates that Stripper 2 made the subsequent steps of the process go more smoothly. In fact, the fibers stripped by the automatic stripper were visibly cleaner than the fibers coming out of the manual stripper. They required less time in the sonicator to remove left over debris, and they caused fewer time-consuming alignment errors in the splicers. This data is a strong endorsement for the value of Stripper 2.

4.4 Discussion of Experimental Results and Recommendations

Based on the outcome of the screening and final selection experimentation, the process equipment was identified for Celestica's corporate standard work station for mass fusion splicing. The equipment set identified was:

- Splicer D
- Splicer A: Second-source Supplier
- Cleaver 1
- Stripper 2

This toolset will be implemented globally wherever Celestica's customers demand mass fusion splicing. The results of the experiment, however, are most useful if they are examined carefully along with the limitations of the experimentation methods.

In designing experiments, assumptions are often made which could impact the results. The design itself often has limitations that need to be considered and discussed. This project was no exception to these realities. It is critical to reevaluate those assumptions and limitations at the conclusion of the project to perform a reality check on the process, and to identify areas which need further study in order to validate certain assumptions or overcome certain limitations.

There were several key assumptions made in planning and executing this project that need to be reexamined. First, only one splicer from each vendor was experimented with. By only experimenting with one splicer of each type, the experiment provides no information about the variability of each mass fusion splicer manufacturer's manufacturing processes. Splicer D dramatically outperformed all other splicers in this evaluation; this does not mean that it is certain that all splicers made by Company D will perform at that level. This assumption had to be made in order to complete the experiment, but it is clearly a significant limitation on the conclusiveness of the results. At a very minimum, Celestica should implement its standardized process for receipt of new equipment, which would mandate that every new mass fusion splicer delivered to Celestica be thoroughly tested by Celestica personnel to verify the expected high level of performance. This procedure was put in place at the end of the project. It is recommended that Celestica work with the manufacturer of Splicer D to obtain several randomly selected mass fusion splicers and perform a study to get an estimate of the variability from splicer to splicer.

Another assumption of this experiment is that the same ribbon fiber was used to conduct the entire experiment. This was a prudent experimental judgment, in that it eliminated the potential noise caused by using different fibers and prevented the test system from being dismantled to experiment with different fibers. However, it is not clear that all ribbon fibers are created equal. Specifically, certain ribbon fibers are said to be more "strippable" than others, which could impact cycle time and splice quality. It is possible that other ribbons might have properties (core-cladding concentricity, fiber curl, geometry of the ribbon, etc.) which could have either a positive or negative impact on the reliability of the process. It is recommended that Celestica undertake a project to study the different ribbon fibers available to characterize the performance of each in Celestica's standard process. This has two potential benefits: 1.) if Celestica is in a position to recommend a type of ribbon fiber to its ONE customers, it would be advantageous to know which fiber is best suited for Celestica's process, and 2.) if Celestica is not in a position to recommend ribbon fiber, it would be beneficial for Celestica to have an understanding of how the customer-specified ribbon fiber will impact the performance of the process so that the contract can reflect the impact, if any, of the ribbon fiber on cost and quality.

The experimental results indicated which equipment would be included in Celestica's corporate standard process for mass fusion splicing, but in some cases the chosen equipment could benefit from further refinement. For example, the fiber clamp on Stripper 2 needs to be modified to work elegantly with the fiber holders from Splicer D. This is only one example of the opportunities to improve the equipment which were identified in the project. The Portsmouth Photonics Lab team was pursuing these modifications and refinements at the end of the project, and they should be completed prior to implementing the process in manufacturing. This will allow for the process documentation, preventative maintenance manuals, and training documentation to reflect the final process as implemented in the factory.

Also, the equipment represents only one piece of the manufacturing process. Other equally important pieces must be brought together in order to create the entire manufacturing process. For example, the equipment must be integrated into an operator workstation that allows Celestica operators to quickly and efficiently complete ribbon splices. Process documentation must be developed to cover training procedures, operating procedures, and maintenance procedures for all of the process equipment. Celestica has existing splicing processes which can serve as a benchmark for the further development of a mass fusion splicing manufacturing process. Celestica personnel have been assigned to aggressively pursue this continued refinement, using the single fiber splicing workstation and documentation as a benchmark.

