Production and Radiation-Source Testing of Scintillator Modules for the MINERνA Neutrino Detector

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Abstract:

MINERνA (**M**ain **I**njector **E**xpe**R**iment for **ν-A**) is an experiment to study neutrino interactions in the Neutrinos at the Main Injector (NuMI) beamline at Fermi National Accelerator Laboratory. MINERνA's fully active construction will help to interpret data from the MINOS (**M**ain **IN**jector **N**eutrino **O**scillation **S**earch) experiment; a much larger neutrino detector with a less active fraction, which is currently running in the NuMI beamline. MINERνA consists of a fully active scintillator interior with nuclear targets, the inner detector, surrounded by the part steel part scintillator calorimeters of the outer detector. Construction of MINERνA is presently underway at the College of William & Mary for both ID (Inner Detector) and OD (Outer Detector) modules. Written procedures were developed and refined for light tightening, retrofitting, fiber polishing, and quality assurance for both ID and OD modules. A 22Na source was used to detect dead fibers in OD towers and in ID planes.

Contents:

1. Introduction:

1.1. Goals

Construction of the MINERνA neutrino detector presents our group with many challenges. Collaborators from various institutions must be able to synchronize the construction techniques for assembling the scintillator modules for the detector, whilst providing rapid quality feedback and adjusting procedures in real time based on results from quality assurance tests. The goals of this project are to improve production and testing techniques for detector planes and to produce procedure documents for the purpose of quickly educating peers at Hampton University and Fermilab on these new methods of construction.

In the past William & Mary has had to wait for correspondence with Fermilab for data regarding plane response and fiber condition. Entire shipments of towers could contain dead fibers and W&M would be unaware upon shipment. In this project simple methods were developed for scanning detectors with a Sodium-22 γ emitter for faster feedback on quality assurance.

1.2. Introduction to Neutrino Physics

The existence of the neutrino was first predicted by Wolfgang Pauli in 1930. At the time it was thought that an electron was the only byproduct of the β decay of a neutron into a proton, however this model violated conservation of energy and angular momentum. The two resultant particles kinetic energies' were not collinear, nor did their kinetic and rest energies add up to the initial energy of the neutron. To resolve this contradiction Pauli proposed a massless, chargeless particle with the proper energy and angular momentum to balance the reaction. This mysterious, nearly impossible to detect particle was later dubbed the neutrino (little neutral one) by Enrico Fermi.[9]

Neutrinos have since been confirmed as fundamental chargeless leptons with very little mass. They are the most numerous matter particles in the universe and are produced in cosmic ray interactions, β-decay and thermonuclear fission. Because of their lack of charge, they interact only through exchange of the weak force, and thus are very difficult to detect.

Neutrinos come in three flavors analogous to the three charged leptons (electron, muon and tau), but with much less mass. All weak force interactions can be categorized into two main types: charged current interactions and neutral current interactions.[5] In a charged current interaction a neutrino exchanges a $W^{\pm}$ boson and produces its charged lepton partner, electron, muon or tau:

$$\overline{\nu_e} + p = n + e^{+} \tag{1}$$

Equation (1) is an example of a charged current interaction, inverse β-decay. In neutral current interactions a neutrino exchanges a Z^{0} boson with a nuclear quark and no such charged partner is produced.

Neutrinos were first observed in 1956 though inverse β-dceay. Clyde Cowan et al. set up a proton target near a nuclear reactor.[9] Neutrinos resulting from the β-decay in the reactor interacted with the protons in the target, producing neutrons and positrons. Direct observation of the coincidence of positions in the target with neutron capture only when the reactor was running confirmed the existence of neutrinos.

1.3. **Introduction to Neutrino Oscillations**

1.3.1. The solar neutrino problem

Nuclear reactions in the sun create a tremendous flux of neutrinos. Using a standard solar model, astrophysicists predicted the flux of ν_e incident on the earth.[4] Every time this flux was measured on earth, beginning in the 1960's with the Homestake Experiment[4] and continuing all the way to 1998 with the Super-Kamiokande detector, only one third to one half of the predicted atmospheric electron neutrinos were found.

First it was postulated that the standard solar model was incorrect, that perhaps the core of the sun was not as active as initially thought. Heat from the core of the sun takes thousands of years to reach the surface, thus it might be possible that the temperature and pressure of the core were a few percent lower, creating a lower flux of ν_e.[4] This solution proved untenable with further advances in the study of helioseismology, the core was just as hot in new models.

1.3.2. Neutrino oscillations

With no fault found in solar models, the discrepancy clearly had to arise from neutrino physics. A new model gave neutrinos mass eigenstates (thus giving neutrinos mass) that were not the same as its flavor eigenstates.[8] This allowed neutrinos that were created as electron neutrinos (with one of the three available masses) in the sun to have a calculable probably to be detected as either muon or tau neutrinos on the earth. Various detectors, such as the Super Kamiokande, measured electron neutrino disappearance from the sun and terrestrial nuclear reactors for years.[4] Their results agreed with the hypothesis of flavor oscillation but did not demonstrate it conclusively.

In 2002, The Sudbury Neutrino Observatory, or SNO, was the first detector to detect both charged and neutral current interactions for all flavors of neutrinos.[9] Dealing directly with solar neutrinos (as opposed to nuclear reactors like Super-K), SNO proved conclusively that neutrino oscillations occur.[9]

In the (simpler) case of two neutrino flavors, say ν_e and ν_μ, each is a linear combination of two mass eigenstates, ν_1 and ν_2:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad (2)$$

where θ is the mixing angle mixing angle. The probability that a neutrino initially in the muon state can transition into the tau state can be derived[6]:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 \frac{L}{E}) \quad (3)$$

According to (2), the probability of a neutrino remaining the same flavor oscillates wildly at low energy and is much more slowly varying at higher energies, as seen in figure 1:

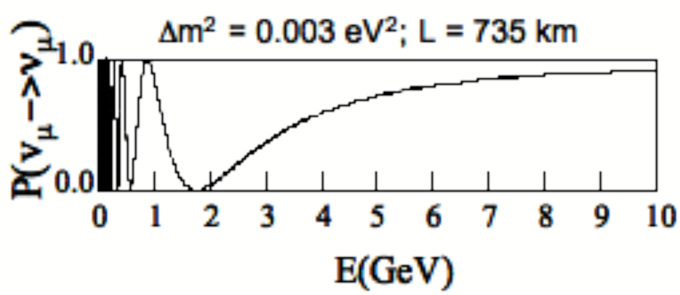

Figure 1: The survival probability versus energy for the muon neutrino

1.3.3. The MINOS detector

MINOS experiment's primary task is to study neutrino oscillations. A proton beam at Fermilab incident on a graphite target creates unstable particles; these in turn decay into neutrinos. A near detector measures the neutrinos near to their production point. More than 700km away in a mineshaft in Soudan, MN a much larger far detector measures the same beam of neutrinos. When a neutrino interaction occurs in either detector, the energy of all of the resultant particles is calculated, revealing the energy of the incident neutrino. By comparing results the energy spectra in the two detectors, neutrino oscillations can be investigated.

The MINOS near and far detectors, respectively (http://www-numi.fnal.gov/)

1.3.4. Problems with measuring oscillations in MINOS

MINOS cannot, however, determine the energy of the particles with good precision. [7] The detectors are composed mostly of iron, with small slices of active scintillator interspersed. Iron, a very massive nucleus, has a greater probability of a neutrino interacting within. Neutrino interactions create many short-lived particles that may disappear within the iron without every being measured within the scintillator. These lost particles can create huge uncertainties when calculating the energy of the incident neutrino.

2. The MINERνA Detector:

MINER*ν*A's task is thus to refine the energy measurements of MINOS. Unlike MINOS, MINER*ν*A's core will be composed entirely of active scintillator material, with steel interspersed between layers of scintillator on the back and sides to prevent charged particles from leaving the detectors while being sampled.

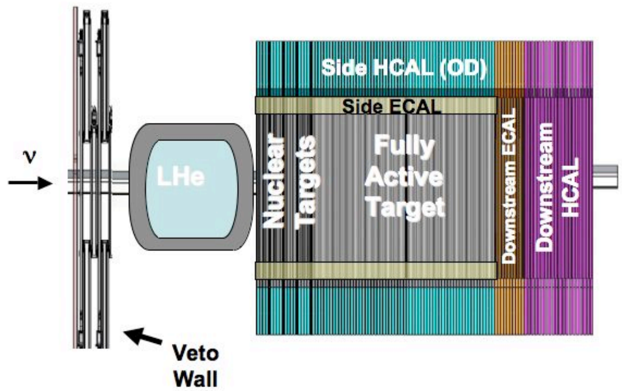

Figure 2: A cross section of the MINERνA detector

It will be placed upstream from the MINOS near detector and its fully active core will allow for much more in depth analysis of particles produced and energy transferred to nuclei in neutrino interactions. This will allow for more accurate modeling of MINOS' data. Figure 3 shows a simulation of a neutrino interacting with a neutron, creating a muon and a proton in MINER*ν*A.

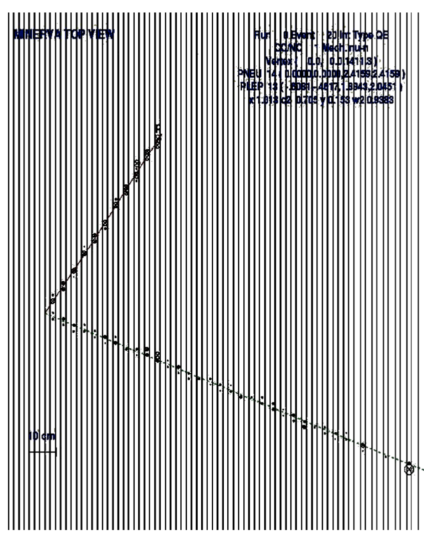

Figure 3: $\nu_\mu n \rightarrow \mu^- p$
A simulated charged current reaction in MINERνA, vertical bars are sample points

MINERνA consists of two major parts: the outer detector (OD) and the inner detector (ID). An OD module is constructed from six trapezoidal steel planes with four parallel scintillator doublets imbedded in slot in the steel that serve as a calorimeter for particles exiting the sides of the detector. A single ID module is made from 128 bars of scintillator with 127 optical fibers imbedded, cut and glued to form a hexagon, inside the six OD trapezoids. The full MINERνA detector will contain 108 modules stacked back to back.

