

Fusion Splicing Fiber Optic Cables in the Aerospace Environment

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ABSTRACT

Successful use of fiber optic interconnects in high-performance platforms and applications depends on viable technologies for their repair and installation. Splicing is often desirable, either to repair a damaged interconnect or to install it, particularly where it is difficult or impossible to access all necessary locations for complete removal and replacement. However, reliable aerospace cable splices must endure conditions as adverse as those for which the original cable was specified. In addition, the splicing technology must be usable with a high degree of reliability under difficult aerospace working conditions. Mechanical splices have shown some promise for the repair of multi-mode aerospace fiber cables, but they face daunting difficulties in splicing single mode fiber cables, which are being ever more seriously considered for new and upgraded systems. Fusion splicing has long been accepted in the telecom industry for making the highest performance fiber splices, both single mode and multi-mode, but the technology has not yet been found adaptable to stricter aerospace requirements. Up until now the prevailing cable repair philosophy has been “remove and replace”, but in many cases this can be near-impossible and very expensive.

This paper will describe new methods of in-situ repair of fiber optic cables using ruggedized fusion splicing machines. New fusion splicers can splice aerospace optical fibers in the field with near-zero insertion loss and unmeasurable return loss. Fusion spliced optical cables resist adverse environments and mechanical stresses with ruggedness approaching that of pristine cable. The new splicers, being ruggedized to satisfy MIL-PRF-28800F, can be used in most difficult-to-reach locations, virtually wherever a person's hands can work. Most recently, a new fusion splicer has been proven explosion-proof, suitable for use on fueled aircraft. SAE and commercial standards are in development to enable formal approval of the equipment for hazardous atmospheres. Extensive test data will be presented illustrating the new repair techniques on a variety of aerospace fiber optic cables, and a forecast of future development and transition to production will be outlined, particularly for commercial aviation.

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INTRODUCTION

Fusion splicing has long been the preferred method for low-loss repair and installation of fiber optic cables. In the telecom industry optical fibers have been fusion spliced since at least 1978. In this process the two fibers to be joined are actually welded together with a high voltage electric arc (see [Figure 1](#)), which if done well results in a very low loss, ultra-low back reflection, stable, and strong joint. The two fibers must first be prepared carefully by stripping the coatings off the glass fibers, cleaning them thoroughly, and cleaving them to obtain flat end faces perpendicular to the fibers' axes. Alignment may be done passively, by laying the two in a common precision v-groove, but single mode fibers, whose signal-carrying cores are only 6 to 11 microns in diameter, usually require micron-scale active alignment for good

results. The arc is controlled in duration and current so as to soften and melt the fiber ends just the right amount, at the right time, while the equipment pushes the fiber ends together by just the right amount. Automatic fusion splicers generate an estimate of the insertion loss after the splice, and often they apply a tension test as well to assure the user that the joint is strong enough to last.

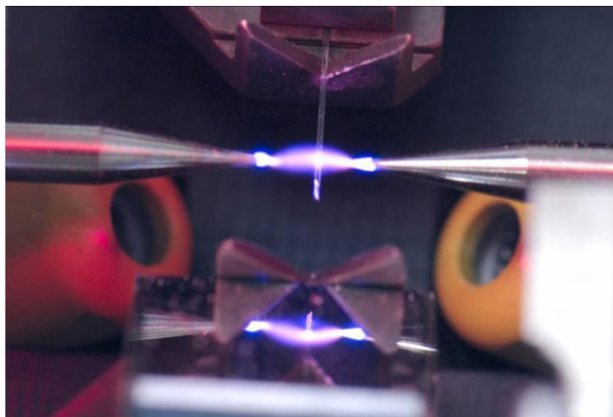


Figure 1. Close-up of a high voltage arc applied to an optical fiber.

There are other ways to splice optical fibers, generally considered “mechanical” because they involve holding the two fibers in close alignment with each other by clamping or gluing. Commonly the prepared fibers are inserted into a common precision capillary or v-groove with their end faces touching, and then they are fixed in position. Either glue or a gel is used to embed the fiber ends and provide a transparent medium between the two fibers to minimize loss and back reflection due to reflections at glass-air interfaces. Mechanical splices have also been used in telecom, as well as aerospace, environments for many years, largely due to the relative simplicity and low cost of the installation tools and equipment, but they have a number of disadvantages. The worst is probably susceptibility to thermal stresses, because as a mechanical splice experiences thermal excursions over a wide temperature range the differential thermal expansion between the fibers and the parts of the splice structure result in relative movement, changes in insertion loss, and in some cases complete failure. Adhesive bonds can fail, allowing the fibers to retract from each other or, worse, move forward and smash against each other. The index-matching medium between two fiber end faces can delaminate, leading to a sudden increase in back reflection which, even worse, is variable with time and temperature. In the telecom central office, cable television head end, or underground vaults thermal variations are modest and mechanical splices are commonly successful, but in the aerospace environment as well as telecom outside plant, thermal stresses, as well as severe shock and vibration, can cause most mechanical splices to fail.

Fusion splicing has many advantages, most particularly the extremely low insertion loss, negligible back reflection, and rock-steady stability under environmental stresses. Fusion splice losses are typically only 0.01 to 0.02 dB, at least an order of magnitude better than mechanical splice losses. (In MIL-PRF-24623, the insertion loss requirement for mechanical splices is 0.5 dB.) But telecom-type equipment has never before been suitable for the aerospace environment. It is commonly bulky, delicate, susceptible to

extreme temperatures, humidity, dust, and salt fog, unable to be used other than level, and expensive. Worst, an electric arc is a classic explosion hazard, unacceptable in areas where fuel vapor may be found. Adverse environments such as these are found in both military and commercial aviation, on airfields or aircraft carrier flight decks, commercial airports and hangars, and even remote refueling or servicing locations. Other hazardous environments where fiber cables are commonly used include both traditional and petroleum mining (oil fields) and underground utility tunnels, where natural gas or methane fumes are common. What has long been needed is some way to employ the advantages of fusion splicing for the repair and installation of fiber optic cables in the aerospace and similar challenging environments.

THE AEROSPACE ENVIRONMENT

What, exactly, are the challenges? In military aviation the requirements for components or equipment are usually defined in MIL or SAE standards, and they are usually specific to particular components, items of equipment, or platforms; commercial aviation refers to DO-160, a collection of requirements produced by RTCA, Inc². Standards in the telecom outside plant market are maintained by Telcordia, now a division of Ericsson. We must begin by making a clear distinction between the equipment used to splice a cable and its product, the resulting splice. The equipment or *splicer* must function properly under a range of adverse conditions in which humans are expected to work, but it will not usually be flown or subject to flight conditions after the job is done. The *splices*, however, which are the result of the process, must endure a full range of stresses characteristic of the aerospace environment, including extreme thermal cycling, high vibration, mechanical shock, aggressive fluids, dust erosion, and the partial vacuum of high altitude.

As suggested by [Figure 2](#), installing or maintaining fiber optic cable on aircraft involves tight quarters and difficult access and working on structures from unusual angles.

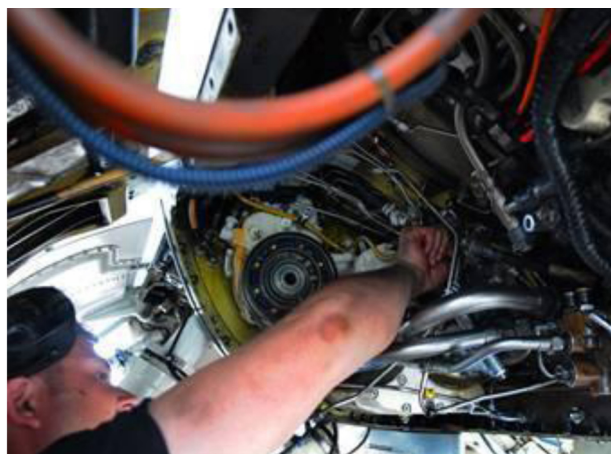


Figure 2. Example of difficult access in servicing equipment on aircraft.

