Extruded Polystyrene

Scintillator for MINOS

Brajesh Chandra Choudhary
California Institute of Technology

DPF 2000, The Ohio State University, Columbus, OH
August 9-12, 2000
OUTLINE OF THE TALK

1. Introduction/Physics of MINOS
2. The MINOS Scintillator Detector
3. Ingredients for the Scintillator
4. Scintillator Extrusion (Drying, Purging, Mixing, Co-Extrusion)
5. Light Yield Measurements
6. Effect of Air Exposure vs Inert Gas on Light Output (LO)
7. Effect of fluor concentration, groove depth and TiO$_2$ thickness on LO
8. Online Quality Control
9. Aging of the scintillator
10. Conclusions
MINOS is a long-baseline neutrino experiment.

Its main goal is to confirm that atmospheric neutrino anomaly is due to neutrino oscillation.

Measure Oscillation Parameter(s).

And determine the Oscillation Mode(s)

a. $\nu_\mu$ to $\nu_\tau$ (Favoured by Super-K and MACRO)
b. $\nu_\mu$ to $\nu_e$ (Limits from CHOOZ and PALO VERDE)
c. $\nu_\mu$ to $\nu_s$ (Disfavoured by Super-K and MACRO)
d. $\nu_\mu$ to $\nu_\tau + \nu_e$
e. $\nu_\mu$ to $\nu_\tau + \nu_s$
f. $\nu_\mu$ to $\nu_\tau + \nu_e + \nu_s$ (?) (A real challenge?)
MINOS PHYSICS GOALS – How to Get to it?

1. Obtain Firm Evidence for Oscillation.
   a. Measure CC interaction rate.
   b. Measure CC energy distribution.
   c. Measure NC/CC rate ratio.
   d. Measure NC energy distribution.

2. Measure Oscillation Parameters from CC Energy Distribution.
   (Statistical Measurement, Oscillation Mode Independent).

3. Precise Determination of Flavor Participation.
   a. Number of $\nu_\mu$ events FAR/NEAR ratio to 1-2%. Probability of $\nu_\mu$ to $\nu_x$ oscillation.
   b. Number of $\nu_e$ CC events FAR/NEAR. Probability for $\nu_\mu$ to $\nu_e$ oscillation down to 2%.
   c. Number of NC events FAR/NEAR. Probability for $\nu_\mu$ to $\nu_s$ oscillation down to 4%.
WHAT MINOS CAN ACHIEVE?

1. **NEUTRINO OSCILLATION** seems to be a reality.
2. MINOS will provide conclusive evidence for oscillation.
3. MINOS will measure the oscillation parameters.
4. MINOS will determine the oscillation mode(s).
5. MINOS can answer other fundamental questions, such as
   a. Distinguish between Neutrino Oscillation & Neutrino Decay Model.
   b. Distinguish between Neutrino Oscillation & models with extra-dimensions with right handed neutrinos.
Minos has two detectors. A far detector (5.4 kT) at Soudan, MN and a near detector (1 kT) at Fermilab, IL.

The Major Parameters of MINOS Far Detector are:

- 2 Supermodules, each of 2.7 kt and composed of 243 planes each
- The shape of each plane is an 8 m wide octagon
- Each plane is a sandwich composed of a steel plate and scintillator strips, each one having a 1 cm x 4.1 cm cross-sectional area
- Light is read out via 1.2 mm diameter Kuraray wavelength shifting fibers and Hamamatsu M16 multi-pixel photocathode

Relatively thin steel thickness was chosen to

- Give good energy resolution for hadronic and electromagnetic showers
- Give sufficiently frequent sampling for low energy running and for atmospheric neutrino studies

Scintillator was chosen to

- Give good energy resolution for hadronic and electromagnetic showers
- Give fast timing important for non-accelerator physics, potential new physics
MINOS FAR DETECTOR

Far Detector

Fermilab

25,800 m$^3$ Active Detector Planes
4 cm wide solid scintillator strips
WLS fiber readout

31 m
(2 sections 15 m long)

Magnetized Fe Plates
486 Layers x 2.54 cm Fe
5.4 kT Total Mass

Magnet coil
$<B>=1.5$ T
STEEL & SCINTILLATOR PLANE LAYOUT

Scintillator plane
Orientations alternate ±90°
in successive planes

Bottom steel plane layer

Top steel plane layer

2-m wide,
0.5-inch thick,
steel plates
- 8 modules cover one far detector steel plane
- Four 20-wide modules in middle (perp. ends)
- Four 28-wide modules on edges (45 deg ends)
- Two center modules have coil-hole cutout
SCHEMATIC VIEW OF THE MINOS SCINTILLATOR SYSTEM

