WAVELENGTH SHIFTING FIBER

INTERACTION WITH VENDORS & SOME TECHNICAL DETAILS

*Brajesh Choudhary, FNAL*
THREE FIBER VENDORS

1. Kuraray Co. of Japan – Meeting with representatives on 31st October. The meeting was attended by:
   2. Kenichi Shigeta – Manager Administration – OPT Division – Kuraray America INC.
   3. Ron Ray – Fermilab - NOβA Depty Project Manager
   4. Carl Bromberg – MSU - NOβA L2 Fiber Manager – By Video
   5. Brajesh Choudhary – Fermilab - NOβA L3 Fiber Procurement Manager
   6. Anna Pla-Dalmau – Fermilab
   7. Joseph Collins, & Leonard Mack – