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## EXTRUDED PLASTIC SCINTILLATOR FOR THE MINOS CALORIMETERS

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### ABSTRACT

MINOS is a long-baseline, neutrino-oscillation experiment. Two iron- and scintillator-calorimeters will be built, requiring almost 300 tons of finished plastic scintillator. In order to lower the scintillator costs, MINOS will use an

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extruded rectangular scintillator strip with a groove for a wavelength-shifting fiber readout. This scintillator has a co-extruded titanium dioxide coating as a reflector. This paper presents the scintillator characteristics and describes the extrusion and quality control procedures.

## 1 Introduction

MINOS (Main Injector Neutrino Oscillation Search) is a long-baseline, neutrino oscillation experiment. It will consist of two large iron and plastic scintillator calorimeters. The near detector is located on the Fermilab site. The far detector is situated 735 km away, 710 m below the surface, in the Soudan mine in northern Minnesota. These two detectors are large iron and plastic scintillator calorimeters. Table 1 lists some of the experimental parameters of these detectors <sup>1)</sup>.

Table 1: *Detector parameters of the MINOS experiment.*

| Parameter                           | Value                                       |
|-------------------------------------|---|
| Near detector mass                  | 980 (metric) tons                           |
| Far detector mass                   | 5400 (metric) tons                          |
| Steel plates (far detector)         | 8-m wide, 2.54-cm thick octagons            |
| Magnetic field (far detector)       | Toroidal, 1.5 T at 2 m radius               |
| Active detector planes              | Extruded polystyrene scintillator           |
| Extruded scintillator strips        | 4.1-cm wide, 1-cm thick, $\approx$ 8-m long |
| Scintillator planes (far detector)  | 484 planes                                  |
| Scintillator planes (near detector) | 160 planes                                  |
| Scintillator strips                 | 105,216 strips in total                     |

The MINOS detectors need a total of 28,000 m<sup>2</sup> (almost 300 tons) of finished plastic scintillator. Commercially-available, cast scintillator is too expensive for such a large experiment. An experimental program at Fermilab carried over the last few years developed extruded plastic scintillator using industrial-grade polystyrene pellets <sup>2, 3)</sup>. The MINOS experiment focussed in developing an extruded scintillator with a co-extruded reflective coating, and in optimizing the manufacturing process for higher light yield and lower costs.

## 2 MINOS Scintillator

Extruded plastic scintillator was considered in order to lower the costs of the detectors. The disadvantage over cast plastic scintillator was that extruded scintillator had poorer optical quality since standard commercial polystyrene pellets are used and the presence of additives and particulate matter in the pellets cannot be controlled. The green wavelength-shifting (WLS) fiber used to readout the scintillator minimizes the effects of the lower attenuation length of the scintillator. The WLS fiber converts the light locally and transports it with a much longer attenuation length.

The profile of the MINOS scintillator strip is shown in fig.1. It has a rectangular cross section of 41 mm wide and 10 mm thick. There is a 2 mm deep groove in the top surface for the 1.2-mm WLS fiber. With the exception of the groove, the scintillator is covered with a co-extruded, reflective cap. This coating is 0.25 mm thick and contains 15% (by weight)  $\text{TiO}_2$  in polystyrene. The WLS fibers are glued into the groove of the scintillator strip and then coupled to clear fibers that go to Hamamatsu multipixel photomultiplier tubes (PMT). In most cases, both ends of the fibers are read out with 8-fold multiplexing.

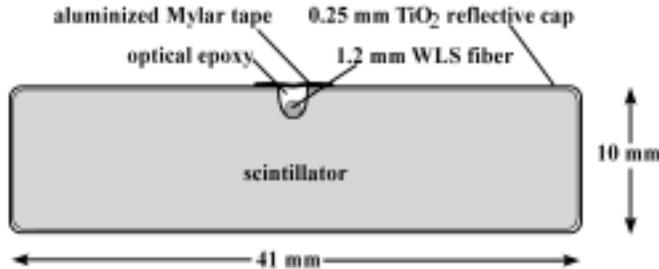


Figure 1: *Profile of scintillator strip.*

The MINOS scintillator uses Dow STYRON 663 polystyrene pellets. The primary dopant is PPO (2,5-diphenyloxazole) which is used in a concentration of 1% by weight. The secondary dopant is POPOP (1,4-bis(5-phenyloxazol-2-yl)benzene) and is used in a concentration of 0.03% by weight. These materials were chosen for their spectroscopic properties as well as their relatively afford-

able prices. The final scintillator costs approximately \$9/kg as compared to about \$40/kg for cast material available on the market. The extruded scintillator also has further advantages in labor savings over cast material. The extruded strips can be directly epoxied into aluminum panels because of the tough outer TiO<sub>2</sub> coating. This simplifies handling and fabrication of scintillator planes. These aluminum panels are built into boxes (called modules) that provide light tightness and strength.