5.0 BUSINESS PERSPECTIVE ON PROJECT RESULTS

While selection of the equipment set was an important outcome of the experimentation, several other business and managerial issues relating to the experimentation warrant discussion to understand how this project serves Celestica's manufacturing needs and how it fits with Celestica's business strategy.

5.1 Foundations of Evaluation Criteria

The equipment selections made in this project were based on the performance of the various pieces of equipment when mapped to Celestica's criteria for evaluation. Celestica's criteria have thus far only been discussed inasmuch as how they relate to the experimental analysis, but it is important to understand how these criteria relate to Celestica's manufacturing requirements and needs.

The primary criterion is actual insertion loss, which is based on the extreme quality sensitivity of the ONE products that Celestica manufactures. The types of products Celestica assembles are leading-edge, sophisticated, carrier-grade telecommunications hardware, and as such must have unimpeachable quality.

The second most important criterion is the capability of the splice loss estimator. Measuring the insertion loss of a splice in the manufacturing process is essentially impossible. The splice loss estimator serves as a critical quality control mechanism in the factory; if it can be relied upon, the need for costly and time consuming process checks can be minimized. Of course, the estimator is not the only quality control mechanism available; preventative maintenance of the splicers can help to prevent bad splices in the field, and the splicers contain internal diagnostics which can be run periodically. Nonetheless, the splice loss estimator is an important feature.

Cycle time and yield together form an important selection criterion: throughput. The speed at which splices can be made and the chance that each splice is "good" determine the number of splices that a given splicer can make over a period of time. Assuming that the mass fusion splicing workstations will operate at or near full-utilization, higher throughput decreases the unit cost of making a mass fusion splice because fewer mass fusion splicers are required to accomplish a set number of splices. In addition, high yield results in lower rework and lower work-in-process inventory, further reducing costs. Cost is critical in the EMS industry, as reduced manufacturing costs through production efficiencies and supply chain management are a key piece of the value proposition of an EMS company like Celestica.

Splice tensile strength is an important criterion for two reasons. First, it was valuable information to discriminate between the possible preparation toolsets. In both rounds of experimentation, the automatic stripper produced slightly stronger splices than the manual strippers, which helped drive the selection of the automatic stripper. Second, there is a belief in the fiber optics industry that tensile testing is a good proxy for the quality of a splicing process. In practice, this means that potential ONE customers require a manufacturer like Celestica to demonstrate its splicing technology, and one of the mechanisms for evaluating competing EMS companies is to compare tensile strengths. Regardless of whether or not tensile strength is intrinsically related to splice quality in any fundamental way, customers perceive value in strong splices; it is important that Celestica's splices be strong.

Finally, an observant reader would immediately notice that the cost of the equipment was not considered in this evaluation. The rationale for excluding cost considerations from the evaluation is that the goal is to determine the actual performance level of each of the available equipment step and to identify the best performers. The cost of the equipment can be used as in post-experimentation analysis to make cost-benefit trade-offs between multiple choices which are well understood. In the case of fusion splicing, this trade-off can be made with reasonable accuracy by some simple intuition. Assume, for the sake of argument, that a mass fusion splicing process cell, including all equipment identified in this experiment, costs a total of $100,000, an obviously large amount of money. Let's also assume that the very cheapest mass fusion splicing equipment toolset costs $50,000, which could potentially offer savings of $50,000 per toolset when compared to the "best" system. These numbers are purely hypothetical. This $50,000 hypothetical potential savings must be compared to the risks associated with purchasing an inferior toolset. For example, more bad splices leads to rework, which not only adds direct cost to the process, but carries indirect costs such as delayed shipments, dissatisfied customers, the need for additional manufacturing capacity to handle rework flow, the need for additional and more complex test systems and quality checks, etc. An opto-electronics board which fails in the field due to a bad splice could be extremely expensive to repair, and will damage Celestica's relationships with customers. An opto-electronics board which must be scrapped in the factory due to a bad splice could be worth more than an entire mass fusion splicing workstation. Obviously, this cost-benefit analysis should be conducted more rigorously, but the potential savings from buying inferior process equipment can, and in this case almost certainly would, be easily overwhelmed by these hidden but very real costs. It is interesting, however, to note that very little correlation was observed in this project between the cost and performance of the mass fusion splicers tested.