- Extruded scintillator, 4cm wide
- Two-ended WLS fiber readout.
- Strips assembled into 20 or 28-wide modules.
- WLS fibers routed to optical connectors.
- Light routed from modules to PMTs via clear fibers.
- 8 Fibers/PMT pixel in far detector. (Fibers separated by ~1m in a single plane.
- 1 Fiber/PMT pixel in near detector (avoids overlaps).
- Multi-pixel PMTs (Hamamatsu M16)
MINOS Near Detector

- 16.6 m long, 980 tons
- 280 “squashed octagon” planes
- **Forward section**: 120 planes
  - 4/5 partially instrumented
  - 1/5 planes: full area coverage
- **Spectrometer section**: 160 planes
  - 3/4 planes not instrumented
  - 1/4 planes: full area coverage
• **MINOS scintillator strips are commercially extruded using**
  – DOW Styron 663 W general purpose Polystyrene without additives
  – PPO (2,5-diphenyloxazole) as primary fluor, and
  – POPOP (1,4-bis(5-phenyloxazol-2-yl) benzene as secondary fluor
  – Co-extruded with TiO₂ reflective cap
  – A groove for wavelength-shifting fiber having K27 dye as shifter
  – PPO and POPOP have reasonable match to K27 dye in fibre
1. During last three years we have extruded and tested scintillators produced at extruders like RDN, Quick plastic, Polycast, and Itasca plastic.

2. We have also tested scintillators extruded by Vladimir Technoplast (through IHEP, Protvino group) in Russia and from Kuraray Co. of Japan.

3. We have Studied
   a. Different Dimensions (4cm x 1cm with groove on side vs 2cm x 1cm with a hole)
   b. Different Fluor Concentrations (varying amount of PPO and POPOP)
   c. Quality of the Reflective Coating
   d. Quality of the Groove
   e. Optimum temperature for the production of the scintillator
   f. Effect of the Environment (Presence of Air vs. Inert Environment)

4. The contract has been signed between MINOS and Itasca plastic for production of nearly 300 tons of scintillator.

5. The average cost of production is about $10/Kg. Total cost about $3M.
1. Prices for pre-production quantities for testing.
   a. DOW PS 663 about $1.45/Kg. $1.45/Kg of produced scintillator.
   b. PPO about $160/Kg. $1.6/Kg of produced scintillator.
   c. POPOP about $1000/Kg. $0.3/Kg of produced scintillator.

2. Final production prices are better.
   a. DOW PS 663 about $1.00/Kg. Itasca plastic buys it. $1.00/Kg of produced scintillator.
   b. PPO about $123/Kg. Fermilab buys it. $1.23/Kg of produced scintillator.
   c. POPOP about $650/Kg. Fermilab buys it. $0.20/Kg of produced scintillator.

3. MINOS pays Itasca an extrusion price of $6/Kg($0.70/ft) including all QC.

4. The overall cost of MINOS scintillator is ~ $10/Kg.
   
   a. Take PS pellets.
   
   b. Dry the PS at about 170°F for 4-8 hours. *Figure.*
   
   c. Purge the dried PS with liquid Nitrogen for approximately 4 hrs.
   
   d. Mix about 100 lbs of dried PS with PPO and POPOP in a mixer for about 15 minutes. The purge with liquid Nitrogen continues. *Figure.*
   
   e. About 200 lbs of doped PS pellets is kept in a drum lined with polythene bag. The purge continues for another 4 hrs or more.
   
   f. About 100 lbs of doped PS pellet is put in the hopper. The purge continues. *Figure.*
   
   g. There are anywhere between 7 to 11 zones in the extruder. The temperature in these zones varies from 360 to 410°F (Ex: 360 - 365 - 370 - 375 - 393 - 405 - 390 F). The liquid Nitrogen purge continues in the extruder.
   
   h. Scintillator with a groove and co-extruded with TiO$_2$ coating comes out of the extruder and goes in the water bath. At this point the scintillator is very hot and rather soft. The dimension of the scintillator (41mm X 10mm) is not exact. Two more sizers inside the bath brings it to exact size.
   
   i. A puller pulls the scintillator out of the water bath and then the exact size scintillator is cut and online QC is done at the factory.
MINOS

NUMI

POLYSTYRENE THROUGH VARIOUS PHASES BEFORE EXTRUSION

Polystyrene Handling

Dried PS being purged with Liquid Nitrogen.

Purge with Liquid Nitrogen continues in the hopper and the extruder.

Mixed sample is again being purged with Liquid Nitrogen.

PS is being mixed with PPO+POPOP (fluors).

170° F
4 hours minimum

DRYER

100 pounds

4 hours

4 hours

Nitrogen

Nitrogen

Nitrogen

Doped
15 minutes

Nitrogen
DRYING THE POLYSTYRENE PELLETS

PS is being sucked from the Gaylord. Dry for 4-8 hours at ~170°F. Total capacity of the dryer is about 800 lbs.

