

OPTICAL NETWORKING EQUIPMENT MANUFACTURING

by

Jason Holman

B.A., Physics, Colgate University, 1996

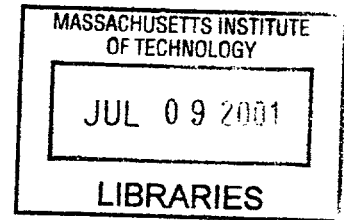
Submitted to the Department of Electrical Engineering and Computer Science
and the Sloan School of Management
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Electrical Engineering
And
Master of Science in Business Administration

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Abstract

Celestica, a global contract manufacturer specializing in printed circuit board assembly and computer assembly, has recently begun manufacturing equipment for the optical networking equipment (ONE) industry. The expansion to include ONE manufacturing requires the development of new skills in handling optical fiber and components, a new supply chain strategy, and a new approach to manufacturing systems control.

Celestica is developing a set of standards for ONE manufacturing that will support the rapid development of the new skills required for this industry. This work outlines the standards and explores the specific issues related to manufacturing with optical fiber, including the mechanical reliability and optical performance of various types of optical fibers. An overview of the telecommunications industry is provided, including an analysis of its supply chain structure. Observations are made on trends in the industry and the ways that these trends have affected Celestica in the past, and could impact Celestica in the future. Finally, Celestica's current approach to manufacturing systems control is evaluated, and suggestions are made for improving systems control and project management when manufacturing for such a rapidly evolving industry.

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Finally, I would like to dedicate this thesis to my editor-in-chief, sounding board, and future wife, Mavyn McAuliffe. Thank you for your patience and support throughout this long and difficult, yet somehow enjoyable, journey

1 Introduction and Overview

This work is based on a six month internship at Celestica that began in June, 2000.

Celestica is a global contract manufacturer with headquarters in Toronto, Canada. At the time of the internship, Celestica specialized in printed circuit board assembly (PCBA) and computer assembly. The company employed over 23,000 people in 33 locations worldwide, and had earned \$USD 5.3 billion in 1999 revenues. Celestica was growing rapidly; in addition to building many new sites, the company had made 20 acquisitions in the previous 3 years.

Beyond its physical growth, Celestica was also growing its portfolio of services, by beginning to manufacture *optical* PCBA's, components, and systems in addition to its standard *electronic* products. These new offerings first appeared at Celestica's Portsmouth, New Hampshire site, which was constructed in 1999 to house operations purchased from Hewlett Packard's system build site in Exeter, New Hampshire. This internship was based at the Portsmouth site, and focused on the site's transition to optical networking equipment (ONE) manufacturing.

1.1 Contract Manufacturing at Celestica: Yesterday and Today

Historically, Celestica has provided design, prototyping, assembly, testing, product assurance, supply chain management, worldwide distribution and after-sales services for original equipment manufacturers (OEMs) in the computer and communications industry. These services were provided for electronic components, printed circuit boards, and systems; all areas where Celestica has a strong base of technical expertise. The Celestica

site at Portsmouth assembled computer workstations and servers for customers like HP and Sun.

In 1999, Celestica's Portsmouth site received a request to manufacture optical networking equipment to be used in optical communications networks. The manufacturing systems and supply chain strategies required to assemble and test optical networking equipment (ONE) are fundamentally different from those required for the computer and printed circuit board assembly that Celestica has done in the past. ONE manufacturing requires new skills in handling optical fiber and other optical components, and the optical networking industry is at an earlier stage of development than the electronics industry. Since the Portsmouth site was Celestica's first site to begin ONE manufacturing, it has experienced first-hand the challenges of controlling processes and inventory in an industry that is so young and turbulent.

1.2 Project Motivation and Description

This project seeks to identify the strengths and weaknesses of Celestica's approach to ONE manufacturing, and to recommend strategies for improving Celestica's ONE manufacturing system. These strategies require a firm understanding of both the technical and non-technical aspects of manufacturing optical networking equipment. Therefore, both aspects are included in the analysis that follows.

Optical fiber forms the core of the optical networking industry, and its presence represents the main technical difference between standard electronics manufacturing and optical networking equipment manufacturing. Therefore, this project identifies the basic

strengths and weaknesses of optical fiber and how they translate into manufacturing requirements. The analysis focuses first on the fiber's optical properties, then on its physical properties and the limitations (and opportunities) that those properties introduce.

Since the telecommunications industry has not evolved to the state of relative stability that the electronics industry has achieved, optical components, product architectures, manufacturing procedures, and supply chains change much more frequently than they do in the electronics industry. This constant evolution stresses the manufacturing system in ways that are difficult to control, and makes a strong system control strategy vital for success. Here the manufacturing system includes not only production, but also supply chain management, marketing, human resources, and all of the other departments that play a role in selling, producing, shipping, and / or supporting products.

Celestica's current manufacturing system control strategy is based on a combination of ISO compliance and World Class Manufacturing (WCM) initiatives. While both the ISO and WCM programs are beneficial, they tend to be executed as separate programs with separate goals. This project suggests ways of integrating the two efforts for enhanced results through a focus on continuous improvements in the manufacturing system. This integration places relatively more emphasis on ISO initiatives than on WCM efforts, as ISO style standardization has more to offer Celestica as it enters a new industry.

Celestica needs to standardize its new manufacturing practices before it can bring them to the world class level.

ONE assembly requires the careful handling of optical fiber, the ability to splice optical fibers together, new testing protocols, and control of unforeseen sources of variability within the processes. Because Celestica is acquiring this knowledge and these skills for the first time, and in order to introduce the new technology in a controlled way, Celestica is compiling a Book of Standards that covers as many generic aspects of the manufacturing system as possible. These ISO style standards will then be distributed to Celestica sites that will embark on ONE manufacturing in the future, so they are an important part of a system control strategy that will allow Celestica to take advantage of strong growth in the telecommunications industry.

The Book of Standards represents one component of a larger system control strategy that will increase Celestica's ability to manufacture quality optical networking equipment. This system control strategy revolves around a serious commitment by all levels of the organization to achieving full compliance with ISO regulations, and a reliance on ISO documents for the day to day management of the company. ISO can provide the framework for Celestica to generate continuous improvement efforts in every area of the manufacturing system, leading to long term gains that significantly outweigh the costs of initially bringing the organization into full compliance with ISO regulations.

The supply chain for optical networking components is also very different from that of the electronics industry. Until the market crash of 2000-2001, optical components were in short supply relative to demand. Furthermore, they are expensive and they are constantly evolving. This project analyzes the current state of the industry from a supply

chain point of view, and attempts to predict the evolution of the industry over the next few years as well as how that evolution will affect Celestica. By understanding the supply chain dynamics, and partnering with the proper members of the supply chain, Celestica can create strategic advantages over its competitors.

Finally, the project makes recommendations for steps that Celestica can take, in addition to improvements that have already been made at the company, to increase its level of performance in ONE manufacturing. These recommendations are based on the technical, organizational, and supply chain analyses that follow.

2 Manufacturing with Optical Fiber

Optical fiber forms the heart of any optical communications network, and overcoming the challenges related to manufacturing with optical fiber requires an understanding of the fiber's fundamental physical and optical properties.

2.1 *The History of Optical Fiber*

Before 1870, scientists believed that light always traveled in a straight line, although it could be reflected by a mirror or refracted at the intersection of two different media. This property of light severely hampered people's ability to use light as a communications medium, since signal routing equipment (mirrors) would be needed at every bend in the communication path. All of this changed when, during a lecture before the British Royal Society in 1870, John Tyndall demonstrated that light will follow a curved transparent medium [Kuecken]. However, it was not until the 1950's that the ability to bend the path of light was put to practical use, when VanHeel, Hopkins, and Kapany developed the fiberscope and coined the term "fiber optics". The fiberscope was a flexible optical scope that allowed users to see around corners or into hard to reach places, such as jet engine compartments and human cavities.

Unfortunately, no practical method for communicating via light through the fiber optics could be found, because no source existed with enough focused light energy to send signals very far through the medium. Then, in 1958 Townes invented the laser, which generated enough optical power to make optical communication feasible. The first optical communications links were free space links, with a laser on one building sending

light through the air to a detector on another building. However, weather related interference made these links unfeasible. (It is interesting that similar approaches are being explored today for use in the last mile segment of the telecommunications market, and weather continues to be a major concern.)

Optical fiber offered advantages over both free space links and copper, because it allowed the transmission of optical signals without exposing the communication link to external interference. The attractiveness of optical fiber as a communication medium led to a series of improvements aimed at reducing the attenuation of optical signals traveling through them. Even though lasers could generate high powered and focused light beams, excessive attenuation in optical fibers ($\gg 20$ dB/km) required prohibitively short links between sets of expensive optical signal regenerating equipment (called repeaters). A major breakthrough occurred when Kapron, Keck, and Maurer, of Corning Glass Works, developed long fibers (hundreds of meters) with attenuation of less than 20 dB/km in 1970. Attenuation is typically measured in decibels, and is a relative measurement that compares the optical power launched into a fiber to the optical power that emits from the fiber after traveling in the fiber for one km:

$$Attenuation = -10 \times \frac{PowerOut}{PowerIn}$$

The improvements to optical fiber continued, with the first telephone field trials in 1977 using gallium-aluminum-arsenide laser diodes as sources. These lasers emitted at 850 nm, and the signals traveled through multimode optical fiber with losses of around 2 dB/km, requiring optical signal repeaters every few kilometers. Since then, numerous

improvements to the optical telecommunications equipment and infrastructure have made fiber optic communications ubiquitous. The full story of optical fiber development can be found in City of Light: The Story of Fiber Optics, Oxford University Press, 1999, by Jeff Hecht.

Much effort was put into developing fiber optic communications systems because they offered a number of benefits over copper systems. These benefits included the potential for huge gains in bandwidth (from 10^2 MHz to 10^8 MHz), the elimination of electrical isolation requirements, smaller size and weight, and the potential for cost savings in the long term¹. Manufacturing issues also play an important role in making optical communications feasible, since the equipment that networks require must be assembled without adding too much cost to the system. Today, researchers continue to make changes to the optical and mechanical characteristics of optical fiber to improve the manufacturability of optical networking equipment. As a contract ONE manufacturer, Celestica is well positioned to take advantage of those improvements and pass the savings, or at least some of the savings, on to its customers.

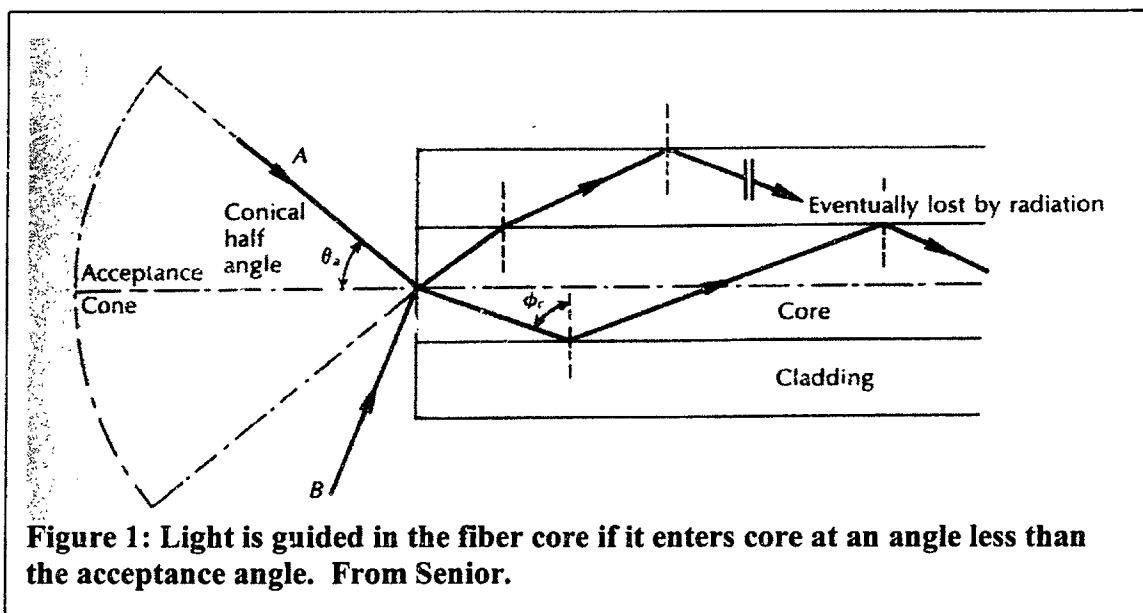
2.2 *Optical Properties of Optical Fiber*

Optical fiber guides light by using glass of slightly different refractive indices to confine the light to the core of the fiber through total internal reflection. Since the core of optical fiber has a slightly higher index of refraction than the surrounding glass (the cladding of the fiber), a ray of light that travels from the core to the cladding within some maximum acceptance angle is reflected back into the core (see Figure 1). The ray of light is

¹ Based on information from J. Senior's Optical Fiber Communications.

restricted to the core of the fiber until it reaches the fiber's end, where a detector can be used to receive information that has been transmitted through the fiber.