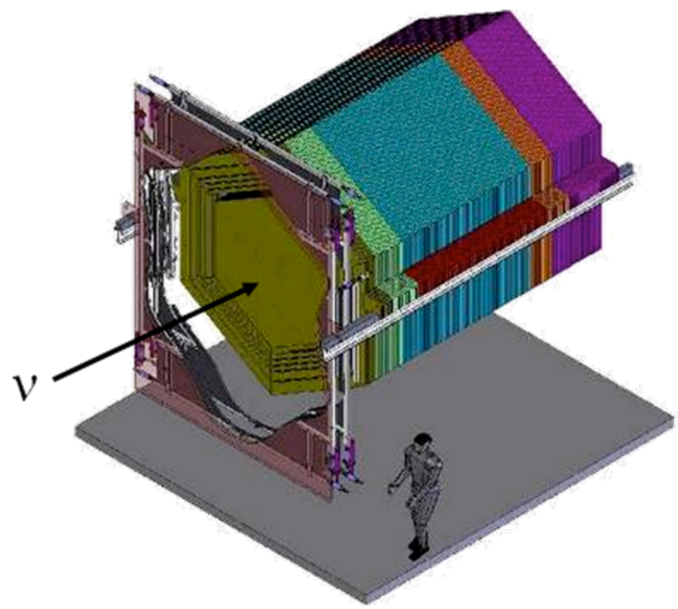

Figure 4: Visual representation of the MINERνA detector, person below for scale.

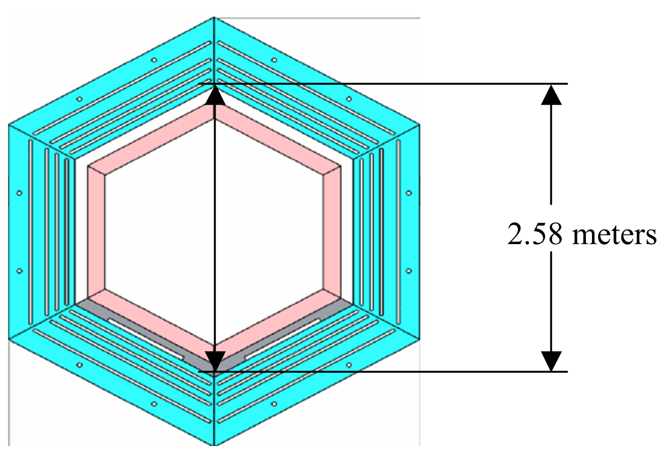

Figure 5: A single MINERνA module, OD in blue and ID in white.

2.1. **Inner Detector**

An ID plane consists of 128 scintillator strips glued between two sheets of Lexan. On either side of the module are PVC side rails, and the weight of each plane is supported by the lower combs. The fibers exit the scintillator on the two top sides of the module and are routed through the upper comb into a black canvex bag and by groups of eight into optical connectors. After the connectors, light is carried through clear optical cables into a multi-pixel photomultiplier tube (PMT). The PMT produces electrons from the incoming photons by way of the photoelectric effect; these electrons are accelerated towards dynodes (charged plates) at increasingly higher voltages. When an electron strikes a dynodes, more low energy electrons are emitted by the process of secondary emission. These electrons, in turn, are accelerated to the next dynode, and finally to an anode, where the accumulation of charge results in an observable current.

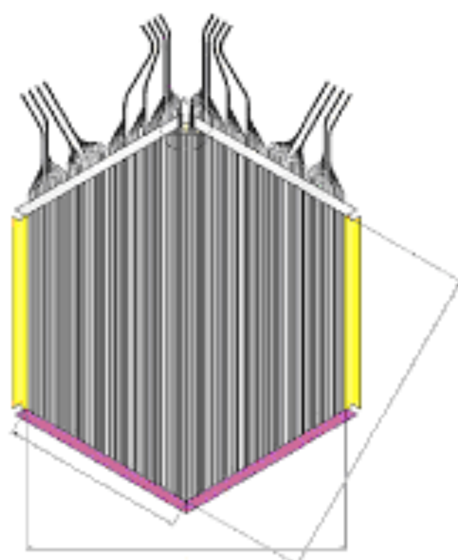

Figure 6: A more detailed look into the ID module. Side rails are yellow, lower combs in magenta. All 127 fibers are routed through the upper combs (pictured white) in pattern shown.

ID modules are built in five phases, each one corresponding roughly to a single day of construction, optimized to allow epoxies to cure overnight. Phase 1 consists of gluing together the planks (1/5th plane sections of scintillator manufactured at Fermilab) with the bottom Lexan skin and the side rails. In Phase 2 the top skin and upper combs (from which the fibers exit the scintillator) are glued into place. Phase 3 sees the baggies (light tight canvex[1] bags) taped into place around the exiting fibers and aluminum support rails attached to the sides. Fibers are inserted into the plane and routed through the upper combs and baggie in Phase 4. Finally, Phase 5 consists of fly cutting the fibers (polishing their ends to improve light transmission), potting (filling the scintillator holes with optical epoxy), fixing them into their connectors and sealing the baggie. Before the planes are shipped to Fermilab, they are tested for light leaks.

2.2. **Outer Detector**

Two pieces of rectangular scintillator are glued together to form a doublet. An optical fiber is routed through each scintillator piece. Four doublets of tapering size are attached to a trapezoidal piece of foam (a temporary backing for shipping and installation). This set of four is referred to as a tower. The eight fibers are then glued into an optical connector, polished and then sealed using a similar bagging procedure as the ID. Each tower is finally tested with a PMT for light leaks. As a part of the module, the outer detector serves as a calorimeter, with doublets of scintillator surrounded by steel to catch particles leaving the detector.

2.3. **Optical System**

The scintillator strips have small holes housing optical fibers with the remainder filled with optical epoxy. Neutrinos interacting in the detector create charged particles within the scintillator, which in turn create photons. These photons bounce around inside the

[1] A black poly-ethylene reinforced material

mirrored scintillator strips until they are absorbed by the fibers and re-radiated as green light. The green light travels down the fiber through the connector and eventually to a photomultiplier tube. From this we can read an electrical current.

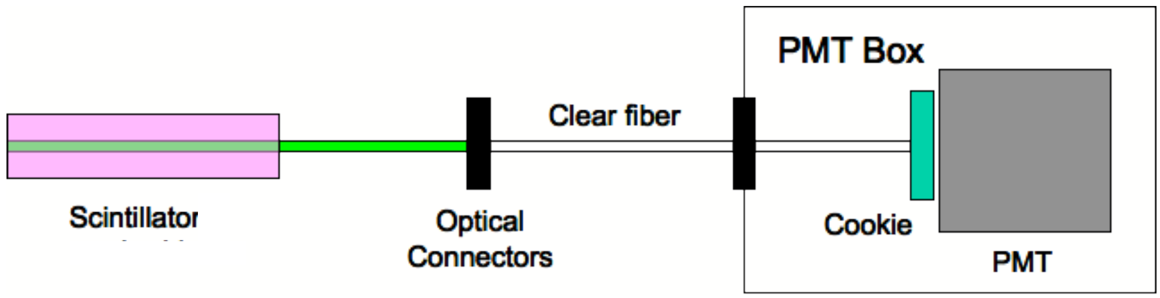

Figure 7: Diagram of the optical system in MINERνA

Light testing is a necessary quality assurance procedure that uses the system shown in Fig. 6. Output of the PMT is measured for every component while exposed to indoor fluorescent light as well as with the lights off. When lights are on the PMT should output no more than 110% of the output when the component is in the dark.[2] This is done so that ambient light within the detector hall does not dominate the readout of MINERνA.

3. OD light tightening

3.1. **Problems with towers**

Unlike planes, towers have a much more complicated topography, and thus a greater potential for leaking light. This problem was not totally anticipated by their designers.[3]

Initial production of outer detector towers in the summer of 2008 yielded systematic light leaks. Doublets leaked substantial amounts (on the order of 10 times the lights off reading) of light along the sides where the two seams of tape met up. Doublets also leaked at the back ends, as well as where they met the baggies.

[2] The 110% is set more or less arbitrarily, it could be higher, but the lower the better
[3] From personal correspondence with Jeff Nelson

3.2. **Retrofitting**

New procedures were developed and documented for the sealing of OD towers. These procedures addressed the following problems. Though a single piece of tape could wrap an entire doublet, leaks at the seam created a need for a second piece along it. A procedure of "gift wrapping" the back side of the doublet was formulated, as well as a method of collaring the front portion. With these procedures output with the lights on reach well within specifications versus lights off:

Before Retrofit		After Retrofit
Lights off	Lights on	Lights on
4.0nA	357.6nA	4.2nA

Table 1: Readouts from Tower H018R, before and after retrofit (in nanoamps)

Along with light tightening, procedures for proper placement of optical connectors and baggie sealing were created. These new procedures were documented and sent to Hampton University, allowing them to modify their fabrication techniques and streamline the entire OD construction process. This document saved a great deal of time for the both universities. (*Retrofit OD Towers* Document in appendix)

4. **Documentation of ID procedures**

4.1. **Goals of documentation**

William & Mary is primarily responsible for inner detector assembly. Procedures for all phases of construction were initially developed at William & Mary and plane construction has only recently begun at Hampton University and Fermilab. Some form of documentation became necessary to quickly educate HU and Fermilab as to the specifics of plane fabrication, as well as to be used as a reference and to educate and train new students joining the project at William & Mary.

4.2. **Overall refinements**

Separate documents for all five phases of ID construction were written and are in a constant state of refinement (see appendices a and b). A column for justification and safety procedures is included on each. This column is used to justify procedures that can seem overly laborious or counter intuitive.

For example, in order to lift planes from the crate when they arrive Fermilab uses a vacuum lifting system locks into the holes in the side rails. They also use an optical system that utilities these same holes for orientation when radiation-source scanning planes. These corners also tend to be problematic for light leaks. To cure these leaks, the holes were being covered with tape by technicians. A new more complicated method was developed to seal the leaks without covering the holes using cutouts in the skins and extra layers of tape in the cutouts. In this instance the right hand column was used to explain how Fermilab need the holes to be clearly visible.

4.3. **Canvex baggie attachment**

A full module consists of two planes of slightly different widths (X and U/V) and one set of towers surrounding. This design allows for only 2mm of extra thickness to each plane. In the fall of 2008, baggies on the U/V planes were routinely violating this, forcing Fermilab to perform time consuming retrofits. Baggies also proved to be chronic sources of light leaks. A new baggie design, with little to no overlap of the top and bottom skins was created. With no overlap the planes stayed within the 2mm tolerance.

Figure 8: Ayana Garcia attaches a baggie in the new style

The new baggies also had new conforming edges to the shape of the plane that were easier to light tight. The process of "darting" baggies was then developed. The lower baggie was cut slightly larger than the upper one. Pieces of the overlapping bottom baggie were folded up and taped with clear packing tape, then with light-tight acrylic tape. This procedure created much tighter baggies and less time was spent light tightening. All was documented in the *Plane Assembly Phase 5* document (appendix b).