Circulate dry air.

Desiccant. Sucks up moisture.


Gaylord of PS
INERT GAS FLOW THROUGH THE SYSTEM

**Nitrogen Flows**

- **Polystyrene From Dryer**
- **Polystyrene From Mixer**
- **Main Extruder**
- **Co-Extruder**
- **MIXER**

Flow rates:
- 50 Standard cubic ft/hr
- 200 Standard cubic ft/hr

Storage tanks labeled as **Liquid Nitrogen**.
MIXING OF PS+PPO+POPOP

Liquid Nitrogen flow continues in the mixer.

Unmixed and mixed PS being purged.
EXTRUSION DETAILS

Doped PS goes here.

HOPPER

EXTRUDER. About 7-8’ long.

DIE

COEXTRUDER

WATER BATH. About 25’ long.
SIDE VIEW OF THE DIE

Side SCREW. TiO$_2$ comes from here.

Size of scintillator 41mm X 10mm is not exact here.
Main Screw – Side View

- Groove Maker
- White Line is TiO$_2$
- Metal Lip
CO-EXTRUDED SCINTILLATOR THROUGH THE WATER BATH

Scintillator going through water

Scintillator is hot and soft. Usually larger in dimension.
THE FINAL PRODUCT
TECHNICIANS MODIFYING THE SETTINGS AND DOING QC

QC TEST

Modifying the settings
AVERAGE SUMMED LIGHT OUTPUT > 7.0 pe
Different Methods of Producing Scintillator
MINOS EXPERIENCE

INITIAL METHOD USED BY MINOS FOR PRODUCING SCINTILLATOR

1. A gaylord of Polystyrene (2000 lbs) is purged w/Ar/N₂ for 3-4 days before extrusion.

2. Polystyrene in smaller quantities are put in dryer and heated at 170°F for 2-3 hrs. The Ar/N₂ purge may continue in the dryer. Possibility of air presence.

3. Warm polystyrene is mixed with PPO+POPOP. No Ar/N₂ purge while mixing in process.

4. Warm PS+PPO+POPOP to sit by the extruder for sometime, waiting to be placed in the hopper. No Ar/N₂ purge there also.

5. Ar/N₂ purge to resume in hopper and extruder.

IMPROVED/CURRENT/FINAL METHOD OF PRODUCING SCINTILLATOR

1. Step 1 is not necessary. During Step 2 there is no need to purge the polystyrene.

2. COOL the HOT polystyrene for several hours. Ar/N₂ purge to continue.

3. Mix PS+PPO+POPOP at room temperature. The process takes about 10-15 mts. Ar/N₂ purge to continue while mixing is in progress.

4. Doped PS purged with Ar/N₂ for ~4 hrs. Cool mixture goes in the hopper. Ar/N₂ purge to continue in hopper and extruder.
Presence of Air during extrusion reduces light output. Extreme case example.

~25% higher light output when no Air was present.
MINOS SCINTILLATOR PRODUCED AT ITASCA PLASTICS

**ITASCA - 2/2000 Batch Scintillator Light Output Compared to QP97**

- **20 - 30% EXTRA LIGHT**
- **2/2000 BATCH**

**ITASCA - 5/2000 Batch Scintillator Light Output Compared to QP97**

- **ABOUT 30% EXTRA LIGHT**
### FLUOR CONCENTRATION vs LIGHT OUTPUT

<table>
<thead>
<tr>
<th>S. N.</th>
<th>PROCESS</th>
<th>DATE</th>
<th>PPO(%)</th>
<th>POPOP(%)</th>
<th>RELATIVE LO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Two Step</td>
<td>9/97</td>
<td>1.0 %</td>
<td>0.015 %</td>
<td>1.00 (Ref. Batch)</td>
</tr>
<tr>
<td>2.</td>
<td>Two Step</td>
<td>6/98</td>
<td>1.0 %</td>
<td>0.015 %</td>
<td>0.77-0.83</td>
</tr>
<tr>
<td>3.</td>
<td>One Step</td>
<td>6/98</td>
<td>1.0 %</td>
<td>0.010 %</td>
<td>0.82-0.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.015 % 0.85-0.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.030 % 0.93-0.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.045 % 0.89-0.91</td>
</tr>
<tr>
<td>4.</td>
<td>One Step</td>
<td>6/98</td>
<td>1.5 %</td>
<td>0.010 %</td>
<td>0.86-0.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.015 % 0.83-0.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.030 % ~ 0.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.045 % ~ 0.60</td>
</tr>
<tr>
<td>5.</td>
<td>Two Step</td>
<td>9/98</td>
<td>1.0 %</td>
<td>0.030 %</td>
<td>~ 0.90</td>
</tr>
</tbody>
</table>