The fiber has a number of properties that affect how light travels through its core, and some of these properties have a large impact on the processes used to manufacture optical networking equipment. Those properties include intrinsic and induced attenuation, polarization rotation due to stress in the fiber, and the mode field diameter of the fiber.



2.2.1 Intrinsic Attenuation

The main breakthrough made by the Corning team in 1970, which allowed them to drastically reduce the attenuation of light of certain wavelengths traveling through optical fiber, was the reduction of impurities in the pre-form used to draw the optical fiber.

While pure silica (glass) has extremely low optical attenuation, any impurities will absorb light and lower the transmitted power of the optical fiber. Corning used carefully made fused silica pre-forms to avoid introducing impurities into the fiber, and has continued

making improvements to reach the current attenuation level of only 0.2 – 0.3 dB/km at certain wavelengths.

The pre-forms are deposited with dopants that raise the refractive index of the center of the pre-form slightly above that of the outside diameter of the pre-form. The pre-forms are then heated and drawn into optical fibers with outer diameters of 125 μm , and cores of 62.5 μm (for multimode fiber) or 9.8 μm (for singlemode fiber) (Senior). The difference between multimode and singlemode fiber is detailed in a later section.

While process improvements can continually remove more and more impurities, certain sources of attenuation are more fundamental and set the physical limits of optical loss for fibers. Rayleigh scattering is one example of such a source of attenuation, and occurs when the light interacts with index fluctuations in the fiber that are small relative to the wavelength of the light. These index fluctuations are created by the freezing in of density fluctuations in the fiber at the time of fabrication. Optical fiber is currently pure enough that Rayleigh scattering is the dominant cause of attenuation, and attenuation less than the current 0.2 – 0.3 dB/km cannot be achieved in silica (Senior).

As mentioned above, optical fibers only reach the Rayleigh loss limit at certain wavelengths, while other wavelengths have higher attenuation. At wavelengths between 800 nm and 1200 nm, Rayleigh scattering dominates. It should be noted that Rayleigh scattering itself is wavelength dependent, and losses tend to drop as wavelength increases. Water that is dissolved in the glass causes a large peak in attenuation between

1200 nm and 1500 nm light, and above 1700 nm infrared absorption causes high attenuation. Dips in absorption occur at 1310 nm and 1550 nm, and this is where most long distance optical communication systems are designed to operate: due to the molecular composition of the fiber, both Rayleigh scattering and absorption due to impurities are low (see Figure 2).

In the US and Europe, 1310 nm wavelengths are used for metro and short haul applications, while 1550 nm wavelength bands are used for long haul applications. In Japan, 1310 wavelengths are used for long and short haul communications. For very short distances, within a vehicle, office building, or small enterprise, 800 nm wavelengths are used. For all of these wavelengths, intrinsic attenuation in the fiber is low enough that it can be considered negligible for the 0.5 – 1 meter lengths of fiber that Celestica

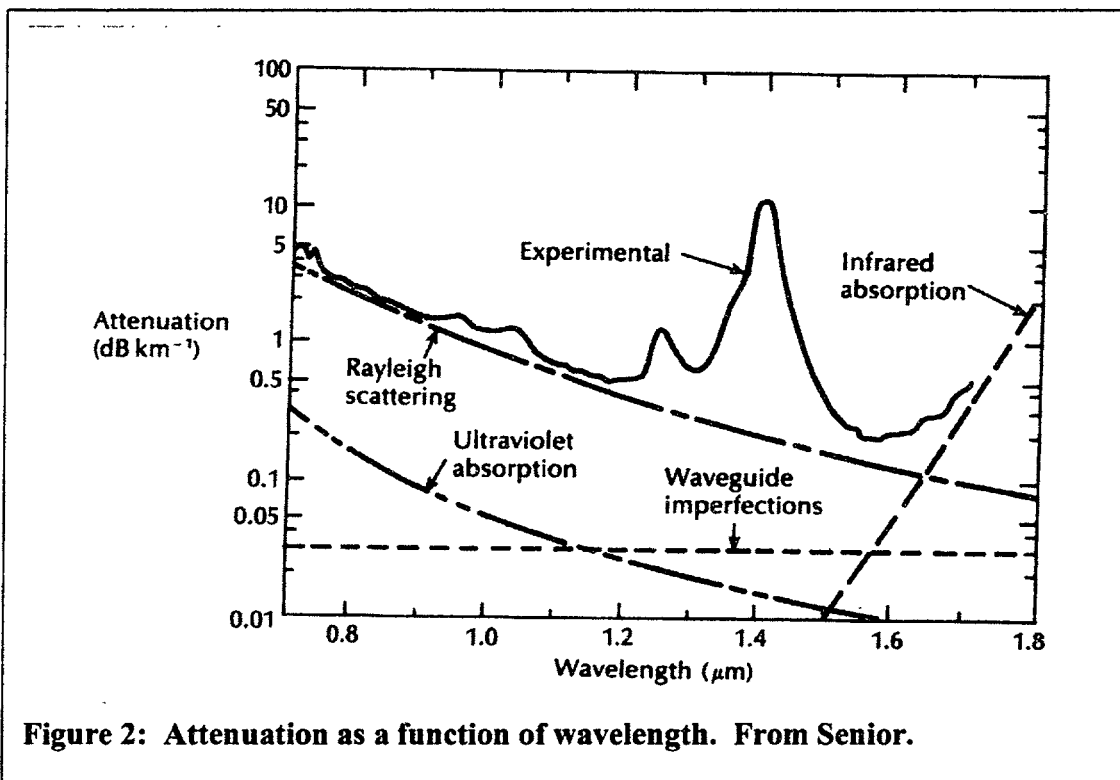
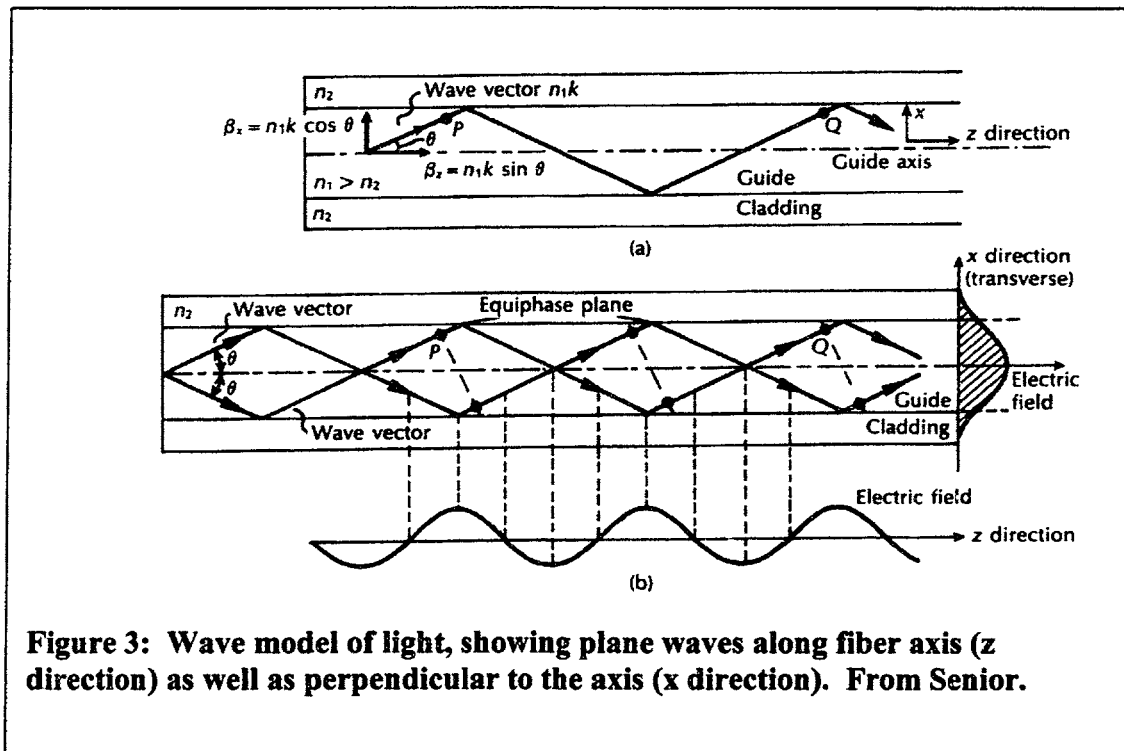


Figure 2: Attenuation as a function of wavelength. From Senior.

uses in optical networking equipment. Therefore, fiber attenuation observed in an ONE manufacturing line can always be attributed to some external factor which has caused “induced attenuation”.

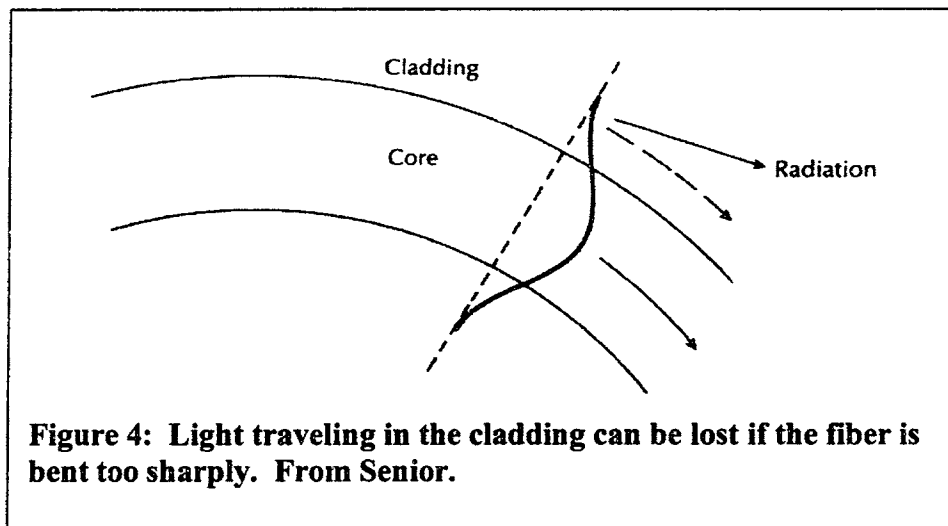
2.2.2 Induced Attenuation through fiber bends

Excess attenuation in optical fiber can be induced in a number of ways, all of which must be taken into account when establishing a manufacturing process. Within a continuous length of fiber, loss can be induced by bending the fiber through a radius of curvature less than some minimum value, or by pinching the fiber.



While viewing light traveling through optical fiber as a ray that is trapped in the core by total internal reflection is useful for understanding the guiding mechanism of optical fiber, viewing the light as an electromagnetic plane wave is more useful for a detailed

understanding of optical fiber properties. The plane wave can be broken into two component plane waves: the plane wave propagating along the axis of the fiber (z direction), and the plane wave propagating perpendicular to the axis of the fiber (x direction) (see Figure 3). The plane wave in the x direction can be viewed as a standing wave bounded by the edges of the core of the fiber, although in reality the edges of the core do not form a strict boundary. Part of the wave always travels through the cladding of the fiber, as well as the core (see Figure 4).



When a fiber is bent, the light traveling through the cladding of the fiber on the outside of the bend must travel farther than the light in the cladding of the fiber on the inside of the bend. In order to maintain a wavefront perpendicular to the direction of propagation, the light in the cladding on the outside of the bend must travel faster than the light in the cladding on the inside of the bend. However, since it is impossible to travel faster than the speed of light, some of the light in the cladding on the outside of the bend is lost. If the bend is extremely tight, with a radius of curvature less than around 30 mm, a significant amount of light may be lost from the cladding through radiation (Senior).

Attenuation caused by bent fibers poses a significant challenge to ONE manufacturing, which typically requires operators to attach numerous optical fibers to printed circuit boards and route them around hot components and other obstructions. Clips used to position the optical fibers can pinch the fibers if too many fibers are placed in a single clip, creating tight bends that are difficult to see with the naked eye. Fibers placed between mother and daughter boards are hidden from view, making tight bends or taught fibers almost impossible to identify without disassembling the system. These considerations make careful initial fiber routing essential in a manufacturing environment, a task that can be simplified through the use of fiber spools and similar fiber routing devices that prevent or discourage sharp fiber bends. At Celestica, standards have been created which clearly identify the proper approach to handling and positioning optical fibers to avoid bending problems.