2.1 Characteristics

The MINOS scintillator strips show strong absorption at wavelengths shorter than 400 nm. The maximum emission is at 420 nm with a tail extending to longer wavelengths. Most of the light produced in the scintillator is collected by a wavelength-shifting fiber within 2-3 cm. The distance is relatively short because of reflection losses and bulk absorption. The average number of photoelectrons from a scintillator module is shown in fig. 2 as a function of position along the strips. This module consists of 20 scintillator strips, 8 m long.

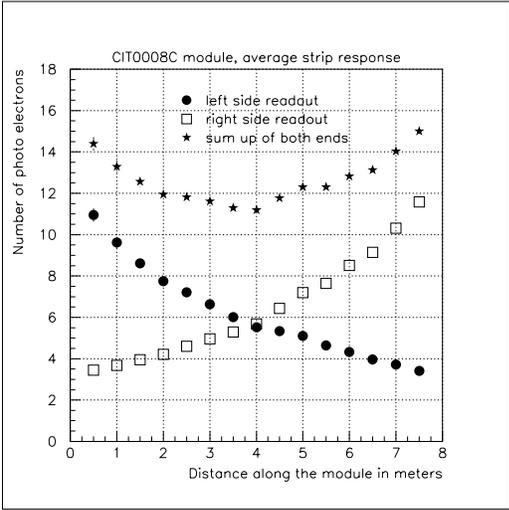


Figure 2: Number of photoelectrons as a function of position along the module.

On the average, green wavelength-shifting (WLS) fibers extend an addi-

tional 1 m from each strip-end along manifolds to an optical connector. There, the WLS fibers are coupled to 2-m long clear fibers. The attenuation lengths of the 1.2 mm diameter WLS and clear fibers used for readout are 5-6 m and 11-12 m, respectively. For this module, the average number of photoelectrons (pe) for a cosmic ray in the middle of the strip is 11 (both ends summed). These measurement typically ranges between 9 and 14 pe. For single-sided readout, a minimum ionizing particle through the near end of the module yields about 11 pe while yielding about 3 pe when measured from the far end.

### 3 Extrusion of the Scintillator

A schematic view of the extrusion process is shown in fig. 3. The extrusion of the MINOS scintillator entails first the preparation of the materials for the core and the capstock of the strips. The raw materials are then fed to the extruder and co-extruder and the strips produced. The last step is a series of quality control (QC) tests.

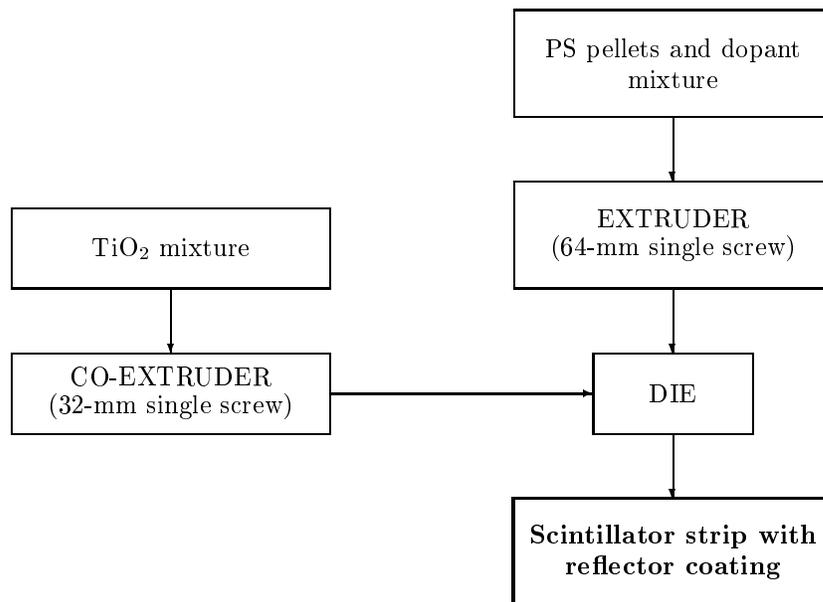


Figure 3: Extrusion process.