Figure 9: "Darting" the baggie

4.4. **Fly cutting**

In order for the fibers to effectively transmit light to the PMT, they must be polished on their connector end. This is accomplished with a diamond-tipped, rotating fly cutter. This is one of the more dangerous parts of plane construction, and required many safety precautions in the right hand column of the procedure document.

After some time polishing, Fermilab noticed some deterioration in the light transmission of William & Mary's planes. It was discovered that the diamonds had experienced significant wear and one had even broken. Now users of the fly cutting jig record how many cuts each ferrule took, so that William & Mary can confer with Fermilab over the wear and quality of polishes versus time. Based on results of transmission tests made at Fermilab[4] we now swap out diamonds after every 4 planes (64 connectors).

4.5. **Travelers**

With the detailed information for every plane or tower, travelers were added. A traveler is a templated checklist for every plane or tower, containing basic procedures that must be completed in order, a spot for initials after every step and information on which scintillator bars it is comprised of. These primarily allow Fermilab to keep track of locations of scintillator so quality assurance measurements can be correlated with the location within the detector. Travelers decrease the possibility that a crucial step will be forgotten (e.g. loading a plane into the crate before light testing), preventing time-costly retrofitting. Travelers also contain information regarding light tightening results and polish depths so Fermilab may have an immediate knowledge of every plane/tower upon

[4] Dummy ferrules were produced every plane and sent to Fermilab for a transmission test using their equipment.

arrival. On each traveler is a small diagram of the plane/tower where locations of light leaks may be noted, so procedures that lead to systematic light leaks (e.g. the corners of the planes and where the doublet meets the baggie on towers) may be modified.

5. Source testing

5.1. **Broken fibers**

It was discovered, through a powerful radioactive source test at Fermilab in Spring 2009 that 20% of the fibers in towers were not transmitting any signal. It became necessary to discover at what point in fabrication or shipping these fibers were being broken. An 18μC Na-22 radioactive source was acquired to test the condition of the fibers post light-tightening. Once towers are light tight, the source is directed at both sides of every doublet, and the reading is marked on the towers traveler. Any dead fibers are noted.

5.2. **Procurement of source**

Initially it was thought that a β source would be ideal for this application, as one would require less shielding and would be able to directly test single fibers without spilling over to others. Both Fermilab and Hampton University source test with Cs-137 (a β and γ emitter). Such sources will penetrate the outer layers of tape easily, and are well suited for scanning entire planes quickly, yet a large cone of radiation is not ideal for isolating single fibers. The first source attempted was a 3.5μC Sr-90 (β emitter), however it was unable to penetrate the tape and very little to no response was seen in the PMT [see Table 2].

The only other suitable source on hand was an 18μC Na-22 source (a β/γ emitter). This source was easily seen by the PMT, giving 15-25% spikes from the dark reading [see Table 3]. The source was clearly able to penetrate layers of tape.

5.3. **OD testing**

The first used of the source was to test towers for broken fibers. Results for the two towers tested are shown below:

Lights on	Lights off		1	2	3	4
19.7	5.3	TOP	5.3	5.4	5.2	5.3
		BOTTOM	5.5	5.2	5.3	5.3
Percentage Increase		TOP	0.0%	1.9%	-1.9%	0.0%
		BOTTOM	3.8%	-1.9%	0.0%	0.0%

Table 2: Results for source testing Tower 97R with a 3.5μC Sr-90 source

Lights on	Lights off		1	2	3	4
19.7	5.3	TOP	6.1	6.6	6.5	6.2
		BOTTOM	6.0	6.7	6.6	6.3
Percentage Increase		TOP	15.1%	24.5%	22.6%	17.0%
		BOTTOM	13.2%	26.4%	24.5%	18.9%

Table 3: Results for source testing Tower 97R with a 18μC Na-22 source

Lights on	Lights off		1	2	3	4
7.5	6.8	TOP	7.9	8.1	8.1	8.5
		BOTTOM	7.6	6.9	8.4	8.1
Percentage Increase		TOP	16.2%	19.1%	19.1%	25.0%
		BOTTOM	11.8%	1.5%	23.5%	19.1%

Table 4: Example of a dead fiber found (2 bottom) Tower 99R Na-22 source

Table 4 shows an instance of a dead fiber in tower 99R. Every fiber shows at least 10% response, except for 1.5% in the bottom of doublet 2 [Table 4]. This fiber was clearly broken during tower manufacture or baggie sealing (or perhaps before, during potting or fibering). Preliminary results (2 towers and 16 fibers in total) with a Na source test show only 6.25% of fibers to be broken before shipping.[5]

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[5] This is only with the extremely preliminary data of two towers, however

To decrease such drastic wear on the fibers during shipping, William & Mary and Hampton University are now etching grooves into the foam directly underneath where the fibers exit the doublet. Plastic strain relief tubing is also being added to the fibers at this point before they are potted. By coordinating source testing at both William & Mary and Fermilab it will be possible to see if the new precautions are working.

5.4. **ID scanning**

The new acquisition of a suitable source allows for scanning of planes before shipping. Scanning is source testing a plane at several points along the surface and modeling its response. Any anomalies can be taken into account when analyzing actual neutrino data. Fermilab currently systematically scans planes with mechanical jig and a 50μC 137Cs source. Though such a thorough scan is impractical in the space available at William & Mary.[6] A rudimentary scan with the Na source will allow for faster feedback regarding, say, any gross damage to fibers within planes or the optical connectors. Thus planes can be retrofit on the spot and procedures can be amended in instances of systematic problems.

The plane was tested at three sites along the surface: Site 1 immediately after the front combs, site 2 in the middle of the plane, and site 3 before the lower combs (Fig. 10).

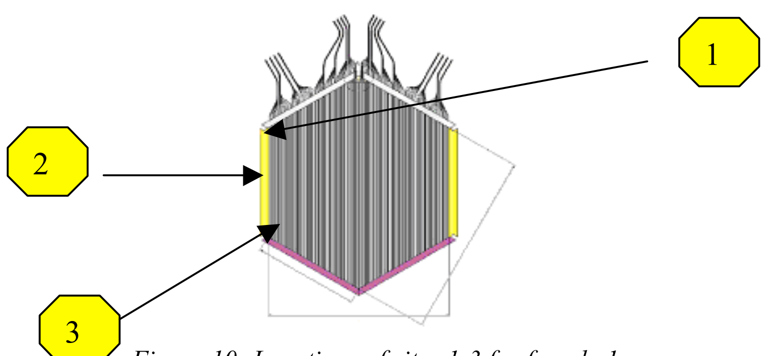

Figure 10: Locations of sites 1-3 for ferrule 1

[6] Lab 3 (where MINERvA is currently being constructed) barely has enough room as is, a full source scanner would occupy at least as much room as an entire plane

Each site was tested a total of five times. Letters *a-e* reflect the source distance from the center of the scintillator bundle connecting to the tested ferrule. Each bundle is 13.52cm from edge to edge. Measurement *a* represents a reading from 6.76 cm to the left (relative to the above drawing) of the edge of the scintillator bundle. Letters *b-e* correspond to rightward movements of the source of 6.76cm, letter *c* being the center of the bundle and *b,d* its let and right edges, respectively. (See figure 11)

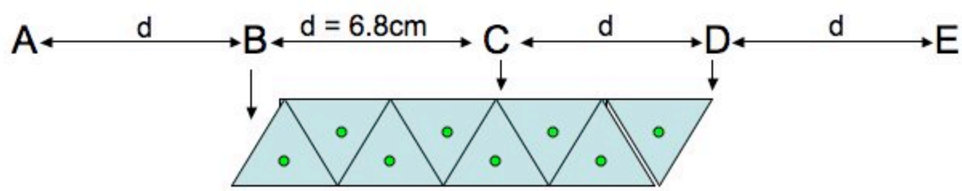

Figure 11: The 5 positions at which each site was tested

Results for this scan are listed in table 5.

Ferrule	Site	Initial	Baggie	Distance				
				a	b	c	d	e
1	1	7.5	8.3	X	10.0	10.1	9.9	8.6
	2				8.5	9.3	10.2	8.8
	3				9.1	9.9	10.4	8.6
2	1	6.0	7.9	8.8	10.6	11.3	10.2	8.8
	2			8.5	9.8	9.7	8.7	7.9
	3			8.5	11.3	11.4	10.6	9.9
3	1	6.6	7.2	7.5	8.6	9.3	8.0	7.4
	2			7.9	8.6	9.8	9.0	8.8
	3			8.4	9.3	9.8	8.5	7.7
4	1	7.6	7.7	8.2	9.8	10.0	9.3	8.8
	2			8.7	9.3	9.3	9.0	8.2
	3			7.6	9.1	9.9	9.5	8.7
Average		6.9	7.8	8.2	9.5	10.0	9.4	8.5

Table 5: Na Source scanning plane W043T (all readings in nA)

Table 5 reflects a one-quarter scan of plane W043T. Initial reading is with the lights off (as are source readings). Baggie reading is with the source on top of the baggie. Site 1 is immediately after the front combs, site 2 is in the middle of the plane, and site three before the lower combs (see Fig. 10).

The source was placed on each site for 20 seconds before the reading was taken in order to allow the source to fully stimulate the scintillator, and removed for the same amount of time between readings to allow the charged particles and photons to dissipate (an entire plane would take some time with this method). Figure 11 shows a plot of the average readings at distances a-e (-13.6cm to 13.6 cm).