Optical fiber manufacturers, such as Corning, are aware of these difficulties, and they occasionally come out with a new type of fiber with improved light retention through bends. The main approach to improving bending properties of fibers is to increase the relative difference between the index of refraction of the core and that of the cladding (Senior). However, while these improvements are valuable, care still must be taken when manufacturing optical networking equipment.

2.2.3 Sources of Induced Attenuation at the Fiber Endface

At the intersection between two optical fibers, or between an optical fiber and a component, excess attenuation can be caused by misalignment of fiber cores, or dirty /

damaged fiber endfaces. In addition, connections between different fiber types will cause excess attenuation at the junction.

The typical diameter of optical fiber is 125 um, or about the thickness of a human hair. The core of the fiber can be as small as 9.3 um in diameter, which makes connecting two optical fibers, or an optical fiber and an optical device such as a laser, a fairly challenging process. Any misalignment between the core of the fiber with another fiber core, or the relevant portion of an optical device, will cause excess attenuation, and in most cases misalignment of only a micron or less can cause the attenuation to reach unacceptable levels. Attenuation is typically measured as insertion loss in decibels, and is a relative measurement that compares the input to a fiber / junction / device to its output (the same equation was used to calculate attenuation in a fiber above):

$$InsertionLoss = -10 * \frac{PowerOut}{PowerIn}$$

While the equation for calculating insertion loss is simple and straightforward, the measurements themselves must be made with extreme care. The difference between the power into a fiber – fiber junction and the power out of the junction may be very small, as low as 0.01 dB, and accurate measurements at this level require specialized equipment. Polarization effects must be taken into account (see below), and mode stripping and mode scrambling techniques may be required (see below). Celestica has created an appropriate standard for both the method and equipment used in making insertion loss measurements.

Automation has emerged as the primary means for assuring accurate alignment of optical fibers. Fusion splicing equipment offers a fairly robust way to connect two optical fibers together permanently, as the equipment uses sophisticated software and hardware to align the cores of the fibers with minimal user intervention. Once the cores of the fibers are aligned, the fiber endfaces are heated with an arc (created between two electrodes) until the endfaces partially melt, and the two fibers are automatically brought together and fused into one continuous fiber.

Fusion splicing demonstrates one method of actively aligning two fibers. Active alignment refers to alignment utilizing feedback on the position of the fiber, which is obtained by either sensing the fiber's physical position directly, or sensing the amount of light that travels through the fiber – fiber junction. The fusion splicer's approach to active alignment uses lenses and special algorithms to align the cores of the fibers physically, with no light sent through the junction during alignment. Once the cores of the fibers are aligned, it is assumed that the signal between them will be maximized. For this type of alignment to be successful and repeatable, optical fibers must have extraordinarily well controlled diameters and concentricity's.

The fibers can also be actively aligned by connecting one of the fibers to a source and the other fiber to a detector. Light is sent through the fiber – fiber junction during alignment, and the fibers are fused together when the signal to the detector is maximized. While this approach will lead to the most repeatable high quality splices, it is not practical in all situations. Often the fibers that are being fused together are attached to devices that do

not generate or detect light, and it is impossible to send a signal through the fiber – fiber junction during fusion splicing. In addition, because the physical properties of optical fibers are so well controlled, the difference in insertion loss between the two approaches to fusion splicing is minimal. The approach that does not require a source or detector for alignment is less expensive, so it is used in most fusion splices. Typical insertion loss values for such a fusion splice are in the 0.02 +/- 0.04 dB range.

On the other hand, automated active alignment with light through the junction is used as much as possible when fibers are attached to optical devices (when devices are ‘pigtailed’). For example, lasers can be powered when fibers are attached to them, and the fibers are fixed in place when the power through the fibers (from the laser) is maximized. Pigtailling includes an extra level of difficulty because the fiber and device must be epoxied together instead of fused together. Fibers tend to move as the epoxy cures and shrinks, so that even if a junction is well aligned before the epoxy is cured, the alignment may be poor after the epoxy is cured. In addition to the use of active alignment with light through the junction to track the performance of the junction as the epoxy cures, this situation can be improved with special epoxies that shrink very little during the curing process. The use of sophisticated (radially symmetric) joints between the fiber and device also improves alignment in these cases.

In any optical communications system, numerous temporary fiber – fiber connections must be made, most often between the system itself and the outside world. These connections are made through connectorized fibers, which include an optical fiber that

has been epoxied into the center of a ferrule. The ferrule is part of a connection mechanism that serves to lock the fiber in place once a connection has been made. Two connectorized fibers can be mated through an adapter, which is a hollow sleeve that acts as the female mate of the connectorized fiber. Such a setup allows temporary, passively aligned connections between fibers that have slightly higher insertion loss than the permanent, actively aligned connections provided by fusion splicing.

Passive alignment occurs when the fibers are aligned with no feedback about the position of their cores or the amount of light going through the fiber – fiber junction. Both fibers are placed into a ferrule or v-groove and the endfaces of the fibers are pushed up against each other; no other alignment takes place. Even with passive alignment, however, relatively low loss is achieved because operators are not required to manually align the fiber cores. The physical properties of the mating device and the fibers themselves determines the quality of the connection, with typical insertion loss values around 0.15 +/- 0.04 dB.

While every connection between two optical fibers will incur some excess attenuation, the level of attenuation strongly depends on the condition of the fiber endfaces at the time the connection is made. Any contamination on the fiber endface will block or reflect light exiting or entering the fiber, as will any scratch or pit in the surface of the fiber endface. Therefore, Celestica has implemented strict standards for fiber and adapter cleanliness, which is assured through visual inspection under magnification. Contaminated fibers must be cleaned with special lint-free cloths, and stubborn stains can

be removed through the use of isopropanol. All connectors not being used must be capped, and the manufacturing area must meet general cleanliness standards.

The final primary source of attenuation at fiber junctions is mismatch in fiber types. Different manufacturers of optical fiber create fibers with slightly different characteristics. Typically, the main source of excess attenuation in this case is a mismatch in core size and/or shape, and is largely unavoidable assuming no alternative to the use of different types of fiber. Fusion splicing can be challenging in this case, because mismatched fiber cores have the potential to confuse the aligning mechanism in the splicer. The best recourse in this case is a careful study of fusion splicers and fusion splicing parameters in order to optimize the particular splicing process required.

2.2.4 Polarization Effects in Optical Fiber

While certain optical networking devices, such as modulators, require a specific polarization of light in order to work, other devices, such as detectors, can see polarization as a source of variability. Operators and testers must pay attention to polarization and its effect on measurements and device performance when manufacturing optical networking equipment.

Many optical detectors are sensitive to the polarization of the light that they measure, so that changes in polarization can cause up to ± 0.5 dB swings in power measurements. In addition, the polarization of light traveling through a fiber can be rotated when the fiber is strained. Even minor strains, such as those caused by moving the fiber from one place on a bench to another, can cause significant swings in power measurements. Under

these conditions, with power measurements only reliable to +/- 0.5 dB, taking insertion loss measurements to determine the condition of a 0.02 dB fusion splice becomes impossible. In addition, excess attenuation caused by tight fiber bends and dirty or damaged fibers is masked. This is an important concern for Celestica, since most communication systems today use sources that generate polarized light.

It is true that detectors with strong polarization sensitivity do have certain advantages, such as the ability to detect optical power levels at specific wavelengths. However, such detectors are inappropriate for some types of insertion loss measurements required on manufacturing lines, which must be accurate and precise enough (i.e. have low enough polarization sensitivity) to alert operators to handling or process problems. Therefore, sites performing ONE manufacturing must make a special effort to have the correct optical measurement equipment available, given the testing requirements of the products being manufactured. This will include detectors that are insensitive to the polarization of the light they receive, in addition to the detectors required to, for example, detect power levels at specific wavelengths. Polarization insensitive detectors and power meters are available from optical test equipment vendors such as Agilent Technologies, and they should be a part of any manufacturing line working on equipment that utilizes polarized optical sources.

Devices that rely on the electro-optic effect, such as lithium niobate intensity modulators, require light to be linearly polarized for efficient operation. The modulator works by splitting its input into two identical paths, which recombine after a set distance. In the

'on' state, the signal is split then recombined in phase with no electric field applied: the signals constructively interfere and continue on to their destination. In the 'off' state, an electric field is used to increase the index of refraction (through the electro-optic effect) in one of the paths, and decrease the index of refraction on the other path (see Figure 5).

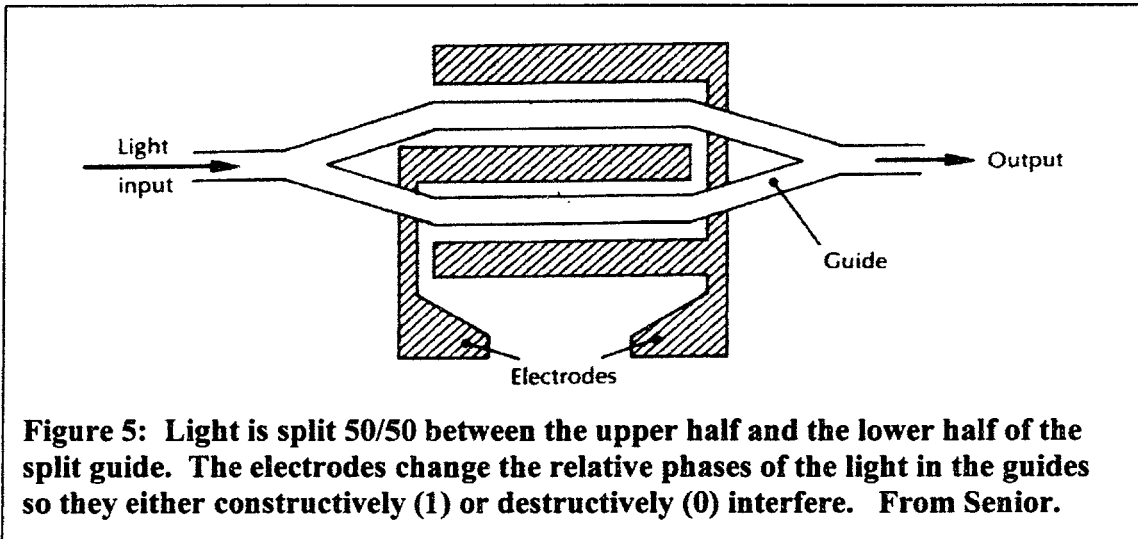


Figure 5: Light is split 50/50 between the upper half and the lower half of the split guide. The electrodes change the relative phases of the light in the guides so they either constructively (1) or destructively (0) interfere. From Senior.

The change in the index of refraction in each path in turn changes the optical phase velocities of the light in the two paths, causing them to be 180 degrees out of phase when they recombine. This results in destructive interference and cancellation of the signal.

The strength of the electro-optic effect depends on the overlap integral between the electrical and optical fields, and therefore control of the polarization of the light entering the device can improve device performance (Senior). The modulators are connected directly to lasers through polarization maintaining (PM) fiber. The lasers produce linearly polarized light, and the polarization is maintained through the PM fiber to the modulators, where the modulators encode the light with data for the communication link. In these digital optical systems, an 'on' signal is a 1, and an 'off' signal is a 0. The laser

itself is always on and running in continuous wave mode, while the modulator turns the transmitted signal on and off.

Numerous types of PM fiber can be found for various applications. However, the electro-optic modulator application is likely to be the application most frequently encountered.

Generally, PM fiber does not form a large percentage of the fiber used in optical networking systems. The most popular form of PM fiber, called PANDA, uses two stress regions in the fiber to maintain high birefringence, which in turn allows only one polarization to travel through the fiber.

Because PM fibers are not radially symmetric, as normal optical fiber is, fusion splicing PM fiber requires special equipment that can rotate the fibers to align the axis of polarization. While a number of fusion splicers are available to perform this function using varying degrees of automation, few if any can perform the function reliably. Therefore, and because of its relatively high price, PM fiber is not used unless it is specifically required for a particular application.

Where PM fiber is required, Celestica must carefully select fusion splicing equipment based not only on the specific requirements of the splice that must be created, but also on the PM splicing requirements that may appear in the future. Manufacturers must determine the tradeoffs, if any, between high quality splices and the ability to splice many different types of fiber (PM or otherwise) with one piece of equipment. Because there is so much technological development in this area, it may be wise for Celestica to build

relationships with one or more fusion splicer suppliers, and arrange leasing deals that allow Celestica to maintain the latest equipment available. If Celestica purchases or leases large numbers of splicers, it can have a positive impact on the splicer design by providing performance feedback and recommendations for future generations of splicers.

To the extent that Celestica can influence a customer's choice of optical fiber through early involvement in the design phase of a new product, Celestica may be able to focus on one type of PM fiber and a standard set of equipment. Since many companies would see similar benefits through standardization, one might expect the standardization of PM fiber in the near future. PANDA fiber seems to be the most likely choice for standardization; it is currently the most popular PM fiber because it works the best at telecommunications wavelengths² and it matches the core size and numerical aperture of standard optical fiber very well³. This is important because a transition will always need to be made between PM fiber and standard fiber. Therefore, fibers that make the transition with the least signal attenuation, such as PANDA fibers, can be expected to thrive.

2.2.5 Multimode vs. Singlemode Optical Fiber

In general, optical fiber comes in two broad categories, singlemode and multimode. Multimode fiber has a larger core size, allowing multiple modes to propagate through the fiber. These modes refer to the plane wave propagating perpendicular to the axis of the

² Based on data found at <http://www.waveoptics.com/assets/images/pmfibers2.pdf>
Wave Optics sells various types of polarization maintaining fiber.

³ Based on claim made at <http://www.ozoptics.com/polcom.htm>
Oz Optics sells various types of polarization maintaining fiber.

fiber. Singlemode fiber, on the other hand, has such a small core size that only one mode is allowed to travel through the fiber for any extended length.

The number of modes in a fiber depends on the wavelength of light in the fiber as well as the core size. For a given fiber core size, short wavelengths will travel as multimode light, while wavelengths above the “cutoff wavelength” will travel as singlemode light. Standard singlemode fiber has a cutoff wavelength just below 1300 nm, and a mode field diameter of around 9 μm . For this reason, only wavelengths above 1300 nm are used in singlemode networks. Fiber cores would have to be unmanageably small in order to propagate singlemode light with shorter wavelengths; as cores get smaller, alignment between fibers becomes increasingly difficult.

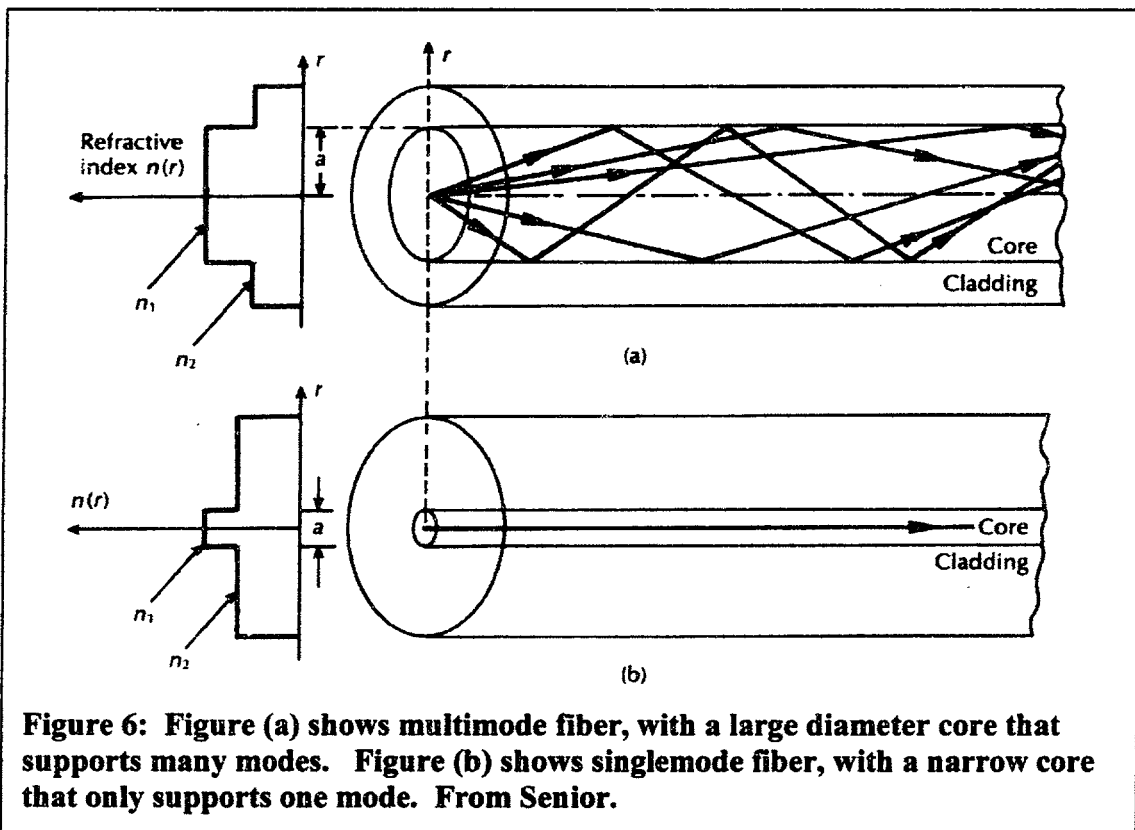
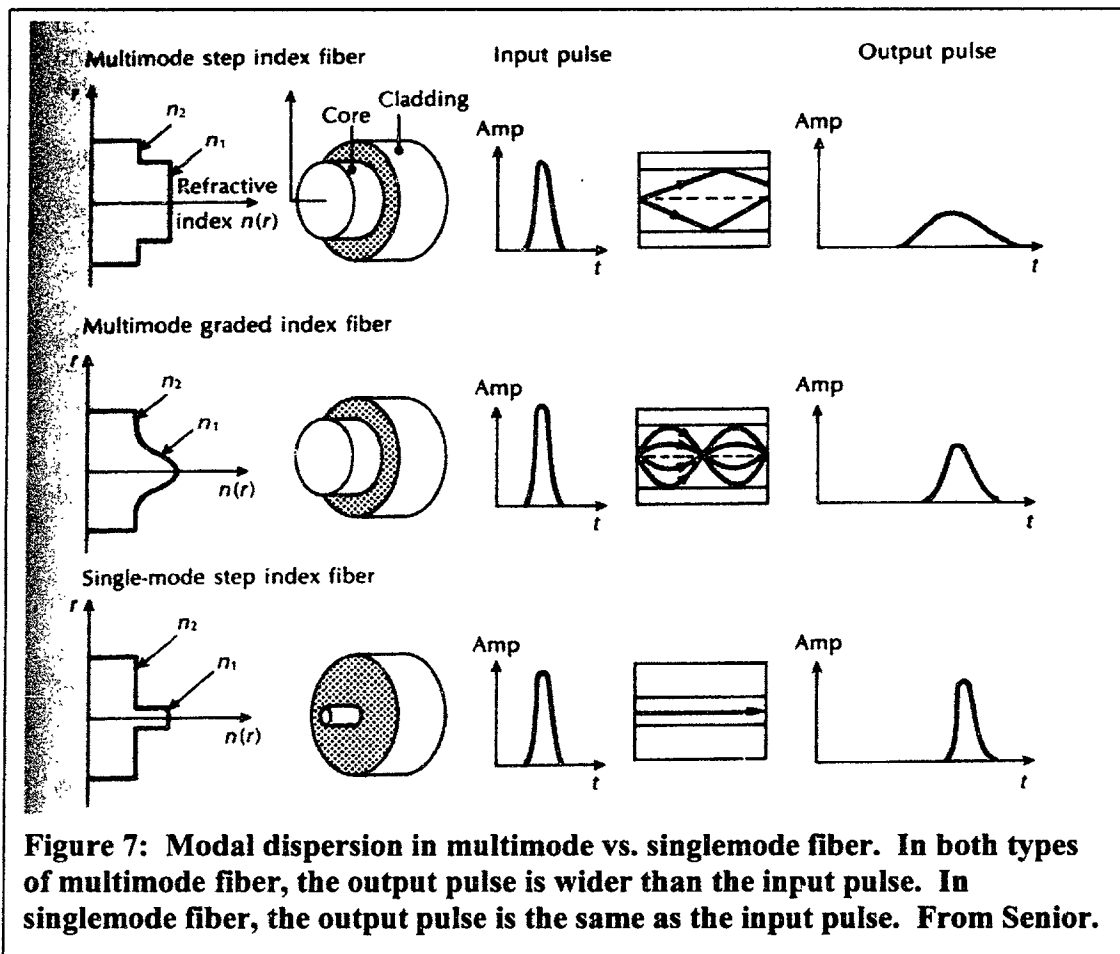


Figure 6: Figure (a) shows multimode fiber, with a large diameter core that supports many modes. Figure (b) shows singlemode fiber, with a narrow core that only supports one mode. From Senior.

As described above, optical communication occurs through digital 'on' and 'off' optical signals. If a detector receives a pulse of light, it is interpreted as a digital 'one', while a period with no signal between two pulses is interpreted as a digital 'zero'. Obviously, the shorter the pulse length, the more information the communication link can carry, because more pulses can be squeezed into a given time period. Therefore, a key determinant of the amount of information communication links can carry, or their bandwidth, is the speed of modulation of the optical signal.



However, when signals are modulated fast enough to yield extremely short pulses, the space between pulses becomes extremely small as well. In multimode fiber, different modes of light travel at different speeds. Therefore, a pulse made up of multiple modes tends to spread out, as the fast modes start to pull ahead of the slow modes: this is called modal dispersion. If the pulses are too close together, this dispersion will cause the fast modes of one pulse to catch up with the slow modes of the previous pulse, and the detector will measure one long pulse instead of two individual pulses. Since modal dispersion takes time to occur, short pulses can travel short lengths of fiber without any interference between pulses. However, over long distance, modal dispersion seriously limits a link's bandwidth.

In singlemode fiber, on the other hand, there is only one mode in any given pulse. Without modal dispersion, pulses can become very short, drastically increasing the bandwidth that can be carried over the link. The improvements in bandwidth make the extra work in aligning fibers with small cores worth the effort for optical networks that cover large areas, while the less expensive multimode connections are still used for many small area, or local area, networks (i.e. within a building, car, or airplane).

Modal dispersion is not the only form of dispersion, however, because different wavelengths of light also travel at different speeds through optical fiber. This causes wavelength dispersion, which is similar to modal dispersion in that it causes pulses to spread slightly as they travel. Fortunately, the spreading is much less than is seen in modal dispersion, and wavelength dispersion is tolerated in many optical networks. In

cases where wavelength dispersion causes a noticeable degradation in bandwidth, it can be corrected with specialty fibers. On the other hand, the fiber that corrects modal dispersion, i.e. singlemode fiber, has become the standard for large area networks.

The main impact of singlemode fiber use on manufacturers such as Celestica is the extra care that must be taken in connecting optical fibers to other optical fibers (through splicing), or to devices (through pigtailling). In general, splicing or pigtailling equipment and procedures will be the same when using both types of fiber, but the processes will have lower yields for singlemode fiber than multimode fiber due to the added sensitivity to misalignment. Therefore, in cases where Celestica can influence the choice between multimode and singlemode fiber in an application, use of multimode fiber should be associated with lower costs due to shorter assembly times and fewer defective connections. Because splices between singlemode and multimode fibers lead to poor signal transmission, multimode fibers should only be used in situations where they do not need to connect directly to the singlemode fibers that are used in all medium to long distance optical communications networks.

2.3 *Mechanical Properties of Optical Fiber*

ONE manufacturers must understand the mechanical properties of optical fiber as well as they understand it's optical properties if they want to manufacture quality products with high yields. Pristine optical fibers have exceptional strength under tension, and optical fiber manufacturers have become masters at producing pristine fibers. Fiber manufacturers have also become adept at controlling the concentricity of the fiber core, the diameter of the fiber, and roundness of the fiber. The end results are optical fibers

that can be connected to other fibers or devices with repeatable results, and optical networks with enough physical integrity to reliably last 20 or more years in the field.

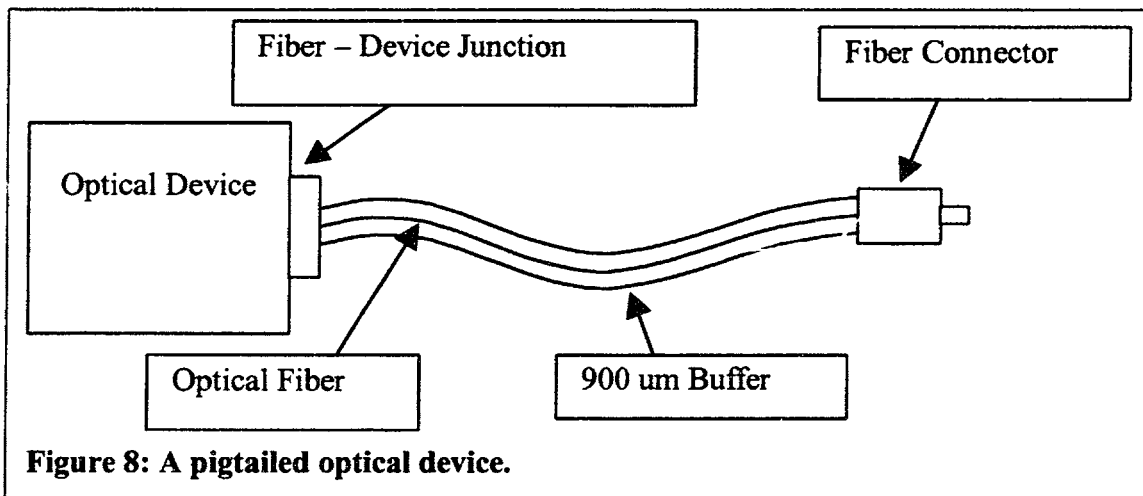
2.3.1 Optical Fiber Buffers

While pristine optical fiber is very strong, any flaw in the surface of the fiber drastically reduces its strength. Flaws act as the starting point for cracks that propagate through the fiber under stress or through exposure to moisture in the air. Therefore, manufacturing with optical fiber requires extremely close attention to two areas of concern: sources of flaws in optical fiber, and identification of flaws once they have occurred.