### 3.1 Preparation of material

The key to producing high quality scintillator is to remove the water and the oxygen from the raw materials (polystyrene pellets and dopants). Oxygen in the hot environment of the extruder causes degradation of the polymer. This oxidation is observed as a discoloration of the plastic matrix due to an increased absorption. As a result, the light output of the scintillator is greatly reduced. The polystyrene pellets are dried for at least 4 hours at 77 °C. After the dryer, the pellets are placed in plastic-lined steel drums for 4 hours under a nitrogen purge. Then the dopants are added to warm polystyrene pellets. The mixture is prepared in 45-kg batches by tumbling pre-measured dopants with the pellets for 15 minutes under a nitrogen purge. This mixture is returned to plastic-lined steel drums and purged with nitrogen for at least an additional 4 hours. The dopant/polystyrene mixture is manually fed to the extruder hopper which is also kept under a nitrogen purge.

The hopper of the co-extruder is filled with a mixture of plain polystyrene pellets and TiO<sub>2</sub>-doped polystyrene pellets. This mixture yields a reflective coating with 15% TiO<sub>2</sub> by weight. The hopper of the co-extruder is also kept under a nitrogen purge. However, this mixture is not dried and purged before it is loaded into the hopper as the scintillator mixture is. The TiO<sub>2</sub>-doped polystyrene is prepared in a compounding factory (color company) as polystyrene pellets containing a high TiO<sub>2</sub> concentration.

### 3.2 Extrusion

Two extruders are used to produce these scintillator strips. The main extruder has a 64-mm diameter single screw. Its function is to melt, mix and deliver the scintillator core material to the profile die. The co-extruder has a 32-mm diameter single screw and is attached at 90 degrees to the profile die. This co-extruder processes and injects the TiO<sub>2</sub>/polystyrene mixture as a reflective coating. The scintillator exits the die face close to the correct shape at approximately 200 °C. The material immediately enters the vacuum-sizing tooling mounted in a 2.4-m long chilled water tank. In this vacuum-sizing tank, differential pressure draws the semi-molten material to the final dimensions. The material is further cooled in a second 2.4-m chilled water section. Upon exiting the cooling tank, the scintillator strip enters a belt puller which maintains the line speed at about 2 m/min. For the MINOS profile, this line speed corre-

sponds to a material throughput of approximately 50 kg/h. After the puller, the material is fed into a traveling saw which is programmed to cut the scintillator to the desired length. The finished product first undergoes quality control tests and is then moved to storage.

### 3.3 Quality control

During production the dimensions of the strips are periodically checked with a caliper. The groove dimensions are tested in-line with a gauge that monitors for collapsing grooves. The optical quality of the scintillator is also determined at the factory using a test that was developed by MINOS. The design of this QC technique was challenging because of these three main requirements: speed, simplicity and safety (no radioactive source). The final solution uses, for a given dopant concentration, a strong correlation between the quality of the strips and the scintillator transmission as well as the capstock reflectivity. This was verified after performing transmission measurements on scintillator strip samples with known light yields. Light yields were determined using a radioactive source and cosmic rays. The results of the UV measurements agreed with the other measurements. The UV technique was implemented as the pass/fail test at the extrusion factory. This technique is shown schematically in fig. 4.

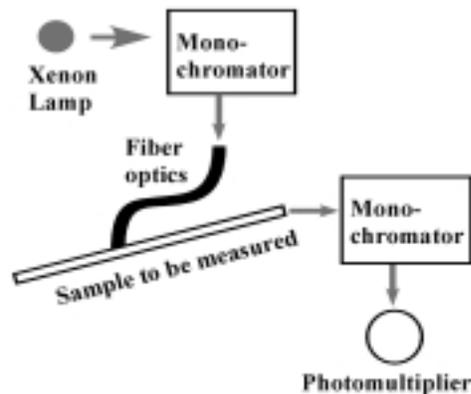


Figure 4: *Setup for quality control at the factory.*

A fluorescence spectrophotometer (Hitachi F-2500) is used. A special

sample holder was designed to adapt the instrument to the desired test. Light at 450 nm is introduced through the groove by optical fibers at about 8 cm from one end of a 14 cm long sample. The intensity of the transmitted light is then measured from that end. The ends are prepared by simply removing the saw cuts with a file. The response is then compared to that of a reference sample with known light yield. The scintillation light yield of the reference sample is determined beforehand using either a radioactive source or cosmic rays. The reference sample utilized at the factory was chosen to have the minimum acceptable response, so that any sample with a greater transmission would also have greater light output. A comparison of results from the UV technique at the factory and the radioactive source measurement at Fermilab is shown in fig. 5. The same samples were measured by both tests. The vertical scale of the UV measurements is shifted by 10% from that of the Cs-source measurements to correspond to a probable error in calibration at the factory. The light yield of a sample is periodically determined by cosmic rays as a cross check and the correlation is excellent.