For final scintillator production MINOS uses ONE Step process with 1% PPO and 0.03% POPOP and gets a relative light output of ~120% compared to standard test samples.
We have also compared light output between extruded groove and machined groove. Within errors of measurement we do not see any difference in light output.
LIGHT OUTPUT vs GROOVE DEPTH

Cosmic Ray Measurement
Fibre Diameter 1.2 mm
Fibre held at the bottom of the groove

LO vs Depth of Fibre Inside the Groove

Cosmic Ray vs Radioactive Source
EFFECT of TiO₂ THICKNESS on LIGHT OUTPUT

1. MINOS has produced scintillators with varying amount by TiO₂ by weight (for example 5%, 10% and 15%) and different thickness of the TiO₂ coating. For MINOS purpose, the optimum amount of TiO₂ is about 12% by weight. In terms of actual thickness the optimised value comes to about 0.25mm. The TiO₂ thickness usually varies between 0.25mm and 0.40mm.

2. It was observed that light output did increase when the amount of TiO₂ was increased from 5% to 10%. But no significant light output increase was seen when the amount of TiO₂ was increased from 10% to 15%. For the same amount of TiO₂ the thicker coating gave higher light output compared to a thinner coating. For Example : One particular batch of scintillator came with very thin coating. For 10% TiO₂ by weight, the measured thickness of TiO₂ coating was between 0.05mm and 0.10mm instead of usual 0.25mm. Light output was measured with these pieces. Afterwards few pieces were coated with several coatings of Bicron TiO₂ paint and the average thickness of coated surface was about 0.20mm. The net increase in light output for different pieces was between 7 to 10%.

3. We did encounter some problems with extrusion process when percentage of TiO₂ was increased. With 15% of TiO₂ there co-extrusion was less smooth than usual.
CORRELATION BETWEEN SOURCE MEASUREMENT AND SPECTROPHOTOMETER MEASUREMENT

FNAL (spectrophotometer) measurement vs CALTECH (source) measurement

Source measured Light Output in QP97 scale vs Spectrophotometer measured Light Output in QP97 scale

- Itasca – 10/99 and 12/99 – 20 samples
- QP – 12/99 – 18 samples
Light Output from 4PPT Module Tests

Average light (summed at the center) for all modules produced for 4PPT. Average summed light output is 5.2 pe.

Light yield for strips in 4PPT modules compared to light measured for sample scintillators at Caltech. We see good correlation.

Gluing problems

This plot also shows nice correlation between source measurements and cosmic ray measurements.
AGING OF THE SCINTILLATOR
PRELIMINARY RESULT

1. Lifetime of the MINOS Detector ~ 8-10 yrs.
2. Scintillators do age. Expect light loss as years go by.
3. Aim – Sufficient light today. Sufficient light several years down the road.
4. Method: Measure light output of identical scintillators kept at different environment and compare them to light output of the reference pieces. We kept the scintillators at room temp (22°C), 30°C, 40°C and 50°C. We also had samples which were kept at 50°C and very high humidity (~100%). The light loss for scintillator kept at 50°C was approximately 15% in six months and 20% in 8 months, which approximates to about 8yrs and 11yrs at normal room temperature. We expect to lose about 2% of light every year but may be not at an uniform rate.

5. The scintillators usually yellows with time but in MINOS detector since the light travels only few centimeter inside the scintillator before it gets captured in the WLS fibre, the effect of aging of scintillator will be different on light output for detectors with different geometry.

6. Detailed analysis to come soon.
WHY MINOS USES 1.2 mm DIAMETER FIBRE?

Light Output is proportional to \((\text{Radius of fibre})^{1.4 \pm 0.1}\).
1. MINOS is the first large experiment to use co-extruded scintillator as active medium.

2. The scintillator extrusion process has been optimised and order has been placed with Itasca plastic for ~300 tons of extruded scintillator at a cost of ~$10/Kg.

3. The scintillator is composed of PS + 1.0% PPO + 0.030% POPOP.

4. Light yield measurements have shown consistent (within +-10%) and high light output.

5. It has been observed that presence of air during the extrusion process severely degrades light output.

6. Groove depth and thickness of co-extrusion needs to be optimised for particular needs. WLS fibre must be completely embedded inside the scintillator. The co-extrusion should be thick enough that no light leaks out of the scintillator.

7. We have established online quality control at Itasca plastic to monitor the quality.

8. We do understand aging of the scintillator. The scintillator will lose about 20% light in ~10 yrs. The light output from MINOS detector is more than necessary to do very good physics even after 10 years.