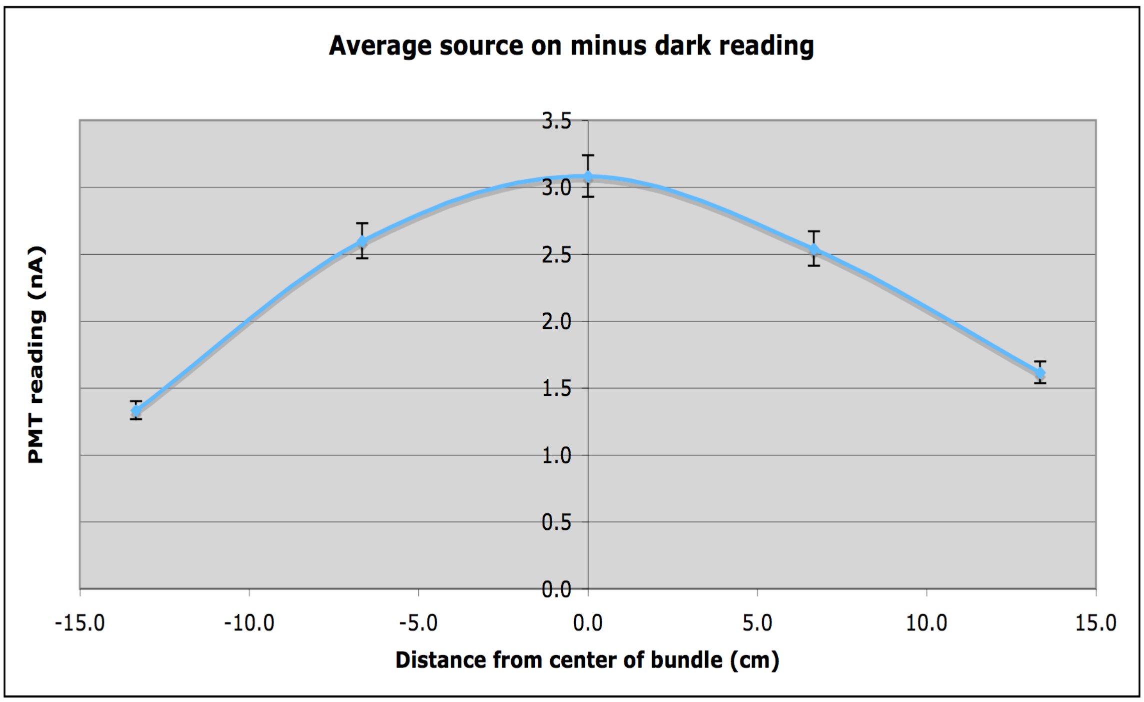

Figure 11: Average readings for each distance a-e

A curve such as the one in Figure 11 is exactly was expected in the testing such planes. The reading should clearly be the highest in the center of the bundle, for the sizeable cone of sodium radiation is exciting many fibers, stay more or less constant towards the edge of the bundle, than fall off rapidly as the tested scintillator strips are no longer irradiated.

Site	Average source on reading	Percentage of lights off
1	9.4	35.44%
2	8.9	29.20%
3	9.2	33.16%

Table 6: Attenuation down the plane

As expected and predicted in Wolthius [1] there is very little attenuation down the length of the scintillator strip. The tested quadrant of plane W043T showed no signs of significant damage.

6. Conclusions

A project as large in scope and geographically distributed as the MINERνA scintillator assembly can experience many problems with coordination and quality control. The nature of its construction using fragile plastic optical fibers can lead to the manufacture of unusable planes/towers if proper attention to detail is not taken. A thorough, clear documentation of all procedures is an essential step to educating other people and institutions on correct plane/tower manufacture. These documents must be constantly maintained as procedures are refined. Safety is always a concern, and annotations in procedure documents are a good way to let new technicians know of safety risks and precautions to take with certain procedures. These procedures can also inform collaborators of the projects' specifications and technical requirements (such as the 2mm tolerance excess thickness tolerance) that may not appear obvious to someone in the trenches of manufacturing.

Source testing will allow for much quicker feedback to the William & Mary group concerning the quality of the MINERνA parts they are manufacturing. Though only recently implemented, source-testing techniques will prevent our group from sending out batches of towers or planes with bad fibers and other issues that should either be retrofitted or scrapped. This will save the collaboration time and money and results in a better detector.

7. References

[1] Wolthius 'Development of Scintillation Counters for the MINERνA Neutrino Detector' Senior Thesis, The College of William & Mary (2007).

[2] Howley 'Assembly Process for Scintillator Planes in the MINERνA Neutrino detctor' Senior Thesis, The College of William & Mary (2007).

[3] Adamson et al. Phys. Rev. D 77, 'A Study of Muon Neutrino Disappearance using the FermiLab Injector Neutrino Beam' (2008).

[4] Longair, M. S. High energy astrophysics. Cambridge: Cambridge UP, 1986.

[5] Perkins, Donald H. Introduction to High Energy Physics. 1st ed. Philippines: Addison-Wesley, 1972. (A basic introduction into neutrino physics and oscillations)

[6] Perkins, Donald H. Introduction to High Energy Physics. 4th ed. Cambridge: Cambridge UP, 2002.

[7] Vahle, Patricia. "MINOS." Neutrino Oscillations: Present Statues and Future Plans (2008): 115-34. Ph D thesis, University of Texas-Austin.

[8] Parke, S. J. "Neutrino Oscillation Phenomenology." Neutrino Oscillations: Present Statues and Future Plans (2008): 1-18. (A more in-depth look into mathematics of neutrino oscillations)

[9] Griffiths, David J. (1987). Introduction to Elementary Particles. Wiley, John & Sons, Inc. ISBN 0-471-60386-4. (Contains a history of famous neutrino experiments)

I would also like to acknowledge Colton O'Connor, Rita Schneider and Ian Howley for their initial fabrication of ID procedure documents.

Purpose: To describe the steps required to prepare the baggies and to attach the bottom baggie, aluminum support rails, and foam

Manpower Required: 3

Action:

1. **Material Requirements**

1.1. Canvex
1.2. Clear plastic baggie templates (lefthand and righthand), for outlines
1.3. Paint pen
1.4. Black tape (Transit-Seal TS50, Americover)
1.5. Scissors
1.6. Fiberglass strips, 26mm x 3mm x 1.22m (= 48")
1.7. Eight 1-1/4" screws
1.8. Handheld electric drill
1.9. Stapler
1.10. PVC top-plane baggie supports
1.11. 80/20 bars
1.12. Clamps
1.13. Zinc blocks
1.14. Paper baggie templates, for connector mount locations
1.15. Pins
1.16. 2-meter stick
1.17. T-square
1.18. Aluminum rails
1.19. Band saw
1.20. Drill press
1.21. File
1.22. Four 10—24 x 2 flat phillips machine screws
1.23. Four 10—24 type "A" wing nuts
1.24. Grip-Rite grip caps
1.25. Clear packaging tape
1.26. 3/4" styrofoam (48"x96" board)
1.27. Plywood templates for foam
1.28. Pen
1.29. Box cutter

2. **Safety Equipment Required**

2.1. Work gloves
2.2. Safety glasses
2.3. Closed toe shoes

3. **Preparation for Phase 3** (2 people, 45 minutes)

3.1. Carefully remove the glue-up bottom combs using the pocket kicker
3.2. Remove the plane from all of the pins
3.2.1. Use the pocket kicker to lift the area surrounding one single pin.
3.2.2. The pins are typically difficult to get out so first trying pulling the pin out using pliers.
3.2.3. If the pin is stuck in the rail or comb, CAREFULLY tap the pin from above until is loosens. Support the area around the pin if this method is required.
3.3. Cover the middle strip of exposed Lexan with the black chemical tape.
3.4. Inspect the plane for welled-up glue.
3.4.1. Using a chisel, dental tools, box cutter, scalpel and ram-rod to clear any excess epoxy from the following areas: (a) the scintillator holes (injection and upper ends - pay particular attention to the plank boundaries); (b) the areas of the side rail that will be glue to the bottom combs in phases 3 (See Figure 1); (c) the top of the plane near the plank boundaries.
3.4.1.1. If, during the injection process, too much epoxy was put into the boundaries it will likely have welled up under the top skin. It may be necessary to cut away large sections of the top skin to access the welled up glue. If this is done, cover the repaired area with black tape.
3.5. Using a thick paint pen, label the plane W****B/T. For example W0002T or W0034B

Figure 1. Area of side rails to inspect

4. **Moving the Plane**
4.1. This point in the plane-making procedure is often the best time to move a plane from the high table to the low table.

4.1.1. As you do this, pause four times – once per plank boundary as that boundary is between the two tables. Apply a long, single strip of TS50 black tape to the underside of the plane along each plank boundary.

4.1.1.1. Use caution: only go underneath a plane that is well supported.

4.1.2. Continue carefully moving the plane until it safely rests on the low table.

5. Preparing the Baggies

5.1. Unroll a large section of the baggie plastic and place one of the baggie templates on it. Trace the outline of the template onto the plastic with a paint pen.

5.2. Cut out the baggie.

5.3. Making efficient use of the Canvex to avoid waste, use the templates to trace three more baggies, so that there are two for the bottom and two for the top prepared.

5.4. Cut out the remaining baggies.

5.5. Roll up the top baggies and store them.

- *We have new baggie templates, make sure to use them.*

6. Attaching the Bottom Baggies

6.1. This process differs depending on whether the plane being constructed is a U/V-plane (bottom plane) or an X-plane (top plane). In either case, follow the instructions to attach one bottom baggie, then repeat to attach the other.

6.2. Position the plane so that the upper edge extends off the table as far as it needs to so that the baggie can be attached without the plane being lifted.

6.3. Position the baggie with respect to the plane. The black side of the baggie should face upward. The baggie must be properly positioned in two dimensions: it can slide along an axis parallel to the upper comb and/or along an axis perpendicular to the upper comb. Use the baggie template as a guide, since it indicates the eventual positions of the connector mounts (which should lie entirely on the baggie) relative to the center and corner pinholes in the plane.

6.3.1. For a U/V- (bottom-) plane, the baggie should completely overlap the upper comb and just barely overlap the scintillator and bottom skin. When using the template to orient and position the baggie, make sure to keep in mind that the baggie will be held flush to the front of the upper comb when it is fully attached.

6.3.2. For an X- (top-) plane, the baggie should only overlap the upper comb by half an inch or less. The TS50 black tape holds better to the comb than to the Lexan skin under the scintillator, so without the extra holding power of screwed-on fiberglass that is used for a U/V-plane, it is best to let the tape be mainly applied to the baggie and comb, not the Lexan.

6.4. With two people holding the baggie firmly in place (one on either side), a third person should get below the plane with TS50 black tape and scissors. Measure out a length of tape to attach the whole edge of the baggie, cut it, and lay it half on the baggie and half on the lexan bottom skin. Smooth the tape outward from the middle, careful to keep it straight and not to produce wrinkles.

6.5. For a U/V- (bottom-) plane:

6.5.1. Drill 1/4” holes in two fiberglass strips (one for each baggie) at locations given in Figure 2.

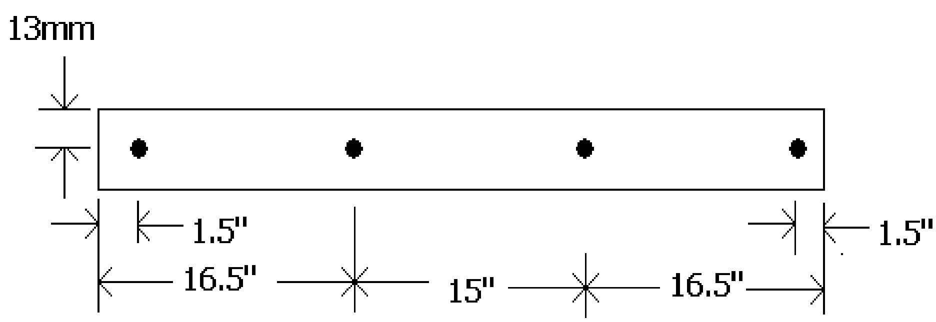

Figure 2. Positions of 1/4" holes in fiberglass strips

6.5.2. Fold the baggie up to hold it flush against the front of the upper comb, tightly wrapped around the corner. Place the strip of fiberglass on the baggie (against the front of the comb) raised 3mm off the table – another fiberglass strip can be placed under it to achieve those 3mm. Use a drill to drive four screws (1-1/4” each) through the holes and into the comb.