Because optical fiber is so sensitive to nicks and scratches, all optical fiber comes with some level of protection against abrasion. At a minimum, all fibers have a 125 um to 140 um thick layer of PMMA that is tightly attached to the fiber surface. This thin layer of PMMA (poly-methyl-methacrylate) provides a nominal amount of protection, and many ONE manufacturers require extra protection for fibers in the equipment that they assemble. However, in a number of cases, space constraints prevent the use of extra buffer layers. Optical fibers with only this primary layer of PMMA cannot be connectorized, because connectors require an extra layer of 400 um to 900 um polymer buffered fiber to support the weight of the connector.

While the glass fiber itself is strong under tension, the epoxied connections between optical fibers and devices may be relatively weak. With an additional 400 um or 900 um polymer buffer over the PMMA layer, manufacturers can create stress relief between the device and the fiber connector through the buffer, reducing the chance that the fiber –

device junction will be damaged during handling. In this case, the connector is firmly attached to the buffer, and the buffer is firmly attached to the device at the other end, while the fiber loosely floats inside the buffer (see Figure 8). When someone pulls on the connector, the buffer becomes taught but the fiber remains stress free (up to a point).



Some fiber pigtailed component manufacturers, such as Lucent, use a 'tight' 900 um buffer on the pigtailed fibers, which does not provide stress relief. However, this tight buffer probably does make it easier for Lucent to align optical fibers to devices when pigtailed, because they have better control over the positioning of the fiber if it is not floating around in a loose buffer. In addition, the 900 um tight buffer still provides more protection than a single PMMA layer against damage to the fiber surface. Even so, given the choice, most assembly operators prefer to work with a loose 900 um buffered fiber, because it is easier to strip off loose buffers. In addition, loose buffered fiber typically has less of a memory effect than tight buffered fiber, making loose buffered fiber easier

to position on a board (or in a fusion splicer) during assembly. Pigtailed devices using loose buffered fiber should be chosen as components for ONE manufacturing if the option is available.

More stress relief can be added if the potential for fiber stress in a given application increases. Most fibers that are exposed to the outside world (after equipment is assembled) typically have a loose 3 mm sheath around the 900 um buffered fiber. Additional stress relief is provided by strands of kevlar fiber running between the connector and the device (or another connector in the case of a jumper cable).

It is important to remember that none of the buffers are hermetic seals, and moisture can and does reach the surface of the fibers. Moisture attacks flaws in the surface of the fiber by leaching out ions that give the fiber strength (Matthewson). Cracks that are under stress will propagate more quickly in the presence of moisture, as the crack draws water in through capillary action, bringing moisture with it as the crack slowly propagates through the fiber (Matthewson).

Researchers have tried hermetically sealing fibers by evaporating metal coatings onto the fiber surface, but the efforts have generally been unsuccessful (Matthewson). Thus, the most important factor in the mechanical reliability of optical fibers still revolves around avoiding defects and stress in the fiber.

2.3.2 Handling Optical Fiber

In the course of ONE manufacturing, operators must often handle optical fiber without its protective buffers. The buffers must be removed before operations such as connectorization, fusion splicing, or device pigtailling can be performed. In these cases, operators must be extremely careful not to damage the bare optical fibers. Even when the buffer is present, operators must be careful: sharp tools or hot components on a PCB can damage the buffers themselves, thus exposing the glass optical fiber.

Manufacturers typically try to minimize damage to bare optical fibers by minimizing the number of touches to the fiber (by human hands or otherwise). This aspect of manufacturing should improve as the use of automated equipment increases in the industry. Unfortunately, at this time, many operations are still done by hand, although that does not mean that the fibers will necessarily be touched frequently.

Fusion splicing equipment provides an excellent example of the ways that manufacturing equipment providers are attacking the mechanical reliability issue. A number of manufacturers sell 'high strength' and 'low strength' equipment. The main difference between the two setups is that operators do not directly touch bare fibers with the high strength setup, but they do with the low strength setup. Of course, the low strength setup costs less and requires less equipment.

The procedures for the two setups are as follows (based on Ericsson Fusion Splicers):

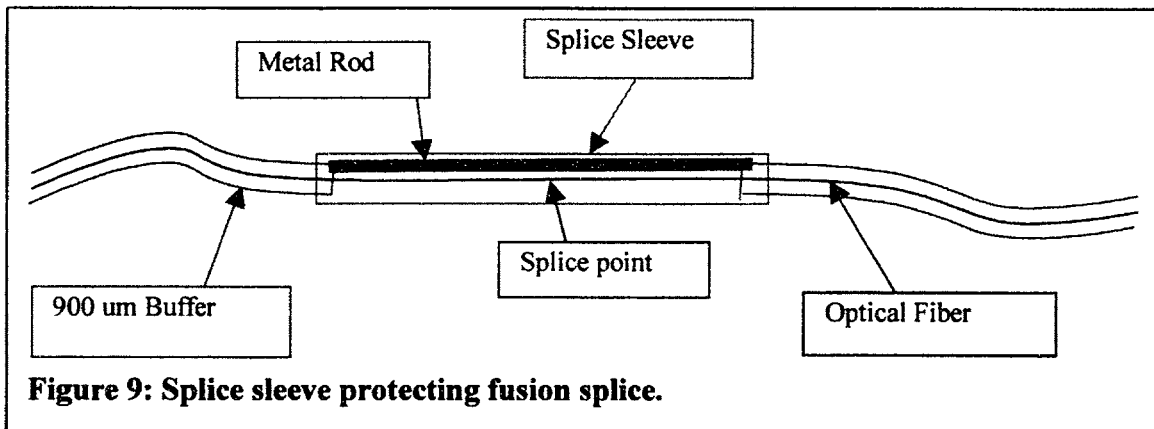
Low Strength Setup	High Strength Setup
1. Use heat stripper to remove buffers from fiber*	1. Use heat stripper to remove buffers from fiber*
2. Clean buffer residue from fiber by wiping with a lint-free cloth dipped in isopropanol*	2. Clean buffer residue from fiber by dipping fiber in isopropanol sonicating bath
3. Cleave fiber (to create a clean endface) by clamping both sides of fiber into cleaving device*	3. Cleave fiber (to create a clean endface) by clamping only one side of fiber into cleaving device (clamped fiber section is discarded)
4. Place fiber into fusion splicer by clamping on buffered portion of the fiber only	4. Place fiber into fusion splicer by clamping on buffered portion of the fiber only
5. Repeat steps 1-4 with second fiber	5. Repeat steps 1-4 with second fiber
6. Use fusion splicer to automatically splice fibers	6. Use fusion splicer to automatically splice fibers
7. Protect splice by using heat-shrink tubing to fix the splice point to a metal rod for stability and strength*	7. Test integrity of splice with 100 psi pull test
	8. Protect splice by recoating a flexible polymer buffer over the bare section of fiber

* Step involves touching the bare fiber

The table shows that both procedures require at least one touch, while the low strength procedure requires three additional touches. The touch in the stripping stage can be removed by using chemicals to strip the buffers from the fiber, but the required chemicals are hazardous and manufacturers are reluctant to introduce those chemicals into the manufacturing environment unless it is absolutely necessary (Matthewson). Each touch of the bare fiber increases the risk that the fiber will be damaged during the operation. Since damaged fibers are weaker than pristine fibers, the splicing process with the *fewest* touches is called the “high strength” process.

The high strength approach also involves a pull test, which places the splice point of the fiber under 100 psi of tension. Any flaws in the fiber surface larger than a certain size will cause the splice to fail the tension test. Fibers that pass have a much higher probability of having only very minor flaws, if any. However, the stress test itself will cause very minor flaws to worsen, so some flaws could be present in the fiber even after the test (Matthewson).

By contrast, the low strength setup does not require a pull test, but instead assures high strength by fixing the spliced area of the fiber to a metal rod using a polymer heat-shrink tube (called a splice sleeve). While the splice sleeve will prevent stress in the area of the splice caused by pulling on the fiber, it could add stress as the metal bar expands and contracts with temperature changes. Since the coefficient of thermal expansion (CTE) of the metal will be much larger than that of the glass, this could put the fiber under considerable stress. In addition, any damage to the fiber caused by the extra touches during the low strength splicing process would not be discovered, because the fusion splice is never tested for integrity. Therefore, this approach could lead to latent failures in the field, after moisture has had time to attack any locations of damage to the fiber.



The fusion splicing example provides just one of many ways that fibers can be damaged or protected, depending on the choices made on the manufacturing floor. Pigtailling and connectorization operations involve similar steps, and similar precautions can be taken to protect the fibers. Mechanical splices between two connectorized fibers provide another area of concern. Thermal cycling results in the expansion and contraction of the adapter holding the connectorized fibers together, which can jam the fiber endfaces into each other and might eventually cause fiber damage (Matthewson). Similarly, frequent removal and reinsertion of connectors can wear down the connector ferrule, leading to poor fiber-fiber alignment. Therefore, it is important to have a maintenance procedure in place for identifying and replacing worn connectors before they cause failures in test or assembly operations.

3 Optical Networking Equipment Manufacturing at Celestica

The customer responsible for introducing Celestica to ONE manufacturing was a small start-up with plenty of experience performing research and development on optical networking equipment, but no experience manufacturing it. Therefore, in addition to developing new technical skills and a new supply chain strategy, Celestica and its customer had to develop a flexible, lean, and robust manufacturing process. High demand for optical networking equipment placed pressure on Celestica to complete these developments in a very short time, resulting in goals and timelines that were very challenging to meet.

3.1 Manufacturing Process Flow of Celestica's First ONE Product

Celestica's first ONE product required the assembly of electronic and optical components onto printed circuit boards in a variety of configurations. The assembly was broken up into two stages: standard electronic components were assembled onto a printed circuit board; then lasers, variable optical attenuators, optical detectors, and / or other optical

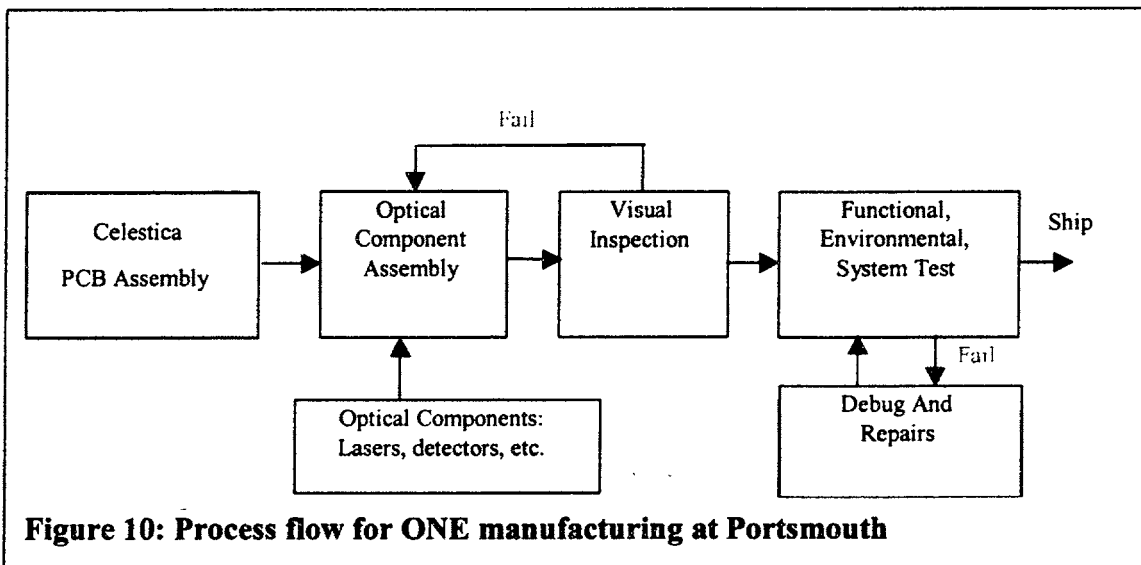


Figure 10: Process flow for ONE manufacturing at Portsmouth

components were added to the boards. Visual inspection of the boards came next, followed by functional testing, environmental testing, and a final system level test (see Figure 10).