Table 1. Some Typical Military Requirements for Electrical and Electronic Test Equipment per MIL-PRF-28800F, Classes 1 and 2.

Environmental or performance criterion	Description
Storage temperature	-51 to +71 C
Operating temperature	-10 to +55 C
Relative humidity	5 to 95%, non-condensing (75% RH above 30 C, 45% RH above 45 C)
Altitude	4600 meters
Vibration	Random, 30 g rms, 10 – 500 Hz
Mechanical shock	30 g, half-sine, 11 msec, without protection
Splash-proof and drip-proof	In transit case
Fungus	Will not support fungus growth
Salt fog	48 hours at 35 C, in transit case
Explosive atmosphere	For hazardous areas, must not ignite stoichiometric n-heptane-air mixture at any altitude or temperature within the equipment's rating
Electromagnetic compatibility (EMC)	Six tests including shielding against either radiated or ambient electromagnetic interference (EMI), conducted emissions or susceptibility through the power cord, electrostatic discharge, and low-voltage safety
Dust	When specified, must tolerate blown dust

A good guide to the mil/aero requirements for portable equipment, such as may be used to splice fiber optic cables, is provided by MIL-PRF-28800³. Although there is not yet any aviation standard specifically for fusion splicers (but see below), Aurora Optics has taken requirements from MIL-PRF-28800F as a good working definition of much of what an aerospace fusion splicer should satisfy, of course in addition to delivering state-of-the-art fusion splices. Key items are summarized in [Table 1](#).

Clearly, adapting a delicate and extremely precise technology like fusion splicing to the mil/aero environment includes some significant challenges.

The final product, a cable splice, is subject to its own set of demanding requirements. Two military standards that supply guidance are MIL-PRF-24623 and SAE MA-5405⁴. Key specifications are abstracted and compared in [Table 2](#).

Again, it will be appreciated that aerospace cable repairs must survive far more severe conditions than telecom splices. The thermal cycling, particularly combined with the three-round high vibration regimen, is the most likely to cause failure, but the fluid immersions, for instance in hot hydraulic fluid and anti-icing fluid, often cause failure of even MIL-spec materials, and the mechanical shock test is famous for destroying every component it meets for the first time.

In summary, to fusion splice fiber optic cables in the aerospace environment, both the equipment and the resulting splices must be designed for some very difficult conditions.

REPAIR PHILOSOPHY

The dominant repair philosophy, at least until very recently, has been “remove and replace”. In other words, if a cable is damaged no attempt is made to repair (splice) it on-aircraft. If the cable can be repaired at all, the repair should

be done in a fully-equipped depot or laboratory, under controlled conditions. A new cable is re-installed on the aircraft in place of the damaged one.

While a brand-new cable may be assumed to be the best, the obvious drawback is that it is often difficult and time-consuming to remove a damaged cable. According to one recent study⁵, some fiber cables on a military fighter can require up to a man-week of labor to remove and replace because they require partial disassembly of the airplane. The cost, which may be in the range of \$100,000, far outweighs the cost of the cable itself. Far worse, however, is that an aircraft which may be sorely needed is put out of action for an extended time. In warfighting this disability could easily put missions or lives at risk.

The ability to fusion splice cables on-aircraft, when it comes to fruition, will enable crews to bypass the remove-and-replace philosophy with an entirely new and far more efficient paradigm. We begin by considering that fiber cables on military aircraft are typically not very long, usually less than 10 meters, but deployed in complicated configurations of cable assemblies or harnesses which connect various items of equipment in various locations, passing many bulkheads, stanchions, and cable tying points along the way. At each end, each cable is terminated with either a simplex connector or one of many termini in a multi-terminus MIL-spec connector. Damage may occur anywhere along the length. Referring to [Figure 2](#), we propose that the various damage locations may be categorized as a) in the connector or terminus itself, b) in whatever length of cable is accessible from the end and can be freed up close to the connector, as far as the first pass-through, bulkhead, or stanchion, and c) “mid-span” - everything far or hard to reach from either end.

Table 2. Some Typical Military Requirements for Splices in Fiber Optic Cables, per MIL-PRF-24623 and SAE MA5405A

Test	Per MA5405A/1A	Per MIL-PRF-24623/6 and /7
thermal cycling	-55 to +125 C; 100 cycles	-55 to +85 C
fluid immersions	Per TIA 364-10	13 fluids per Table 3, omitting gasoline; lube oil at 73 - 77 C
ice/freezing	In cylinder 100 mm ID x 380+ mm long; -10 C for 6 hours; -2 C for 1 hour; loosely coiled; chamber need not be sealed.	In container large enough for 50 m of cable; unsealed; -10 C until frozen; -2 C long enough for optical measurements.
humidity & temperature cycling	25 - 65 C, 80 - 98 % RH; 10 cycles = 240 hours	25 - 65 C, 80 - 98 % RH; 10 cycles = 240 hours
mechanical vibration	a) Sine vibration, 10 - 2000 Hz, 60 g, 36 hours, 20 min. per axis, + 36 T cycles -55 to +125 C; b) Random vibration per MIL-STD-1344, method 2005, condition VI, letter J, 39.6 grms, 16 cycles; c) Random vibration per MIL-STD-1344, method 2005, test condition V, Figure 25 envelope, with 16 T cycles.	random vibration; rms g level not specified; 0.5 hour
mechanical shock		MIL-S-901 500 pound hammer drops; 1, 3, 5 feet; 3 shocks in each axis; all 3 axes
cyclic flexing	Not specified	10 cycles; 5 N tension (1.124 pound), at 30 cycles/minute max.
twist under tension	Not specified	50 cycles under 5 N load (1.124 pound)
tensile stress or strength	50 pounds, then to failure.	10 minutes; 10 pounds load for mechanical splice; fusion splice load not applicable.

We consider that potential forms of cable damage must include:

- terminus end face scratching due to dirt + vibration
- terminus failure due to trauma, incorrect handling, environmental stress, and/or defective termination (e.g. bubbles in epoxy)
- cable break due to bad handling, trauma, chafing, too-tight cable ties, too-small bends, battle damage, etc.

In addition, the choice of repair technology must be consistent with:

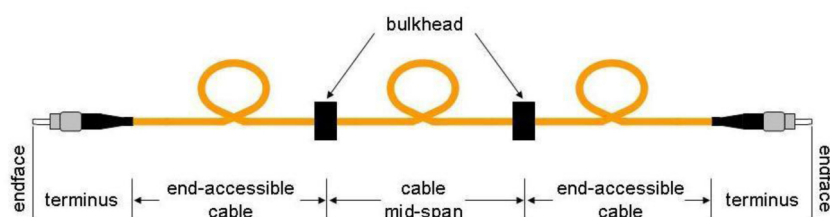
- Location of the damage or fault
- Type of fiber and cable
- Repair situation or scenario
- Availability of equipment

The repair situation or scenario must also be determinative. There will be urgent situations (e.g. battle

damage), where speed is essential, support equipment may be lacking, and the environment may be adverse. On the flight deck, airfield, or flight line repair personnel may be assumed to have more time and support equipment, but fueled aircraft will commonly pose an explosion hazard. In hangar, depot, or shop, finally, one may assume a good array of support equipment, ample time, and little or no explosion hazard.

If a connector or terminus itself is damaged, it may be practical to repair or replace it without splicing at all. Endface scratches, for instance, can often be polished out with diamond polishing film. But anywhere from the end of the cable to the "last bulkhead", we propose, the best way to repair damage is to cut off the damaged cable end and fusion splice back on a replacement pigtail. Furthermore, in cases of mid-span damage, cable can best be repaired by fusion splicing, either drawing two cut ends together (if there is sufficient slack) or splicing in a jumper. In other words, having an aerospace-capable fusion splicing technology would almost by itself enable this new repair paradigm.