5.2 New Process Development as a Core Competence

The field of opto-electronics assembly is changing rapidly. There are few standards in the technology, and there is a great deal of innovation in the industry at the optical component, system, and network layers. While it is a worthy goal for an EMS company to be able to say that they have a full set of processes to handle any need an ONE original equipment manufacturer might require, this is not likely to be an achievable goal. Given that the industry is changing rapidly and technological innovation continues to progress, it is an absolute certainty that new capabilities and processes will be required which are not in use today.

One way to address this potential source of future problems is to develop and demonstrate a competence in rapidly developing and deploying new process technologies. If an EMS company could credibly and repeatably demonstrate this competence, then ONE original equipment manufacturers could feel reasonably assured that even if process technologies are required in the future which their EMS partner does not possess today, their EMS partner will be able to develop those capabilities and continue to perform at a high level.

This is a part of what Celestica is seeking to accomplish in its Opto-Electronics Technology Strategy, by establishing an organization of fiber optics technology-savvy people and identifying new process technologies and capabilities Celestica needs to develop. By establishing a team of technologically competent people and having that team develop new manufacturing processes for Celestica's customers, Celestica is building an internal body of expertise on process development best practices. This will allow Celestica to continue to develop new processes and technologies to respond to changes in the optical networking industry, and to market themselves as an EMS partner that has a strong track record of developing world-class manufacturing processes. This sends a credible signal to potential ONE customers that Celestica will be able to seamlessly satisfy any future needs that may arise, and increases the value of having Celestica as an EMS partner.

This strategy is well aligned with Celestica's overall business strategy, part of which is to become the EMS provider of choice for OEM's of leading edge computing and communications technologies. Celestica seeks to differentiate itself through demonstration of technological capabilities that other EMS companies do not possess; OEM companies who are leading edge in their field will partner with an EMS who has a track record of successfully manufacturing complex, leading edge products. In the ONE industry, companies who are pushing the state of the technology aggressively are the customers that Celestica is seeking; they are also the customers for whom Celestica's competence at new manufacturing process development can provide the most value.

6.0 CONCLUSIONS

By using a disciplined, analytical experimental process, it is possible to identify the best possible equipment for a specific manufacturing task. It is critical to carefully identify the response variables, or outputs, of the experimentation, and to map those response variables to the needs of the manufacturing organization. The systems used to measure the response variables must be studied and verified to ensure that the experimental results are meaningful.

Celestica's Global Opto-electronics Technology Team is organized to drive execution of the corporate strategy in the Opto-electronics field. The organization is decentralized, reflecting the global nature of the contract manufacturing business. Careful consideration must be given to the reporting structure of the decentralized units. The two main issues in this consideration are the extent to which the satellite labs need to support the local site to ensure successful implementation of the strategy and the alignment between the goals of the local site and the global team. If the goals are well aligned and the satellite labs need to interface heavily with the local site, then allowing the local sites to have control over the labs is effective.

In order to maintain its leading position in a rapidly developing technology area like optical networking equipment manufacturing, Celestica must be able to rapidly develop and deploy world-class manufacturing processes to satisfy customer requirements. Undertaking process development projects such as this one help Celestica to develop best practices in process development. By developing and displaying a competence at developing new manufacturing process to respond to changes in the marketplace, Celestica can credibly market its ability to meet any process need a customer might have in the future, even if Celestica does not possess that capability today. This is a potential source of competitive advantage in the optical networking equipment industry.

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