The various boards were assembled into a system after they had been delivered to the customer. Therefore, the assembly operations performed by Celestica were restricted to the board, and not the system, level. The final system level test on an individual assembled board was performed with known good system level components, after which the assembled boards were removed from the system test station and shipped individually to the customer.

Celestica's customer was responsible for much of the design of the first ONE product, especially when it came to choosing component suppliers and establishing relationships with the supply chain. The customer also designed the test stations that Celestica uses to perform functional tests of the completed boards. Most, if not all, of the expertise in handling optical fibers and optical components initially resided with the customer, although Celestica engineers were quick to learn the basic skills. Still, Celestica relied heavily on its customer for guidance in choosing assembly equipment, defining processes, and debugging and repairing failed boards.

Partially as a result of Celestica's reliance on its customer for direction, and its customer's background in R & D as opposed to manufacturing, ONE manufacturing lines were unable to achieve the high level of performance in terms of quality that the

computer system manufacturing lines had achieved. For example, yields were lower on the optical networking equipment manufacturing lines than they were on the computer systems manufacturing lines. The robust quality systems that worked well for the relatively stable and well-understood computer industry did not readily translate to the young, rapidly evolving optical networking industry. For a more detailed discussion of the important distinctions between the rate of innovation in products that are young in their lifecycle versus products that are far along in their lifecycle, see James Utterback's Mastering the Dynamics of Innovation.

Utterback's work predicts the types of problems that the Portsmouth site faced.

Computer system manufacturing may not be easy, but computers are far along in their lifecycle and the number of new product and process innovations is limited. This limited number of innovations allows manufacturers to reduce costs by establishing manufacturing processes and quality programs that are streamlined and that take full advantage of the stability of the industry. However, when those lean and efficient quality programs are applied to a young industry, with new processes and products introduced on a weekly basis, quality levels will likely be lower.

Initially, volumes of the optical networking equipment were projected to be low, which would have given Celestica some time to make improvements to the manufacturing line and bring up yields. Unfortunately, the telecommunications industry has a lightning fast pace of evolution. Production quantities quickly climbed, and while engineers made heroic progress learning new skills and solving problems on a daily basis, no one had

time to completely address the changes that needed to occur to manufacture products in a fundamentally new type of industry. While the Portsmouth site deserves credit for helping its customer grow from a small startup to a well known supplier of optical networking equipment, the site's manufacturing operations will always have opportunities to improve their ability to reliably and profitably support customers.

3.2 Operations Analysis

The constraint of the manufacturing process at Portsmouth occurred at the functional test / debug station, as identified by large quantities of work in process (WIP) inventory in that area. Low yields, combined with complex debug and repair operations, led to the circulation and re-circulation of faulty boards through the: failed test – debug – repair – failed test – debug cycle. Improved yields would greatly increase the throughput of the operation, and numerous efforts to improve yield in the short term had been launched. Longer term efforts to improve throughput focused on adding statistical process controls to the test area, improving maintenance procedures and compliance on key pieces of equipment, and improving the layout of the line to provide operators with feedback on the quality of their work.

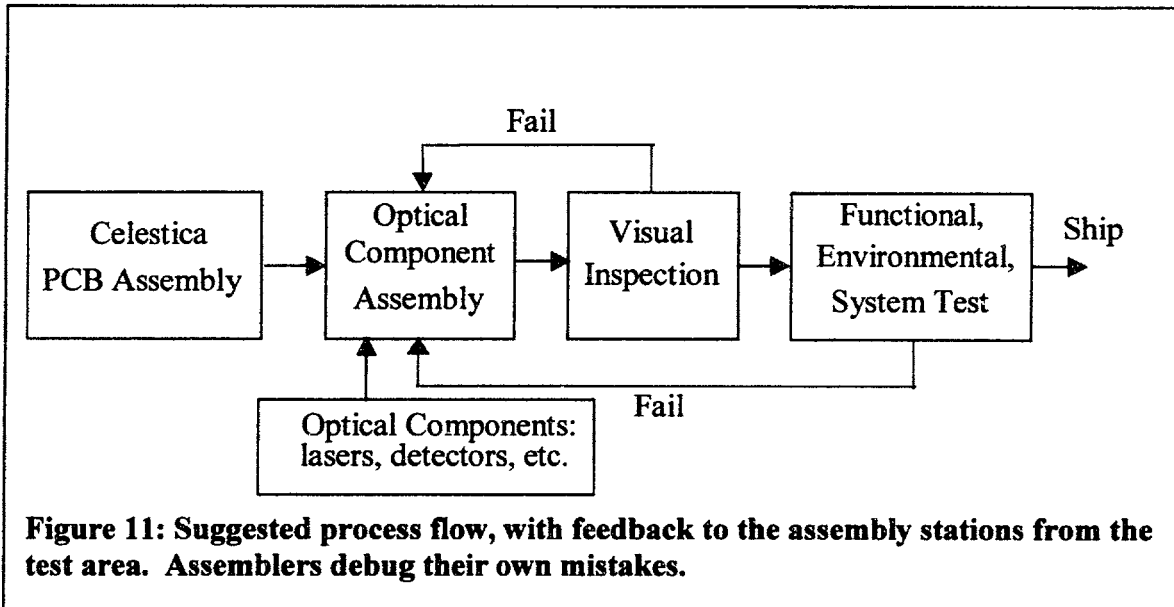
Failure rates for product shipped to the customer were very low, suggesting that the testing stations were successful in identifying faulty boards. However, there were a number of uncertainties at the testing stations over the exact cause of failures, and there was a great deal of variability in test results between test stations. This situation called for a complete reproducibility and repeatability study in the test area, followed by the implementation of statistical process controls that could be used to track the performance

of the testing stations over time. Once the testing stations began producing reliable data on product failures, the information could be used to improve production processes.

The level of preventive maintenance of a key piece of manufacturing equipment provides an example of how the rapid pace of change can cause details to be overlooked. If not properly maintained, the equipment both produced poor results and misled operators about the quality of the products they were producing. However, in all of the excitement of ramping up a new and challenging product, no written preventive maintenance procedure had been generated, and no record of past maintenance had been kept. Properly maintaining the equipment could have a measurable positive impact on yields.

Boards found to be defective in the debug area were sent to a separate rework area to be fixed. This approach prevented assemblers from getting feedback on mistakes they were making, which is very important given the fact that the assembly was a very manual process. Many of the defects were caused by operator handling errors, and a new line layout, consisting of cells, would have improved the situation. Cells would include assembly operators, test stations, and debug technicians all in one area. Boards would not leave the cells until they passed the required tests. Operators would repair their own mistakes, and they would learn how to properly assemble boards in the process. The recommended process flow is shown below in Figure 11.

The changes listed above would not have solved all of the line's problems, but they would have started the site down the learning curve toward higher throughput, higher yields, and higher customer satisfaction. Importantly, they are modifications that are appropriate for a product that is young in its life-cycle. All of the changes listed above were proposed early on in the internship.



3.3 Implementation of Recommendations

Over the course of the internship, progress was made on two of the three recommendations. Maintenance procedures were established and in place for the equipment mentioned, although this implementation occurred some time after the procedures were initially suggested and written. By the end of the internship, the gage R & R study was underway, as were procedures for tracking products through the test and debug area. However, the line was never reassembled in such a way that operators would receive automatic feedback on their performance, or correct their own mistakes. The reasons for the slow implementation can be found in Celestica's system control strategy, described below.

4 ISO vs. WCM: System Control Strategy

Celestica's need to acquire many new skills from a young company in a short time, while simultaneously revamping its supply chain and launching a product, put a considerable amount of stress on its manufacturing system controls. Successfully introducing ONE manufacturing required close communication and coordination between all components of the manufacturing system: from the supply chain management side to the new product / new customer introduction team to the manufacturing floor itself. Considering the challenges associated with launching products based on new technologies, Celestica is working extra hard to offer ONE manufacturing services in a cost effective manner.

4.1 Defining the Manufacturing System

The manufacturing system at Celestica includes all components of the company that are required to successfully build, ship, and support products. Human resources, suppliers, customers, the manufacturing floor, engineering, quality control, accounting and finance, and site management all combine to form the manufacturing system that must produce goods in a cost effective, profitable manner. Every manufacturing system relies on a set of controls to ensure efficient operations, with the level of operations efficiency directly correlated to the effectiveness of the controls. A key benefit of a well controlled manufacturing system is increased predictability of not only quality, but of costs and overall performance as well.

4.2 ISO: Background and Philosophy

As an ISO 9002 registered site, Celestica at Portsmouth can readily base its system control strategy on ISO standards. ISO, or the International Organization for

Standardization, outlines a set of standards for quality management in its 9002 document (now included in ISO 9001:2000). ISO 9002 includes a list of quality system requirements covering: Management Responsibility; Quality System; Contract Review; Document and Data Control; Purchasing; Control of Customer Supplied Product; Product Identification and Traceability; Process Control; Inspection and Testing; Control of Inspection, Measuring, and Test Equipment; Inspection and Test Status; Control of Nonconforming Product; Corrective and Preventive Action; Handling, Storage, Packaging, Preservation, and Delivery; Control of Quality records; Internal Quality Audits; Training; Statistical Techniques. Sites that have all of the requirements in place, in a documented form that passes periodic external audits, are referred to as ISO 9002 registered sites.

A company that truly meets all of the ISO 9002 quality system requirements listed above has a powerful tool for system control, since a well controlled manufacturing system is required to ensure effective quality management. Every aspect of the manufacturing system that could impact product quality must be clearly defined and controlled through up to date documentation. Both internal and external audits ensure that the documentation is complete and current. Failure to maintain documentation, or compliance with the documentation, results in non-compliance reports, which remain on file until the problem is fixed.

However, it is common for a company to go through the motions to become ISO 9002 registered without taking advantage of its benefits. In these companies, ISO registration

is seen as a hurdle that must be cleared in order to go back to business in the usual way, rather than an opportunity to improve quality and maintain control of the manufacturing system. Creating and maintaining ISO documents takes time and effort, so it is tempting to cut corners.

4.3 System Control at Portsmouth

While the “letter of the law” is followed regarding ISO registration at the Portsmouth site, the “spirit” of ISO is not always the number one priority. The site has enough resources dedicated to ISO documentation and internal auditing to meet formal ISO requirements, but adding extra resources may reduce the number of non-compliance’s and lead to a faster response to corrective actions reports.

The lack of emphasis on ISO documentation was less important before the site began ONE manufacturing, because another effective quality control system was in place for the computer system manufacturing businesses. However, the ONE manufacturing line showed that in the new world of frequent innovations and constant change, tight system control is extremely important. ISO registration provides a great tool for making sure the system control strategy is up to date and complete.

For example, one of the ISO requirements listed above is, “Corrective and Preventive Action,” which calls for preventive maintenance on key pieces of manufacturing equipment (ISO 9001:1994). As noted above, this preventive maintenance was not being performed on a piece of equipment on the ONE manufacturing line. Similarly, ISO requirements call for “Statistical Techniques” for “establishing, controlling and verifying

process capability and product characteristics.” The gage R & R, called for above, would fall under this category. More emphasis on the “spirit” of ISO implementation may have led to earlier action on these issues. It also may have led to other improvements that are more subtle, yet would have contributed to an overall increase in ONE manufacturing quality.

4.4 World Class Manufacturing

Although the Portsmouth site does not use ISO as a tool for system control, it does have other resources for improving the performance of one important part of the system: the manufacturing line. The World Class Manufacturing (WCM) group consists of consultants that travel to various Celestica manufacturing sites and use well known process improvement efforts to reduce work in process inventory, increase line throughput, and eliminate non-value add work. The Portsmouth site has a local WCM group as well. This group coordinates with the consultants and leads its own process improvement efforts.

The WCM group prefers to take action in the context of Kaizen Blitzes, during which the manufacturing line management teams up with line operators to fix all of a line’s problems in a one or two week period. A prerequisite for the blitz is permission to make any necessary changes to the line in order to improve its performance, including changes in equipment layout, process flow, procedures, and so on. Goals and metrics for the blitz are clearly defined before it begins, allowing the success or failure of the blitz to be measured as quantitatively as possible. The blitz begins with a tutorial on best practices

in manufacturing, while the rest of the time (about 95% of the total) is spent on the manufacturing floor making changes.

The advantage of the blitz is that it recognizes input from all owners of the line and its processes, especially those operators actually performing the manufacturing steps. It also educates operators and managers alike about why the changes are important. The disadvantage is that it requires the line to more or less shut down for a short time. If a line's problems have created a backlog, it is difficult to convince management to shut it down for a week or two. The blitzes may have to be shortened, or even postponed. The other disadvantage is that the blitzes do not put enough emphasis on long term metrics or ISO style documentation.