6.5.3. Carefully slide the plane back fully onto the table to allow the tape to cure. It may be necessary to provide some lift so that the tape and baggie are not peeled off.

6.5.4. Fold the baggie tightly around the fiberglass. Make as sharp of a crease as possible, using your fingernails or an appropriate tool or piece of metal to score the baggie along this crease. See Figure 3.

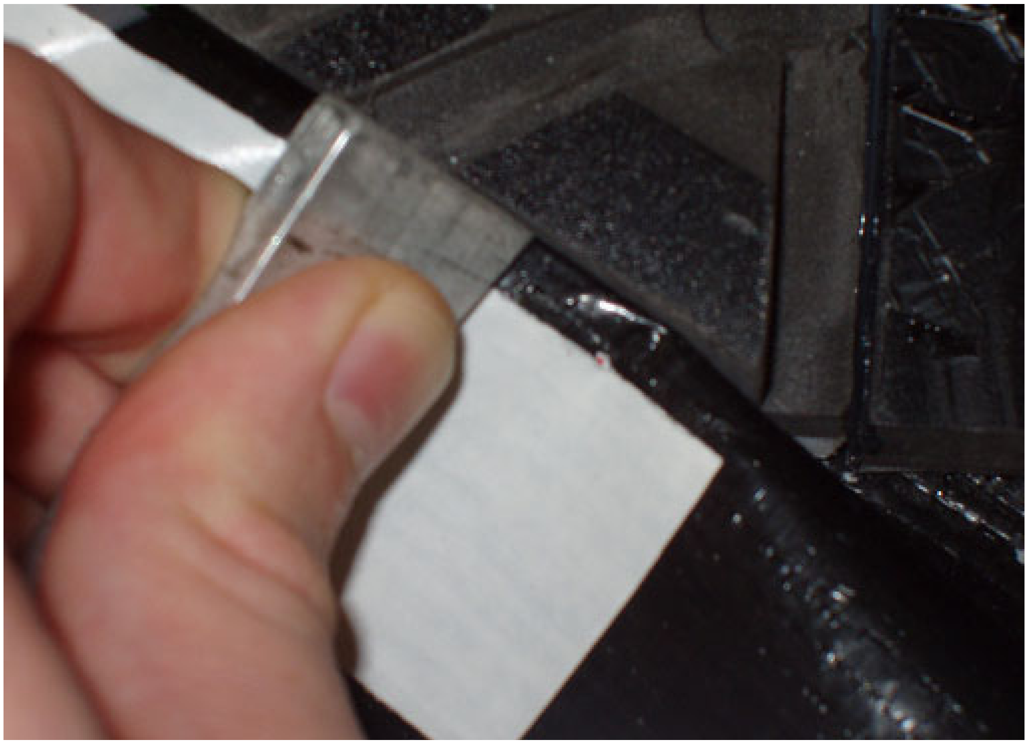

Figure 3. Scoring the crease on the bottom baggie of a U/V-plane

6.6. For an X- (top-) plane:

6.6.1. Fold the baggie up to hold it flush against the upper comb. Use a stapler to staple the baggie to the comb near the top of the comb. Use as many staples as are necessary along the breadth of the baggie.

6.6.2. Carefully slide the plane back fully onto the table. Push the PVC support under the baggie flush against the plane to hold the baggie on as tightly as possible while the tape cures. Additional materials will probably be necessary to hold the support in place, such as a long bar of 80/20 clamped to the table, or a row of zinc blocks.

6.7. Take the fiber routing template and affix it on top of the baggie by using pins to hold the properly marked holes in the template in place on the corresponding holes in the side rail and center comb.

6.7.1. Holding the template flat against the baggie across its entire face, mark the locations of the connector mounts as indicated on the template.

6.7.2. Check that the locations of the two connector mounts on each baggie are collinear using the 2-meter stick.

Z

7. Preparing and Attaching the Aluminum Support Rails

7.1. Using a band saw, cut stock L-shaped aluminum rails to the specifications given in Figure 4. The holes are 1/4” in diameter.

7.1.1. Rather than measuring the exact hole locations from the edges of the piece, hold the piece up against the plane where it will be attached and reach a pen down through the two middle holes in the side rail to mark the locations where holes should be drilled. Make sure to make one left-handed rail and one right-handed rail.

7.2. File the cut edges to remove burs and prevent cuts.

7.3. Use a drill press to put two holes in each rail (see Figure 4). Remember, the left and right rails should be mirror images of each other; they should not be congruent.

7.4. To attach a rail, pull the plane so that the appropriate side hangs a few inches off the table. Align the two holes in the rail with the holes in the middle of the side rail (do not align a hole in the rail with the hole in the upper side corner of the plane).

7.5. Stick a 1-3/4” bolt upward through each hole in the aluminum and through the hole in the side rail, fastening with a nut above the side rail.

7.6. To avoid scratching the table whenever the plane is moved, place a grip cap over the head of each bolt (on the bottom of the rail) and hold it in place with packaging tape.

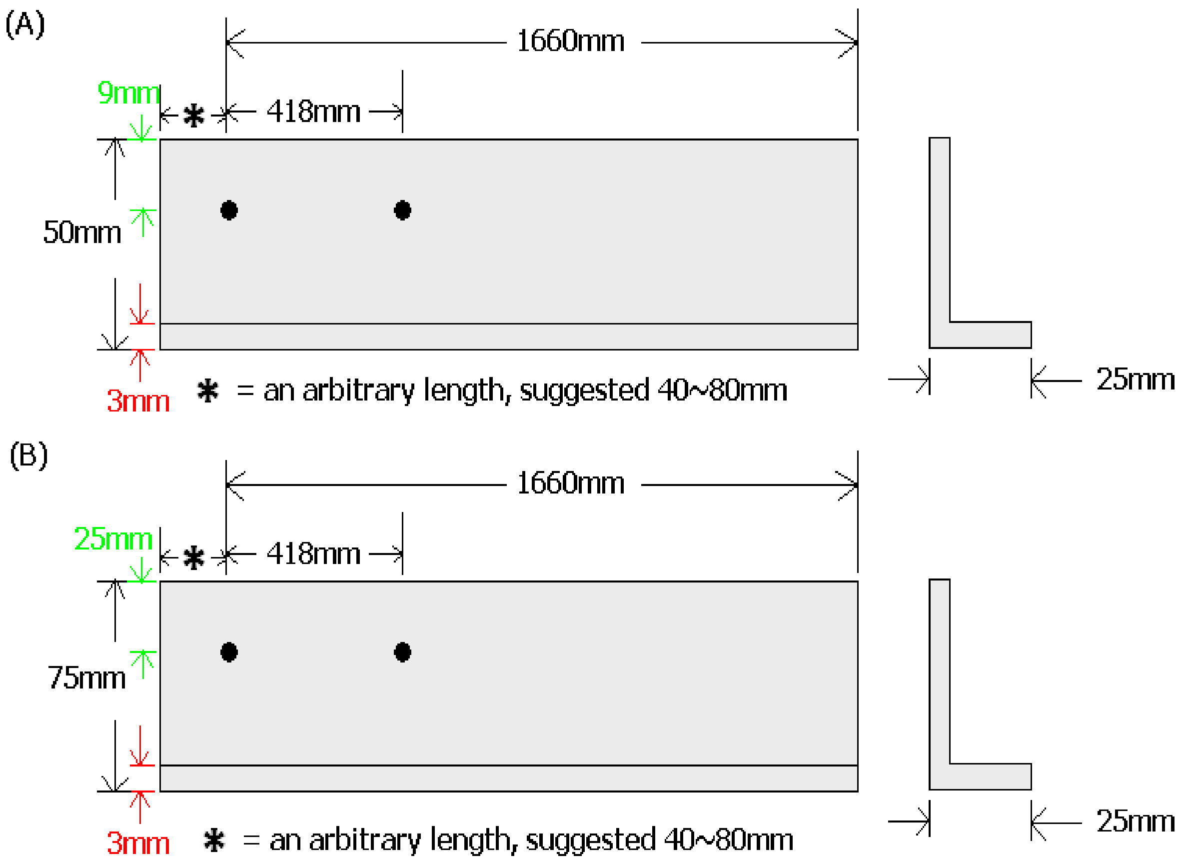

Figure 4: Aluminum support rail dimensions: (A) x-plane, (B) u/v-plane

8. Cutting and Attaching the Foam

8.1. When using box cutters, never pull the blade toward yourself or put your hand in its path.

8.2. Lay out a board of 3/4" styrofoam. Place the plywood template on top and trace its outline onto the foam with a pen. Then slide the template to the right, aligning its left edge with the right edge of the outline, and trace it again. See Figure 4.

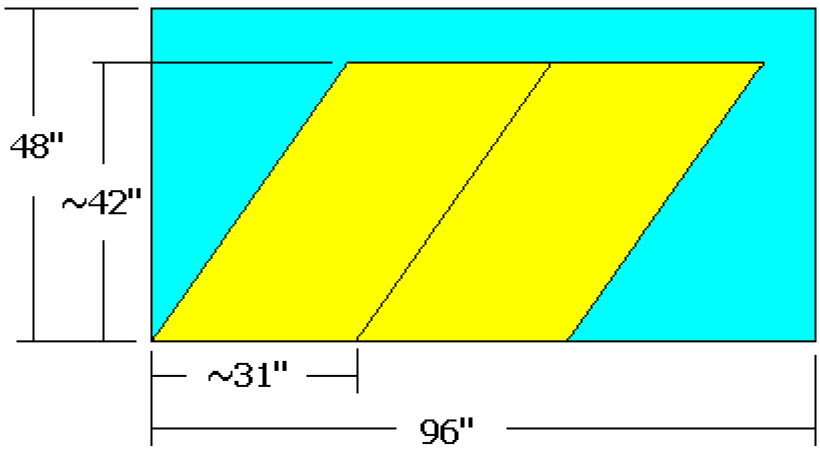

Figure 5. Cutting foam using the template

8.3. Use a box cutter to slit along the outlines, making sure not to cut all the way through the foam in case you damage the floor or table underneath. Snap off the foam, cutting or pulling away the shrink-wrapped plastic on the foam as needed.
8.4. A center support of some kind is necessary so that the foam pieces stay in place when the plane is moved. Three sturdy metal strips may be bolted together in the shape of a capital A, with a bolt passing through the point of the A and the hole in the center comb holding it in place.
8.5. Place the foam supports underneath the baggie, flush to the aluminum support rails.
8.6. Poke holes through the foam near the aluminum support rails. Slip zip-ties through the holes, wrap them around the rails, and secure them to hold the foam in place.