Locations may be organized by the ways they can be repaired:



- Termini endfaces, if scratched, may be repolishable.
- Damaged termini, plus xx* inches of cable
- Cable close enough to a terminus to be removed and replaced
- Cable too far from terminus to be removed and replaced

Figure 3. Schematic Diagram of Locations Where an On-Aircraft Fiber Cable Might Need to be Repaired.

AEROSPACE-CAPABLE FUSION SPLICERS

Two new fusion splicers have been in advanced development for aerospace applications and are approaching readiness for field trials and adoption. This work has been benefited from valuable input from Boeing Aerospace and Lockheed Martin and contract support from the Naval Air Warfare Center, Patuxent River.

Non-Hazardous Environments

For areas where hazardous fumes are not an issue, the new technology is best represented by the miniature modular fusion splicer shown in Figures 3 and 4. Miniaturization is achieved by off-loading the data processing, control, and display functions to a separable controller. The actual splicer retains only those functions that must be performed on or close to the fiber cable: cable gripping, image acquisition, fiber-to-fiber alignment, high voltage generation, and welding. In this way the splicer has been reduced to approximately one pound in weight and 23 cubic inches in volume. The two modules are interconnected by an umbilical cable, nominally 8 feet in length, that can be doubled to 16 feet. With such low mass the splicer is more readily ruggedized, and an elastomeric jacket further insulates the precision mechanism from mechanical shocks and vibration.

Prototype MiniMod fusion splicers have been evaluated against approximately 50 performance criteria ranging from software functions to electrode life, battery life, splice losses, loss estimation accuracy, splice tensile strengths, working orientations, and the environmental goals outlined above. Without going into the many trivial specifications, key items are summarized below in Table 3.

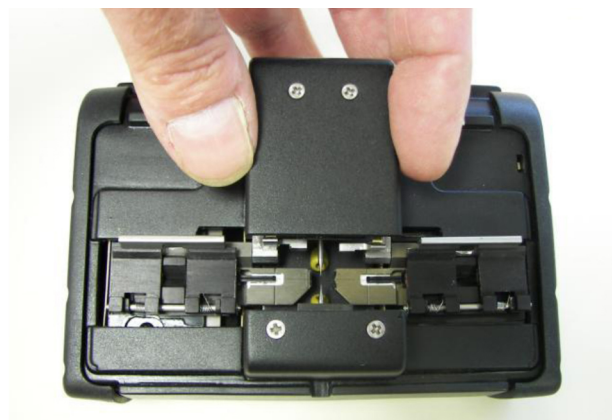


Figure 4. “MiniMod” miniature modular fusion splicer, with the fusion cover pulled open, showing the electrodes, fiber alignment stages, fiber/cable holders, and outer shock-protective jacket.



Figure 5. Electronic controller and umbilical cable.

A key requirement, which does not yet appear in MIL or commercial specifications, is *operational orientations*. Given that splicing may have to be done at arm's reach, in hard-to-reach locations, behind equipment or harnesses or other equipment (see Figure 2), or overhead, it was judged important that the equipment function properly when used sideways or upside down. In splicing tests the MiniMod delivered virtually perfect splices when used side-vertical, back-vertical, and upside down (see Figure 6). Similarly, the equipment was evaluated for the ability to splice properly in a very small space, as shown in Figure 7.

Fusion splices on both single mode fiber (SMF) and 62.5/125 μm multimode fiber (MMF) were consistently excellent. The mean insertion loss value for SMF was 0.023 dB, and the average for MMF was 0.004 dB. Histograms of the statistical data are shown in Figures 8 and 9.

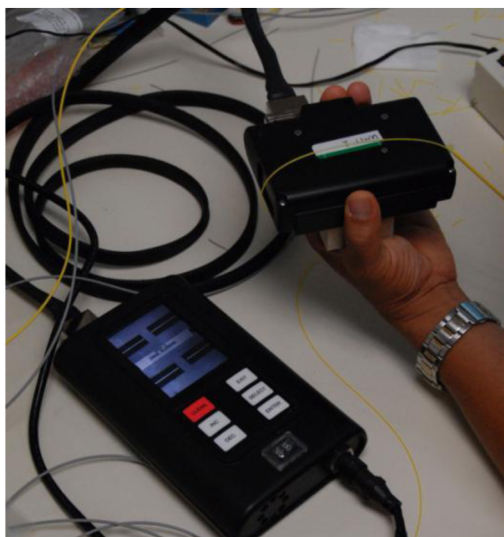


Figure 6. Fusion splicing upside-down and hand-held.



Figure 7. Splicing in a very small cramped space.

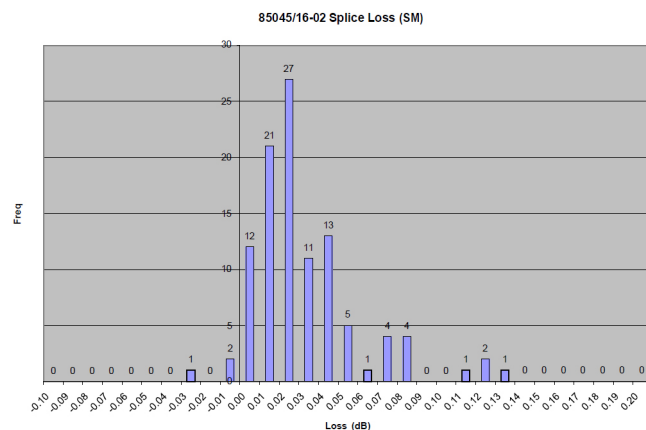


Figure 8. Summary results of splice qualification testing on SMF; MiniMod fusion splicer; true insertion losses; mean 0.023 dB.

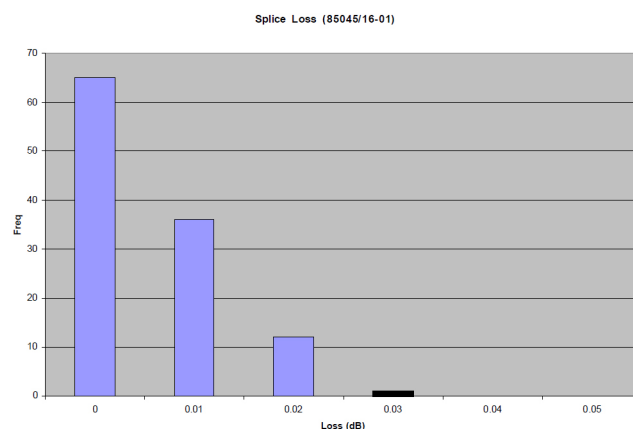


Figure 9. MiniMod true insertion losses on 62.5/125 μm MMF; mean value 0.004 dB.

High altitude testing was performed on Pike's Peak (altitude up to 4300 meters). All necessary operational and test equipment were transported to the site, including 1550 nm optical power source, Agilent power mainframe and dual power meter, SMF cable test set-up per FOTP-34, and fiber prep tools. AC power for the equipment was provided by a 12 VDC inverter. A minivan was used as a mobile test lab. Again it was shown that built-in sensors for barometric pressure plus software to adjust the fusion parameters for altitude were successful in insuring proper fusion splicing at all altitudes tested (see Figure 10).

Vibration testing was performed in accordance with MIL-STD-810F, method 514.5, cat. 4 (restrained cargo), which includes frequency scans from 10 to 500 Hz and an acceleration level of 30 g rms. Though the MIL spec envisions testing equipment in its normal cushioned packing or transit case (i.e. as "cargo"), in Aurora's tests the splicer was hard-mounted directly to the vibration table. As with