4.5 *The Interaction Between ISO and WCM*

The success of WCM teams inherently relies on the presence of an underlying system control strategy, which would allow the manufacturing system to digest the rapid improvements of a kaizen blitz and build upon them through continuous improvement efforts. The site's adoption of the spirit of ISO 9002's quality system requirements would provide the necessary framework for making WCM improvements last.

The WCM group and the Quality Management group (responsible for ISO documentation) are separate entities, and no interaction between the two groups typically occurs during a Kaizen Blitz. Figure 12 below shows the interaction between WCM and ISO efforts, and is based on system dynamics models discussed in Peter Senge's The Fifth Discipline. As a line at the Portsmouth site drops in performance, Celestica's

customer becomes displeased. As a result, complaints about the Portsmouth site increase, causing Celestica's top management to assign WCM resources to resolve the problems at Portsmouth. In turn, the WCM resources make improvements to the line that are immediately evident, reducing the number of complaints by the customer. This is the upper loop in the diagram. On its own, this situation would balance out at some low level of complaints (preferably 0) from the customer.

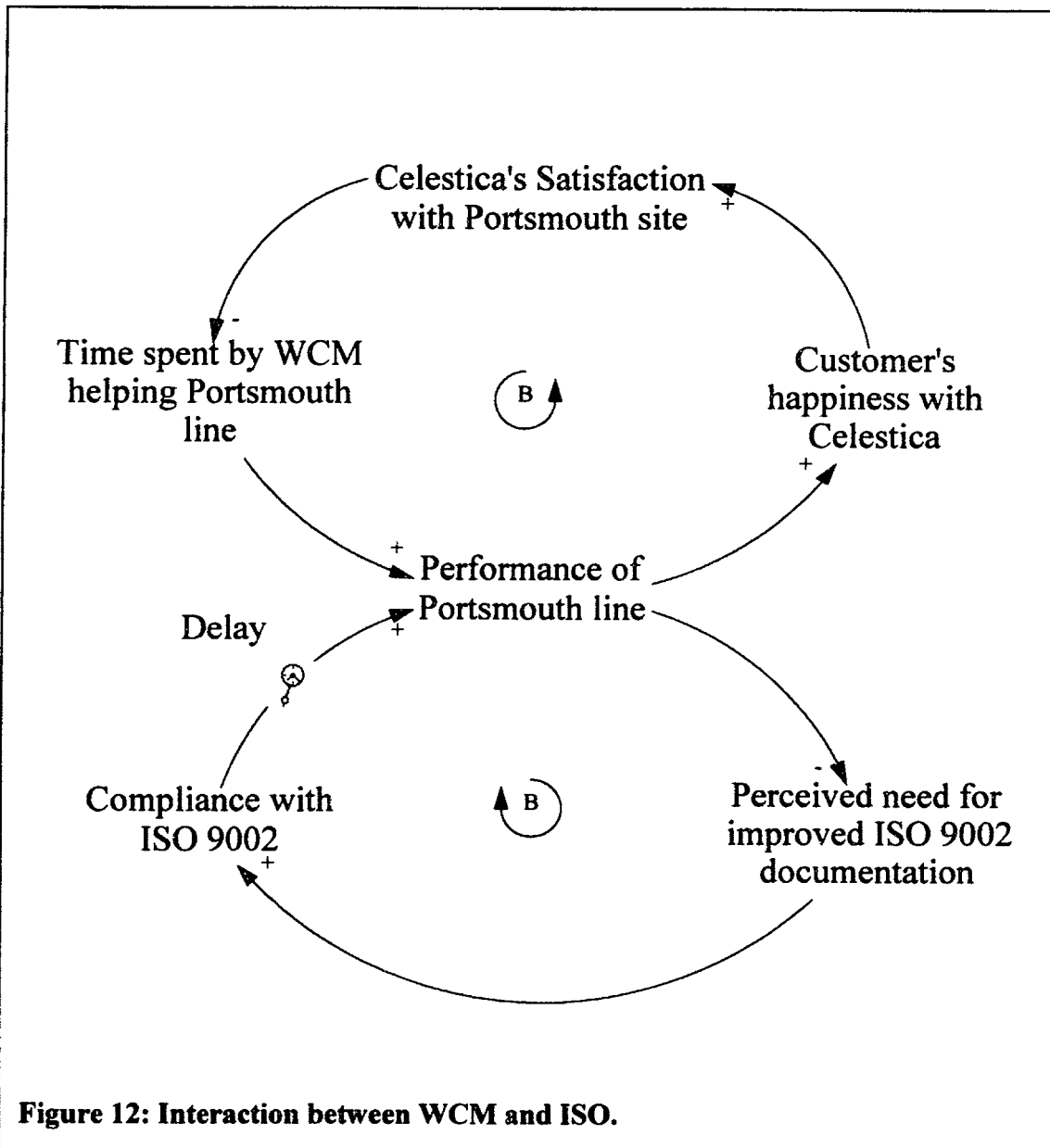


Figure 12: Interaction between WCM and ISO.

However, another set of interactions exists that is based on the ISO requirements. Since improvements made by WCM teams are not captured in ISO style documentation, they may not last. As product or process changes are made, there are few foundations for carrying over the best practices established by WCM teams on previous products and processes to the new ones. Unfortunately this interaction is masked by a delay between the time ISO documents fall out of date and when the performance drops. Improvements made by WCM teams are immediate, so managers and production workers associate WCM efforts with real results. When WCM teams get fast results without relying on ISO documentation, and without calling for ISO compliance as a part of a Kaizen Blitz, they reinforce the belief that ISO compliance is not a priority for high performance.

This is shown in the lower loop of the diagram: when the line is performing well, there is less of a perceived need for ISO documentation and compliance with ISO requirements. ISO compliance drops, which leads to poor line performance over time. Customer complaints increase, and WCM teams are once again dispatched to the Portsmouth site. Short term improvements are again made without any emphasis on ISO, ensuring that the improvements will not last.

It should be noted that when the line is not performing, there *is* a perceived need for improved ISO compliance. However, because immediate help is available from WCM, managers understandably look there for help instead of going through the trouble of creating ISO documents. When lines are not performing well, the site is usually working

hard to put out fires and get product out the door, and employees may not feel they have the time to sit down and create or update procedures. The best long term solution lies somewhere in the middle, with immediate improvements by WCM combined with strict compliance with ISO requirements. This will gradually lessen the reliance on WCM quick fixes, and move the site toward a continuously improving and robust manufacturing system.

The interaction described here is very similar to what Senge calls the “Limits to Success” archetype. In Portsmouth’s case, the key limit to success is too little emphasis on the “spirit” of ISO registration. In these situations, Senge identifies the typical response as pushing harder on the upper loop of the model, without recognizing the importance of the lower loop. This response has occurred at Portsmouth, with multiple attempts by WCM teams to improve the manufacturing line. However, until the limit to success is removed, pushing harder on the upper loop only has limited results. Senge suggests dealing with this situation by actively seeking out the limits and removing them, or in this case, improving compliance with the spirit of ISO registration. This will happen naturally if WCM efforts are combined with ISO efforts as a matter of policy.

5 Proposed System Control Strategy

Celestica can improve the control of its manufacturing system at the Portsmouth site in both the long and short term by creating standards for ONE manufacturing, increasing compliance with the spirit of ISO requirements, and improving communication on site. Successful implementation of these actions may require a shift in the culture at the site, which will be a valuable by-product of these efforts in and of itself.

5.1 *The Book of Standards*

The process development engineers at Celestica's Portsmouth site, as well as those at the company's corporate headquarters in Toronto, are acquiring a great deal of information and expertise in manufacturing optical networking equipment. The Portsmouth site is learning as it builds equipment for its customer, and headquarters is learning by both manufacturing optical modules and developing processes in a laboratory. In order to take full advantage of this learning experience, Celestica has undertaken a project to record a set of standard processes and procedures for this type of manufacturing in a Book of Standards, which will be available company wide.

Many of the processes that Celestica is learning have been developed by other companies that have been manufacturing optical networking equipment for a few years. Therefore, a number of the standards can be derived directly from information available in books or on the internet. These topics include safety in handling optical components, procedures for cleaning optical fibers and connectors, fusion splicing procedures, skills requirements for operators, and production environment requirements. Celestica's process

development laboratory in Toronto, in collaboration with the Portsmouth site, created a set of standards covering these topics during the course of the internship.

However, a number of Celestica's equipment choices and processes will be unique to the company, so the development laboratory is evaluating manufacturing equipment and processes on a continuous basis. Because the industry is so young, there is plenty of room for improvement and clarification of the existing standards, and new products that require modified processes are emerging constantly. A current area of research is in optical fiber handling on boards that require large numbers of fusion splices. As optical networking equipment becomes more complex, the manufacturing challenges become more significant. The Book of Standards is Celestica's template for continuous improvement in ONE manufacturing, and it is expected to continually evolve, help Celestica develop skills worldwide, and allow the company to maintain a position at the forefront of ONE manufacturing technology.

An important part of The Book is the standardization of equipment across Celestica sites, which will lead to economies of scale in the purchase and maintenance of critical capital equipment. Celestica's ability to leverage its power as a large purchaser of equipment will be important in this industry, since optical manufacturing equipment is in such high demand and occasionally suppliers have few incentives to improve equipment performance. However, the ability to standardize equipment is restricted by the rapid pace of equipment evolution, as well as the wide variety of specialized equipment required for various processes in the industry.

As The Book and Celestica's knowledge base grow, process development will increasingly spread to other parts of the company. In order to accommodate this growth, a process development laboratory is under development at the Portsmouth site, and at other strategic sites where ONE manufacturing is expected to occur in the near future. Rapid deployment of standardized practices should give Celestica an edge in keeping up with the explosive growth in the industry.

5.2 ISO Documentation

The Book of Standards is one example of the increasing use of ISO documentation at the Portsmouth site, since each standard is just an example of ISO documentation that is specific to ONE manufacturing. ISO documentation should form the heart of Celestica's system control strategy. Not only is ISO registration already a requirement for the site, but full compliance with the spirit of the requirements automatically solves a number of the site's most pressing problems.

The need for repeatability and reproducibility studies in the test and debug area, as well as the need for improved preventive maintenance on a key piece of equipment (issues mentioned above), could both be traced to missing, or out of date, ISO documentation. In addition, a walk through the manufacturing line revealed a number of day to day difficulties that would not have existed with improved compliance with the spirit of ISO. With the documentation in place, processes become visible and solutions to minor difficulties become more obvious. At the same time, flaws in the system that gradually

lead to the accumulation of inventory, or piles of failed products, can be identified early and the root cause of the problem can be corrected.

ISO compliance encourages steady, continuous improvement at all levels of the organization. However, in order to see the real benefits of using ISO documentation as a system control strategy, and to avoid having it deteriorate into an exercise in record keeping, the ISO documents should become the basis for decision-making at the site. For example, the procedure for changing a process step in the line should start with an examination of the ISO documentation that refers to that process step. Then the ISO document should be updated and distributed to the operator performing the step, and finally, the operator should implement the new process. In this way, the ISO documentation is guaranteed to be up to date, and operators can always refer to current documentation if they have a question about a step in the manufacturing process.

Enforcing compliance with the spirit of ISO will require extra time dedicated to creating documentation where none exists, updating old documents, and performing audits. In areas of the organization that are running smoothly, creating documentation should not take long; it simply requires writing down procedures that already exist in practice. In cases where no set procedure exists even in practice, the documentation will take longer to create. However, these are exactly the situations where the documentation is most beneficial.

Finally, the Portsmouth site should take steps to make sure the ISO documentation is available to anyone who needs it. Fortunately, Celestica already has a corporate wide database of ISO documentation. This database currently holds the Book of Standards for ONE manufacturing, and Portsmouth can add other ISO documentation to the database in a straightforward manner. Therefore, all of the pieces are in place for the Portsmouth site to begin using ISO registration as its primary system control strategy.

5.3 *Communication and Cultural Issues*

The success of the manufacturing system relies on frequent, in depth interactions between different parts of the system, and channels must explicitly exist that will promote those interactions. Currently, cultural boundaries exist between some parts of the system and others, and these barriers should be removed for the system to function properly.

In particular, the Quality Group, responsible for auditing for ISO compliance and maintaining the database of ISO documents, must not become isolated from the rest of the system. The Quality Group should be seen as an asset to all managers and operators on the production floor, and should work closely with others to solve quality problems. Any part of the organization that sees the Quality Group as threatening or restrictive should be educated about the benefits of high quality levels. Close communication between Portsmouth's Quality Group other groups, and with related quality groups at the company's headquarters, is vital.