9. Clean Up

9.1. Put away all materials in their proper storage locations. Do not remove the painter's plastic, as it will remain under the plane until the lower combs have been glued on.
9.2. Dust off the band saw and drill press.
9.3. Vacuum the area where the foam was cut.
9.4. After the tape has cured for at least 48 hours, remove any supports used to hold the bottom baggie in place. Other phases of construction may proceed before these supports are removed.

Purpose: To describe the steps required to fly cut the ferrules, glue in the fibers, attach the connector mount and top baggies, and glue on the lower combs, completing the construction of a plane.

Manpower Required: 2

Action:

1. Material Requirements

1.1. Left and right lower combs
1.2. Four connector mounts
1.3. Fly cutting jig
1.4. 5/32” hex-head screwdriver
1.5. Calipers
1.6. Pneumatic gluing machine
1.7. Gray Luer Lock adaptor
1.8. Mixing nozzle ME 08-32
1.9. Nozzle sheath
1.10. Rubber tip sheath, cut at a 60° angle
1.11. Aluminum foil
1.12. Pre-cut top baggies
1.13. Paint pen
1.14. Scissors
1.15. Transit-seal TS50 Americover black tape
1.16. Black electrical tape
1.17. Painter's plastic
1.18. Pocket kicker
1.19. Pneumatic glue gun
1.20. 3M Scotch-Weld Epoxy Adhesive DP-190 Gray (structural adhesive)
1.21. Mixing nozzles ME 08-32
1.22. Box cutter
1.23. Shop air
1.24. Air hose
1.25. Ring clamps
1.26. Screwdriver
1.27. Kim wipes
1.28. Plastic scrapers
1.29. Pins
1.30. Pliers
1.31. Center punch
1.32. Mallet
1.33. Sixteen connector boxes
1.34. Adhesive foam

1.35. Thirty-two Halo-Krome #4-40 X 6/16 button-head cap screws (yellow box)
1.36. RTV rubber, such as GE Silicone II sealant
1.37. Box tops
1.38. Twenty Camcar 8-32 X 1/2 flanged button-head cap screws

2. Safety Equipment Required

2.1. Latex gloves
2.2. Safety glasses
2.3. Closed toe shoes
2.4. Old clothes or aprons

3. Preparation for Phase 5

3.1. Examine the back of the plane, where the lower combs will be attached. Remove any leaked epoxy that has hardened, using a dental tool or scraper. All holes should be covered with scotch tape.
3.2. Clean off the portions of the top and bottom Lexan skins that hang off beyond the scintillator so that they are clean and flat.
3.3. Make sure that there are holes punched in the bottom Lexan skin where the holes of the lower combs will be.

4. Fly Cutting

4.1. Make sure that, whenever the fly cutting jig is in use, the clear plastic shield is in place to protect the user and bystanders from fiber and ferrule debris. Never attempt to slow or stop a spinning part or band by hand; always allow them to come naturally to a stop. Be aware that the jig has two diamond blades on the cutting wheel.
4.2. Once the epoxy holding the ferrules in place has hardened, remove the scotch tape and fiber supports (popsicle sticks).
4.3. Bring the fly cutting jig near the table. Position the plane so that the first ferrule to be polished can easily reach the jig without being bent much.
4.4. Use an air hose to quickly blow out the nest where the ferrule will sit for polishing.
4.5. Insert the first ferrule into its nests (leave the second nest occupied by the dummy ferrule which should already be in the fly cutter). Use a 5/32" hex-head screwdriver to fasten the bar that holds them in place. As you fasten, keep a finger on the back of the ferrule, applying forward pressure so that it doesn't move from the exact location it should occupy, fully forward in the nest. Make sure it is securely held in place, but do not over-tighten the bar.
4.6. Initialize the fly cutting jig.

- *We have found, over the period that we have been using the fly cutter, that polishing one ferrule at a time results in a much better polish.*

4.6.1. Apply the brake on the fly cutting jig's cart by stamping down on the lever between the two front wheels.
4.6.2. Attach the air hose to the wall, release the valve.
4.6.3. Turn the dial back greater than 50 thousandths of an inch using the brass dial behind the cutter itself.
4.6.4. Turn on the air by twisting the green knob to the right of the polisher clockwise.

4.7. Polish fibers.
4.7.1. Start the jig by placing left hand on the cylindrical motor and pulling back and placing more tension on the belt while starting the motor by pushing with right hand on the black pedal on the table. The motor will begin to spin.
4.7.2. Using the brass knob again, set the dial to 20 thousandths.
4.7.3. Flip the switch next to the pedal and wait as the cutter moves from left to right, cutting away the fibers on the installed ferrule.
4.7.4. Wait until the left side of the cutter is well beyond the right side of the ferrule being cut, lift hand from pedal (slowing the motor) dial back to 50 thousandths or higher, and flip the switch back to down position. The cutter will immediately jerk back to the left.
4.7.5. Repeat steps 4.7.1 – 4.7.4, setting the dial initially to 4 thousandths instead of 20.
4.7.6. Wait for the motor to stop spinning. Remove ferrule from nest, measure depth with the micrometer from the back ridge of the ferrule to the ends of the fibers. Micrometer should read 10.60 mm or 0.4173 inches if the fly cutter is properly calibrated. If not, refer to the calibration section.
4.7.7. Reinstall the ferrule into the next, re-repeat steps 4.7.1-4.7.4 now with the dial set to 0.

4.8. Storing the fly cutter
4.8.1. When finished with all fly cutting turn off the air, unplug the cutter and make sure to store the 5/32" hexhead screwdriver and micrometer on the cart with the fly cutter.

(Pictures needed: proper measurement, dial usage)

- *Make sure to wear cover goggles for this procedure and that the plastic, semicircular shield is down, as small pieces of fiber or plastic can fly off of the cutter at high speed.*
- *The left hand is necessary when starting the motor to prevent the belt from falling off.*
- *While watching the cut do not move from behind the fly cutter, this minimizes risk of injury.*

5. Gluing in the Fibers

5.1. When working with 815C and TETA, always wear gloves and safety glasses. Chemical masks may be desired as well. If lightheadedness or headache develops, stop working and take a break to breathe fresh air before returning.
5.2. Refer to **Glue Machine Use** procedure, Step 3.
5.3. Position one person at the back of the plane (near the mirrored ends of the fibers) with the glue machine and another person at the front end to watch

as the glue comes out of the scintillator into the upper combs. Have Kim wipes on hand for leaks, spills, and overflows at either end.

5.4. Insert the tip into the hole in the first scintillator. Although you must punch through the scotch tape that is across the back, be careful! It is important that you not poke the mirrored end of the fiber. Once you have the tip inserted next to the fiber, the rubber sheath should allow you to firmly press the tip into the hole. Begin filling.

5.5. When enough glue has come out into the upper comb to fully cover the aperture of the hole in the scintillator, stop filling. Ideally, that aperture will be covered by glue but glue will not overflow the comb or get onto the baggie.

5.6. Proceed in this fashion, filling each of the 127 scintillator strips with glue. Be particularly careful when filling those nearest to the middle of the plane, as it can be difficult to tell when to stop filling.

5.6.1. If you ever poke the tip of the glue gun directly into a fiber, the fiber will probably pop out a little bit on the far end. Your partner should alert you of this so that you can readjust before pumping in any epoxy. Leaving the tip up against the fiber will damage the fiber and dramatically slow down the filling process.

5.6.1.1. For this reason, if a strip is taking much longer than usual to fill, try readjusting the glue gun tip. However, it may be due to blockages partway down the hole. If this is the case, continue filling as long as there is not excessive or unstoppable leakage flowing back out at you.

5.6.2. The person who is watching for glue at the top of the plane should keep a gentle hand on the fiber currently being epoxied just where it exits the scintillator at the upper comb. Otherwise, pressure from the incoming epoxy can cause the fiber to gradually pop further and further out, often forcing it to bend in damaging ways.

5.6.2.1. If a fiber is gradually being pushed out the top of the plane in this way, it can be gently and slowly pushed back down even while the glue gun continues to pump epoxy into the hole.

5.6.3. Every once in a while (at least every 16 strips), apply a new layer of scotch tape over the holes that have been punched for gluing.

5.6.4. If fibers are popping out of their slots in the comb and actually lie above the edges of their respective slots, they should be held down while the glue hardens. An opposite-handed comb can be placed upside-down on top of a comb full of fibers, slightly offset so that each groove in one comb lines up with an anti-groove in the other. Alternatively, a light strip of plastic can be placed across the fibers where they are popping out of the upper comb, with large nuts placed on top of the plastic to hold everything down in place. Be careful not to get glue on the upside-down comb or plastic strip.

5.7. Once you are done, refer to **Glue Machine Use** procedure, Steps 4 and 5.

5.8. Before leaving the back of the plane, look carefully at each fiber's mirrored end. Write down the number of each fiber that has a chipped mirror. (Recall that the rightmost fiber, viewed from the bottom comb end of the plane, is number 1, and the leftmost is number 127.) This defect results from poking the fiber with the glue gun.

6. Attaching the Mounts and Top Baggies

6.1. Wrap adhesive foam around the base of each connector box.

6.1.1. The adhesive foam comes on a roll 1” wide. Cut a 6cm strip, then cut it in half lengthwise (to get two 6cm x 1/2” strips). Line up the pure edge of each strip, i.e., the one you did not just cut, with the bottom of a connector box and wrap the foam around.

6.2. For each group of fibers, slide the clip all the way up to the ferrule and snap the two together. Clip on a connector box.

6.2.1. Test that the ferrules were fly cut properly by using the “long” (10.5mm) and “short” (10.4mm) test clips. Each test clip looks like the last 10in of a PMT's input clip and has the length of the ferrule written on it. If either test clip cannot properly fit into any connector box, the ferrule inside that connector box was not fly cut properly. If possible, remove that connector box and adjust the ferrule and/or fly cut it again.

6.3. Press each connector box firmly into place in the mount, such that the back of the clip is flush against the back of the cut-out area of the mount.

6.4. Push the small button-head cap screws through the two holes in each connector box, pushing through the adhesive foam as necessary. Screw them into place using a 1/16” Allen wrench.

6.4.1. Use scissors to trim away excess foam so that it wraps fully around the connector boxes but does not overlap itself.

6.4.2. Using a single piece of electrical tape, cover the holes on the faces of all of the clips. Extend the tape past the last clip on either side. Try to have the front edge of the tape just over the front edge of the clips and slightly onto the ferrules. See Figure 1.