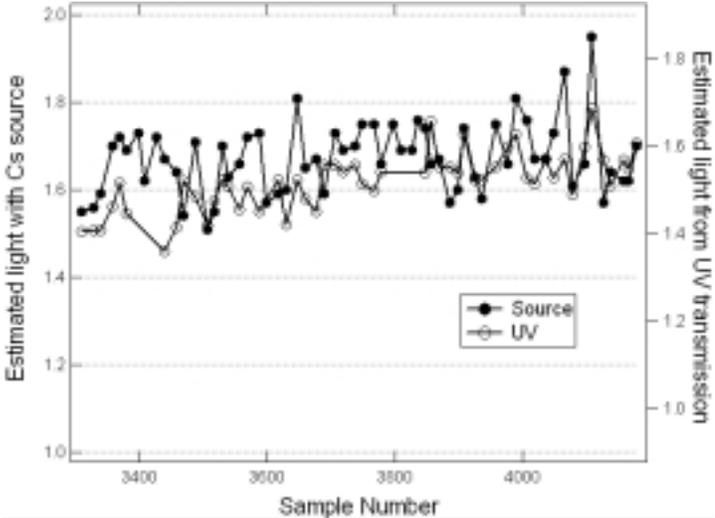


Figure 5: Comparison of UV and radioactive source measurements.

The UV test at the factory is affected by dopant concentration. Material produced with lower concentrations of dopants would exhibit higher transmis-

sion values. A fluorescence measurement was established to register possible dopant problems. This quick test is performed at Fermilab using a Hitachi F-4500 fluorescence spectrophotometer. The end of the sample is excited with 320-nm light and the dopant emission spectra recorded. If the concentration of the dopants varies, the emission spectra will also change. Fig. 6 shows the fluorescence spectra for three samples with measured light outputs of 164%, 84% and 50% of the reference sample. The spectra were normalized in amplitude to peak A which is a PPO emission band. Peak B is a POPOP emission band. The ratio between peak B and peak A needs to be above 1.2:1 in order to have the right dopant concentration and consequently, high light yield.

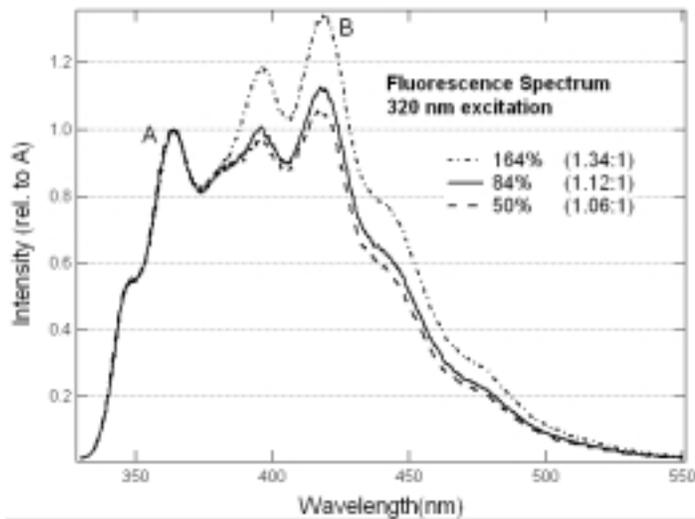


Figure 6: Comparison of emission spectra of three samples with different light yields.

#### 4 Conclusions

High-quality extruded plastic scintillator can be produced in an industrial environment. The material is considerably less expensive than standard cast scintillator. The strips can effectively be read out with wavelength-shifting fibers. The co-extruded reflective coating that MINOS has chosen improves light collection as well as handling of the strips at the module assembly facto-

ries. The QC techniques that have been developed allows the extrusion factory to monitor the quality of the scintillator in almost real time without the use of a radioactive source. At the present time, MINOS has extruded approximately 30 tons of scintillator, only 0.5% of which had to be rejected because of low light yield resulting from inadequate dopant concentration. The light yield of the current scintillator strips is 50% higher than the initial values used in the MINOS Technical Design Report <sup>1)</sup>.

## References

1. The MINOS Detectors, Technical Design Report, NuMI-L-337 (1998).
2. A. Pla-Dalmau, A.D. Bross and K. Mellott, Extruded Plastic Scintillation Detectors, in: DPF Proceedings, January 1999 (Fermilab-Conf-99/095).
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