In addition, communication between various sites that are performing ONE manufacturing, and between the laboratories developing processes, should increase. As

the process development program got started, there was a fair amount of fragmentation between various groups, and a minimal amount of communication between the manufacturing operations in Portsmouth and the process development team in Toronto. Over the course of the internship, a lot of progress was made in improving communication between these groups. The planned installation of a new laboratory in the Portsmouth facility should improve communications and the sharing of ideas, as well as quicken the pace of standardization at the site.

The culture of the Portsmouth site should reflect continuous improvement through increasingly efficient processes, based on current and accurate data. Fortunately, the site is headed in the right direction, with numerous standards from the Book of Standards implemented, and a serious effort in data collection underway.

6 Supply Chain Analysis

Supply chain issues impact Celestica's manufacturing system as much as the issues on the manufacturing floor itself, so a supply chain strategy that takes advantage of trends in the telecommunications industry can improve operations significantly. The components that Celestica uses to manufacture optical networking equipment are expensive, frequently on allocation with long lead-times, young from a lifecycle perspective, and are required in many different flavors. At the same time (during the internship), there was as much demand for Celestica's manufacturing capacity as there was for components, giving Celestica the opportunity to carefully choose its partners/customers. By choosing the right partners, Celestica may be able to alleviate some of the supply chain difficulties listed above.

6.1 Snapshot of the Telecommunications Industry

During the internship, the rapidly evolving telecommunications industry was dominated by three large, vertically integrated companies: Lucent, Alcatel, and Nortel. The table below shows the supply chain of the industry, starting with the *microelectronics* that underlie the optical, wireless, or electrical communication media, and include the RF and other electronics for processing communications signals. The next level, *optoelectronics*, is one of the most important in the industry. It includes products such as lasers, optical attenuators, optical fibers, and other components required to support the rapidly growing optical networking infrastructure. The *printed circuit board assembly* layer refers to the well established process of assembling microelectronics onto printed circuit boards, while

the *optical assembly* layer refers to Celestica's new area of business: adding optical components to the printed circuit board assemblies.

Transport platforms are the physical systems that make up the core of communication networks, and include routers, switches, and nodes that work together to form a network.

Network management includes the software and services included in running the network over the transport platform. *Last mile solutions* connect individual consumers or

businesses to the network core. *Application appliances* are the computers, phones, and other devices that users use to interact with the network. *Application software* resides on application appliances such as computers, allowing them to communicate with, and through, the network. The *service providers* provide customers with telephone, cable, and/or internet access.

Microelectronics	NORTEL	ALCATEL	(Agere)	Intel	Sumitomo	Analog Devices	Motorola		
Optoelectronics			-----				JDSU	Corning	
Printed Circuit Board Assembly						Celestica		Solectron	Flextronics (Wave Optics, Fico Optics)
Optical Assembly				LUCENT			Cisco	Photon-Ex	
Transport Platforms					Sycamore	NTT			Siemens
Network Management					Cayman				
Last Mile solutions (DSL, cable modems, wireless)									
Application Appliances (Computers, cell phones, etc.)	Dell		IBM	HP		Nokia	Motorola		
Application software	Netscape	Microsoft			Siemens		Qualcomm		
Service providers	ATT	Road-runner			World-com	Earthlink	Sprint	AOL	

This is not a comprehensive list of important companies, but examples of types of companies at different places in the supply chain. Different companies that share a row or column are not necessarily related in any way. The larger (taller) the company's box and the more segments of the supply chain covered by that company, the more vertically integrated the company.

6.2 Industry Wide Supply Chain Trends

While there are many players at individual points in the supply chain, the three largest players play the most important role. For example, even though JDS-Uniphase and Corning are very important manufacturers of optoelectronics, Nortel, Lucent, and Alcatel account for roughly 75% of optoelectronics sales in the industry. These “Big 3” companies control their whole supply chains, from the manufacture of optical fiber (Lucent and Alcatel), to the installation and maintenance of networks.

However, it is not unusual for a vertically integrated industry such as this to become more horizontally integrated over time (See Clockspeed, by Charles Fine). As one section of the supply chain becomes standardized and appears to hold promise for rapid growth and high profits, competitors start to appear and integrated firms are tempted to spin off those components of their businesses. Once a high-growth segment of a company is separated from the rest of the company, it has an easier time raising the capital required to realize its growth potential. In the middle of 2000, the optoelectronics portion of the supply chain seemed to be just such a high-growth segment, which led to a response by 2 of the Big 3.

Lucent decided to spin-off its optoelectronics and microelectronics groups into a company called Agere in 2001 (shown in the table separated by a dashed line). Over 75% of Lucent’s sales from these groups came from outside the company, and Lucent felt more external sales would come if the groups were independent of the larger company. Lucent competed with many of its optoelectronics and microelectronics customers further

down the supply chain, and those customers did not like to support Lucent with component purchases. Lucent also spun off its enterprise networks group into a company called Avaya, furthering the trend toward a more horizontally structured industry.

Lucent's actions, however, were not totally driven by the restructuring of the industry. Lucent has suffered significant losses recently, and the company needs the cash from its divestitures in order to restructure itself and regain some profitability. Both Alcatel and Nortel have avoided divestitures because they consider their optoelectronics groups to be strategic assets. In addition, the "irrational exuberance" (according to Federal Reserve Chairman Alan Greenspan) that led to such high valuations for optoelectronic pure-plays like JDS-Uniphase has since passed, reducing the reward for spinning off optoelectronic groups.

Nortel discussed selling its optoelectronics group to Corning in August, 2000, but the deal fell apart because Nortel would not give up a majority stake in the company. Similarly, Alcatel issued a tracking stock for its optoelectronics group, which allowed it to raise capital to grow the business without losing access to the components. Both companies realize the huge strategic advantage they have with an internal supply of quality, high performance components. Since component availability is a constraint for new system builds industry wide, the need to purchase components from the Big 3 is even more of a disadvantage for competitors.

High barriers to entry, in the form of technological expertise, are slowing the entry of new firms into the optoelectronics industry. Startups that offer truly revolutionary or performance enhancing components, such as tunable lasers and MEMS optical cross-connects, are quickly bought by the larger companies. In fact, with the exception of the struggling Lucent, the large companies show few signs that they are willing to give up core competencies or strategic advantages in any part of the supply chain. Cisco is expanding vertically into optical systems, providing an example of how the industry is resisting horizontal integration.

Technological expertise will continue to form a high barrier to entry for new firms as long as networking technology continues to evolve rapidly. Once network and component designs stabilize to some degree, dominant firms can begin to emerge in individual areas of the supply chain. This shows another advantage the large companies have: since networks are by their nature highly integrated systems, the large firms have a much greater ability to influence network-wide standards and technological approaches to networking. It will be very difficult for a dominant network or component design to emerge from outside one of the large companies.

For example, a small company cannot sell a few tunable lasers here and there and succeed, since whole sections of the network must be optimized to use tunable lasers before they improve network performance and lower costs. Therefore, tunable lasers are much more potent in the hands of Nortel, which recently purchased tunable laser start-up Coretek, than the lasers would have been in the hands of Coretek alone. Nortel can

optimize the tunable lasers to work well with Nortel's other components, then install the new systems in its own networks.

Therefore, the trend within the telecommunications industry seems to be a continuation of the vertically integrated structure, with a few dominant firms setting the direction of the industry. The exception to the rule could come in the form of pseudo-vertical integration through partnerships between component suppliers and systems integrators. Still, it would be an uphill battle to create networks with significantly different physical or service level properties than those created by Alcatel or Nortel.

6.3 *Impact of Supply Chain Trends on Celestica's Operations*

Celestica has entered into the optical networking industry, which is a subset of the overall telecommunications industry, by working with a small company serving the transport platforms and network management areas of the supply chain. While the customer does not manage networks on its own, it provides the software and systems that its customers use to do so. Celestica's customer relies on outside vendors for its components, and on Celestica for its manufacturing expertise: the customer has managed to take a narrow, horizontal slice out of a vertically integrated industry. Not only do the Big 3 have better access to components, but they also have the technological capabilities to manufacture optical networking equipment that Celestica has had to develop while scaling up its customer's products.

Celestica and its customer were forced to purchase at least some of the components from the Big 3, because they were the only sources for some high performance components.

Those components tended to be short in supply and high in demand. Since Celestica's customer competes with the Big 3 further down the supply chain, there was little incentive for the larger companies to provide the components quickly or at low cost. Instead, due to the long lead-times in the industry, Celestica ordered the components months before receiving them, and was exposed to the risk of holding excess inventory if its customer's system level orders changed after the component orders had already been placed. Thus, the supply chain structure of the industry contributed to Celestica's inventory costs and shipment lead-times.

6.4 Recommendations for a New Supply Chain Strategy

If Celestica could have entered the ONE manufacturing business by partnering with one of the Big 3, they may have had better access to some of the required components, faster turnaround for component repairs and replacements, and better purchasing terms (assuming that the extraordinary boom in demand for optical components still occurred in this imaginary scenario). In addition, they would have had access to the very valuable manufacturing expertise that resides primarily in those larger companies. Such a partnership would have allowed Celestica to provide capacity instead of expertise, while actually gaining manufacturing expertise from its customers.

As Celestica's Portsmouth site expands its ONE manufacturing capacity, it could increase its skills and ease its supply chain woes by partnering with one of the large, integrated firms. These firms would be more likely to provide long term commitments than small start-up firms, which only have a small chance of survival to start out with. Partnering with large firms takes some of the guesswork out of finding partners who will last,

although Lucent's experience shows that the large companies are not invincible.

However, one of Lucent's strategies for getting back on track and cutting costs is to work more with contract manufacturers, not less.

By following this approach, Celestica could strengthen the skills it needs to partner with smaller companies and take advantage of the rapid growth that can come with such relationships. When the industry does become more horizontally integrated, Celestica would be well positioned to provide services for whoever seems to be taking the reigns of the optical networking industry.

7 Conclusion

As Celestica's Portsmouth site continues to make the transition to ONE manufacturing, it faces a number of challenges, including the introduction of new technologies and processes, the need for increased manufacturing system level controls, and its induction into the young and volatile telecommunications industry. Fortunately Celestica can take, and in some cases has already taken, a number of steps that will smooth the transition.

Working with optics and optical fiber presents the most formidable technical challenge in ONE manufacturing. It is important to understand and account for the variability that is introduced into optical measurements by a fiber's optical characteristics, such as polarization effects, dispersion, and attenuation. Certain pieces of optical equipment, such as polarization insensitive detectors, are vital for accurate and repeatable measurements. In addition, a fiber's physical characteristics, such as tensile strength and buffer size, influence the ease with which systems can be manufactured. Once again, specific equipment sets, such as high strength fusion splice kits, will directly impact both the short and long term reliability of manufactured items. With a complete understanding of these properties, Celestica can advise its customers on product designs that minimize manufacturing costs, such as the use of multimode fiber and/or buffered optical fibers, when those options are available and in the customer's best interests.

System level manufacturing controls, which regulate the interactions within and between different components of the manufacturing system, are vital for high quality manufacturing. The efforts of the various system components, such as human resources,

finance, supply chain management, and operations, must be aligned, and the groups should have a common language for communicating and delivering quality products to the customer.

Full compliance with the “spirit” of ISO regulations can provide alignment and a communications medium that would benefit the Portsmouth site. While more people are required, much of the infrastructure already exists for such a thorough implementation, including a small staff of quality engineers and a database for compiling and sharing ISO documents. Celestica’s Corporate Headquarters has recently taken another important step in this direction, by requiring regular reporting of a site’s outstanding ISO corrective actions.

Current production process improvement efforts, led by WCM teams, should integrate their operations with those of the Quality Group. This includes using ISO documents as the beginning and ending points for WCM improvement efforts. Integrating the efforts of these two groups will both create an environment of continuous improvement, and make both groups more efficient and productive.

The Book of Standards, which provides details about various aspects of ONE manufacturing, is and will continue to be a valuable tool for corporate wide system level control through ISO style standardization. It will also allow other sites to quickly develop ONE manufacturing capabilities, boosting needed capacity in a growing industry. As Celestica builds its skill base and experience in ONE manufacturing, its

internal proprietary standards may eventually influence industry-wide manufacturing trends. Competitors could be forced to comply with Celestica's high standards, giving Celestica significant influence in the telecommunications industry.

Finally, Celestica must choose its partners wisely as it expands its operations in the telecommunications industry. A few large, vertically integrated companies, such as Alcatel and Nortel, would make good partners / customers insofar as they would provide increased access to components, as well as acting as a source of manufacturing expertise. These are important points for Celestica, especially since components may once again become short in supply industry wide. If Celestica can combine access to components with manufacturing skills and a robust manufacturing system, it will have significant advantages over its competitors in ONE contract manufacturing.

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