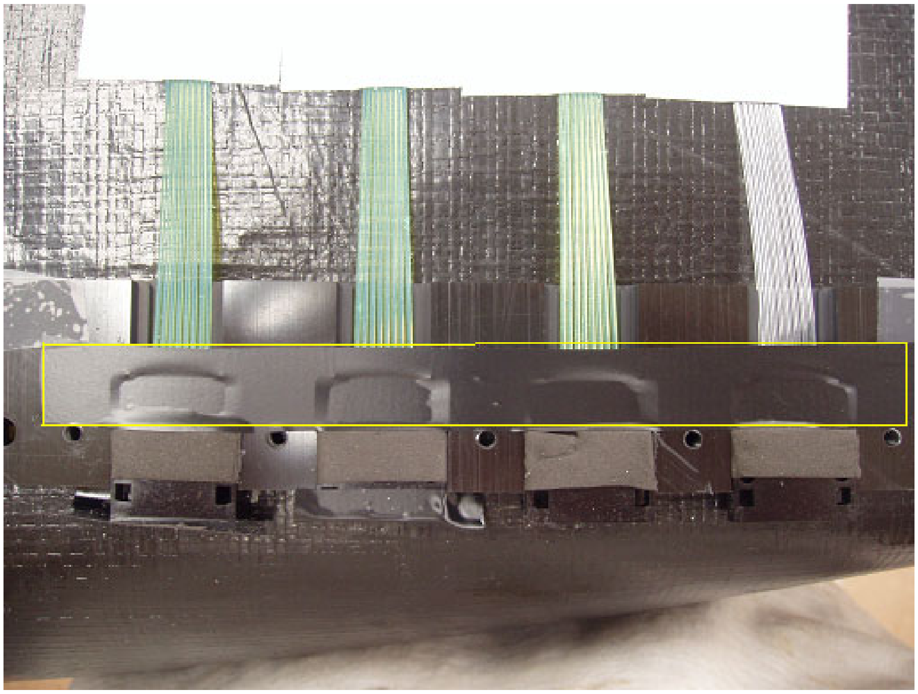

Figure 1. The yellow outline shows the location of the strip of tape across the holes in the clips

6.5. Using a Q-tip, spread some RTV (room-temperature vulcanizing) rubber in a line between each connector. See Figure 2.

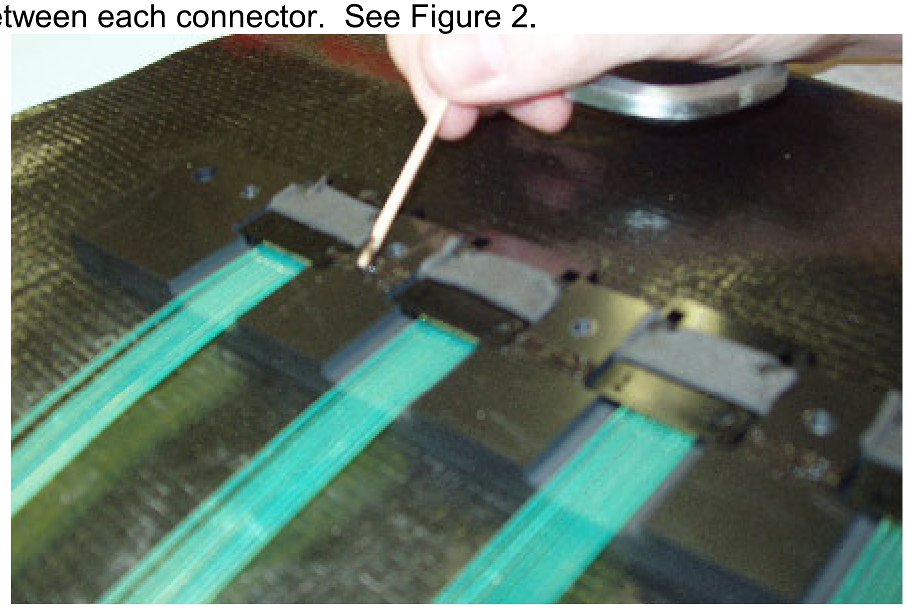

Figure 2. Spreading RTV rubber on a full box

6.6. Put on the mount tops, screwing them into place with the large button-head cap screws. There should be five holes for the screws in each box.

6.7. Repeat this procedure for each mount:

6.7.1. Place the mount in its proper location, given by the dots on the bottom baggie that line up with the holes in the mount.

6.7.2. Trace the outline of the mount, or at least of its lower corners, in paint pen on the bottom baggie.

6.7.3. Remove the mount. Trim the baggie so that its furthest extent from the plane is a straight line (parallel to the plane) that will overlap the mount by about 1cm. It is crucial that the baggie will partially overlap the mount, but will not overlap the holes in the box.

6.7.4. Hold the mount and baggie so that the mount lines up with the outline of its bottom corners. Apply electrical tape to the bottom of the mount and baggie, then cover it with TS50 black tape that overlaps the mount as much as possible without covering the holes. The TS50 black tape should cover at least a 2cm width of baggie.

6.8. Lay the top baggies over the fibers. The white side of the top baggies should face upward. Line the top baggies up with the bottom baggies, making sure that they extend far enough toward the plane to overlap the scintillator by a centimeter or two.

6.9. Apply TS50 black tape to the top baggies and the plane where the two overlap. Use one long strip per baggie, with half of the tape's width on the baggie and the other half on the top Lexan skin of the plane.

6.10. Trim the top baggies in the same way the bottom baggies were just trimmed so that they also overlap the box by about a centimeter. If it is necessary to trim the baggies further in other places so that the top and bottom ones have roughly the same outline, do so, but not much.

6.11. Apply TS50 black tape to the top baggies and the mounts in exactly the same way as was done with the bottom baggies. Most of the tape's width should be on the baggie, but as much as possible should be on the mount without even partially covering the holes.

6.12. Proceed to seal the entire perimeter of the baggies. Use as many strips of TS50 black tape as are necessary, overlapping half the width on one baggie and folding over to wrap the tape around to the outside of the other baggie (See figure 3). A total light-tight seal is needed.

Figure 3. Proper cutting and folding for baggie sealing (before chem. tape)

6.12.1. Make sure especially to use enough tape to form a seal where the baggies meet the plane and around the mounts.

6.12.2. Black electrical tape may be useful, especially for corners. Whenever electrical tape is used, hold down both ends of it with TS50 black tape, which (after curing) is far less likely to peel back.

6.13. On the front face of the outermost connector mount on each side of the plane, write the plane's number in bright paint pen. See Figure 4. Also make sure that the plane's number is clearly written in large, bright lettering on the top skin.

Figure 4. Where to write the plane's number

7. Light Tightness Testing

7.1. Light tightness testing may be conducted either at this point or (preferably) after Step 5.
7.2. Refer to **Plane Assembly Light Tightness Testing** procedure.

8. Gluing the Lower Combs

***NOTE: THE CURING TIME FOR THE STRUCTURAL ADHESIVE IS 90 MINUTES – STEP 8.4 MUST BE COMPLETED WITHIN THIS TIME**

8.1. When working with the pneumatic glue gun, always wear gloves and safety glasses. Chemical masks may be desired as well. If lightheadedness or headache develops, stop working and take a break to breathe fresh air before returning.
8.2. Assemble the glue guns with new glue cartridges and mixing nozzles:
- 8.2.1. Attach the air hose to the wall and to the gun using ring clamps to be sure the connection is tight.
- 8.2.2. Remove the collar from the glue pack.
- 8.2.3. Attach the mixing nozzle to the end of the glue cartridge.
- 8.2.4. Replace the plastic collar.
- 8.2.5. Insert the cartridge into the pneumatic glue gun.
- 8.2.6. Using a box cutter, cut the end of the mixing nozzle to the second ridge on the tip.

8.3. Prepare the skin, scintillator, and lower combs:
- 8.3.1. Inspect each part for bits of material that could cause imperfections in the flatness of the plane or that could damage the Lexan
- 8.3.2. Wipe any dust or dirt from each piece using a damp Kim wipe and compressed air.
- 8.3.3. Lay down painter's plastic under and around the bottom Lexan skin that extends from the back of the plane. It may be necessary to lift the plane slightly with a pocket kicker to get plastic underneath it.
- 8.3.4. Remove as much scotch tape as is easily possible from the back holes of the scintillator. Use a scalpel or dental tool (or, if the fibers were glued earlier on this same day, a Kim wipe) to remove any hardened pools of epoxy from near the holes.
- 8.3.5. Insert pins through the Lexan and plastic into the holes in the assembly table where the holes of the lower combs will go.

8.4. Using the cut-tipped mixing nozzle, dispense gray epoxy in a tight squiqqle pattern onto the bottom skin that extends beyond the plane. Also place a bead of epoxy at the lower scintillator/Lexan boundary at the back of the plane, and put a little bit of epoxy on the vertical faces of the side rails that will attach to the lower combs.

8.4.1. Using plastic scrapers, spread the glue evenly across the visible portion of the bottom skin. Do not spread the bead along the scintillator/Lexan boundary. Do spread the small amount of glue that is on the side rail evenly across that face.

8.4.2. One at a time, carefully lay the lower combs into position.

8.4.2.1. Make sure that each lower comb is on top of the bottom skin, under the top skin, pressed firmly against the side rail (and the other lower comb), and pressed firmly against the scintillator. This should be achieved simply by making sure that each pin in the assembly table finds its way into the associated hole in the lower comb. Use a mallet to ensure that the comb goes down all the way onto the pins.

8.5. Hold the lower combs in place as necessary. The pins may provide all the fixture that is needed. It may be desirable to additionally clamp a bar of 80/20 into place along the outside of the lower comb, pressing it firmly into the plane while the epoxy hardens. Be careful if zinc blocks are used , as they could damage the many small arms of the lower comb if they rest on top of it.

8.6. Once the epoxy has hardened, remove the painter's plastic. Be very careful, as this may involve lifting the back of the plane slightly.

8.7. Be even more careful in removing the pins from the lower combs. This will require lifting the plane somewhat and retrieving the pins from either the table (using pliers) or the lower comb (using either pliers or a mallet and center punch).

8.8. Slide the plane off the back of the table so that the lower combs extend fully off the table.

8.9. Apply long strips of TS50 black tape to each lower comb and each side rail, leaving uncovered the holes in the side rails.

8.9.1. First, overlap one strip of tape slightly with the bottom Lexan skin. Wrap it around the lower comb, smoothing it with fingers or with a plastic scraper, avoiding any wrinkles in the tape. Make sure the pin holes are covered.

8.9.2. Next, overlap one strip of tape slightly with the top Lexan skin. Wrap it around the lower comb in the same fashion. Make sure the pin holes are covered.

8.9.3. Use however much TS50 black tape and black electrical tape are necessary to fully seal the lower combs, at the corners of the plane and at any other gaps.

8.9.4. Continue applying TS50 black tape, now to the side rails, to completely wrap them except for the pin holes. Do overlap the tape with both the top and bottom skins. Do not occlude any of the four holes in each side rail.

8.9.5. Wherever electrical tape is used, cover both ends of it with TS50 black tape.

8.9.6. Avoid any hanging flaps of tape, however small. Creative folding can help prevent these flaps at corners, but slitting them off and covering the slit with more tape is also an option.

8.10. If light tightness testing was not conducted earlier, proceed to that step now.

8.10.1. Refer to **Plane Assembly Light Tightness Testing** procedure.

9. Clean Up

9.1. Put away all materials in their proper storage locations. When the plane is moved, or when it is convenient, the painter's plastic may now be removed from beneath it.

9.2. Allow the nozzle to dry while still on the cartridge. Place it on its side to prevent back flow into the chamber. Break of the dried nozzle later and replace with a cap.

9.3. Never dispose of any materials (e.g., the nozzle and tip) containing or covered in epoxy until it has fully hardened.

9.3.1. If any cups were filled with hardener and resin to prime the glue machine, do not dispose of them until the contents have fully hardened. Until then, put them in a safe place like on aluminum foil in a chemical hood as the contents will heat as they harden, possibly melting the cup.

9.4. Wash hands thoroughly.

Purpose: To describe the steps required for preliminary light-tightening of OD towers that were not properly constructed.

Manpower Required: 2

Refers To:

Action:

1. **Material Requirements**
    1.1. Black chemical tape
    1.2. Black electrical tape
    1.3. 2 pairs of scissors
    1.4. Carpet tape
    1.5. Red Marker
    1.6. OD ferrule placement template
    1.7. 1 ferrule
    1.8. 1 ferrule box

2. **Safety Equipment Required**

    2.1. Work gloves
    2.2. Safety glasses
    2.3. Closed Toe Shoes
    2.4. Clothes that can get gluey
    2.5. Exhaust system for vacuum pump

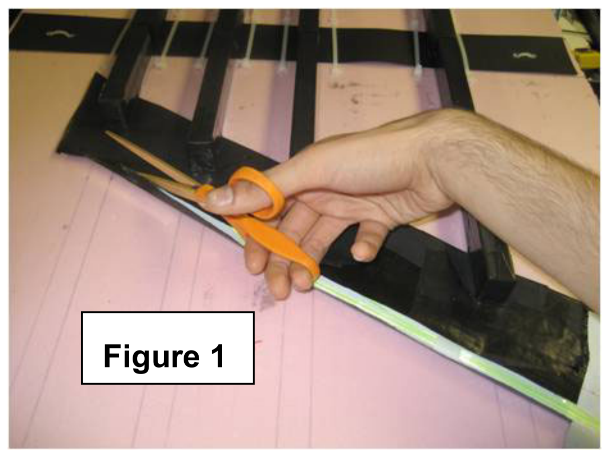

Figure 1

3. **Fix baggie and place ferrule** (1 person, 15 minutes)

    3.1. Open baggie
        3.1.1. Remove and cut tape near first beam, cut baggie lengthwise until near final beam (make sure not to cut fibers!) [Figure 1]
    3.2. Re-position fibers
        3.2.1. Remove pieces of paper and tape currently holding down fibers.
        3.2.2. Tape fibers down using carpet tape. Make sure subsequent fibers joining the path to the ferrule end up on the inside (near the tower), and fibers do not bend with a radius smaller than 2.5”. (This can be accomplished by allowing the two new fibers to cross the path of the rest of the fibers, then come back across to the inside.)
    3.3. Mark ferrule placement
        3.3.1. Place the longest doublet through the square hole in the plastic template.

3.3.2. With a marker, create marks on the baggie through the small holes in the template. [Figure 2]

3.3.3. Place one ferrule inside a box (numbers upwards on both components).

3.3.4. Slide onto fibers, ferrule first, until marks on baggie line up with holes in box.

3.3.5. Use marker to mark fibers at the back of the ferrule.

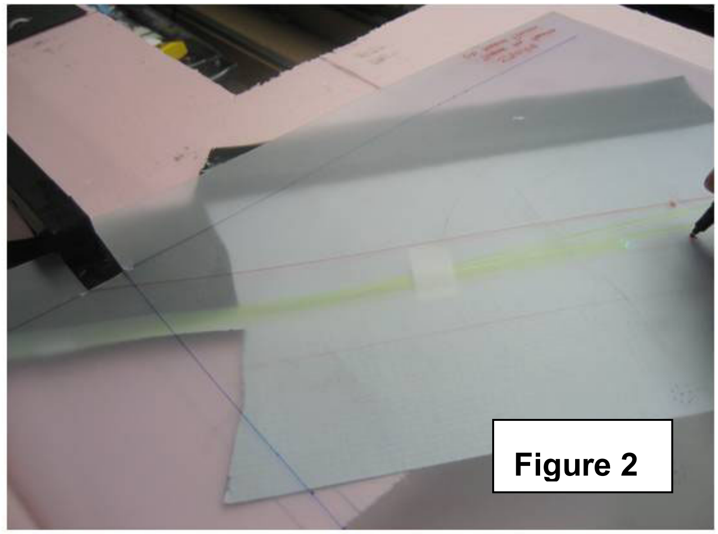
Figure 2

4. **Retrofit sides** (1-2 people, 20 minutes)

4.1. Find seams along the sides of taped scintillator.

4.1.1. Each beam will have one seam along the entire side; the previously applied tape will overlap itself no more than 2 cm.

4.2. Prepare chemical tape.

4.2.1. Cut a piece of chemical tape as long as the distance between two lexan attachments, small overlap is acceptable.

4.2.2. Cut tape into four pieces lengthwise.

4.3. Apply tape to seam.

4.3.1. Repeat procedure for other doublets until all seams are covered .

5. **Seal doublet ends** (1 person, 20 minutes)

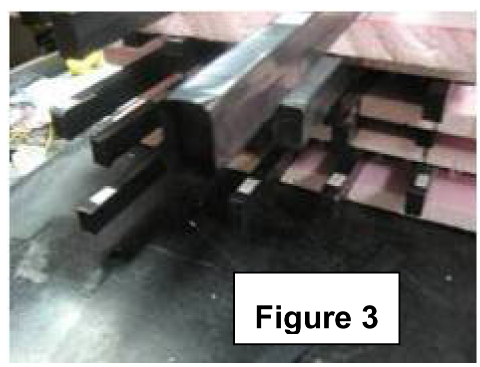
Figure 3

5.1. Cut a piece of chemical tape ~5 cm width.

5.2. Move serial number if it could be potentially covered by tape.

5.3. Tape around the end of the doublet, sealing tightly with no wrinkles, allowing ~.5 cm to hang off the edge. [Figure 3]

5.4. “Christmas wrap” ends by pressing down firmly on top and bottom tabs, then left and right. [Figure 4]

5.5. Cut a square of chemical tape the size of a cross section of a doublet (2 cm x 3 cm) and completely cover the end. (A template is recommended if many are to be made)

5.6. Apply a piece of electrical tape to the seam of the chemical tape, tape all the way around once without stretching (stretched electrical tape peels back). [Figure 5]

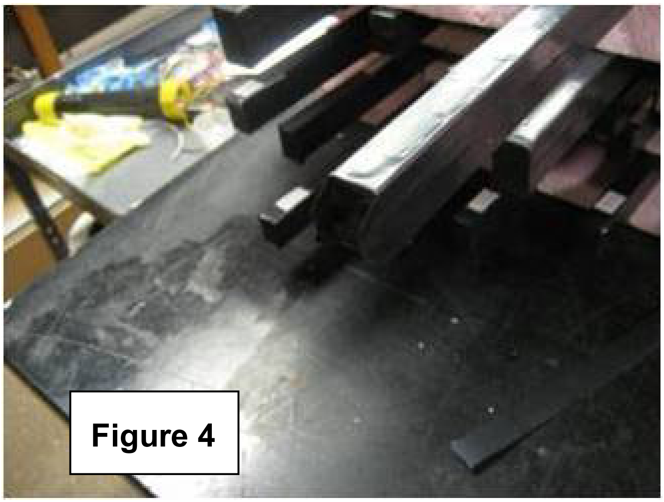

Figure 4

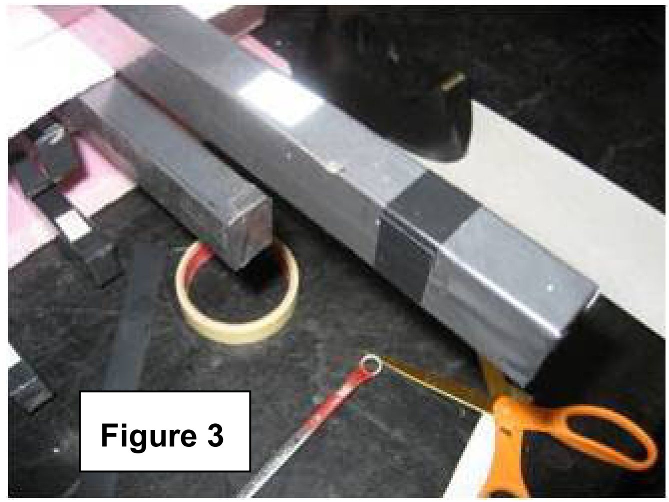

Figure 3

6. **Seal doublet fronts** (1 person, 30 minutes)

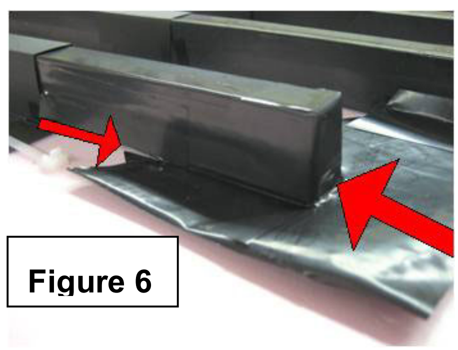

Figure 6

6.1. Cover front, back lip with electrical tape, wrapping slightly around the sides, stretching OK. [Figure 6]

6.2. Create a collar for the doublet [Figures 7-9]

6.2.1. Cut a piece of chemical tape ~5 cm in width.

6.2.2. Cut a slit up the middle to 3 cm from the end.

6.2.3. Cut two, 1 cm diagonal slits at a 45 degree angle upwards from the initial slit

6.2.4. Fold back the three tabs such that the resulting piece will fit on the OD like a collar.

6.2.5. Place collar on doublet, cut away unneeded tape (any that does not lie baggie)

6.3. Apply collar to doublet

6.3.1. Cut away the backing on only a portion of the collar, tape it in the proper position, then remove the remaining backing and tape remainder.

Figure 7

Figure 8

Figure 9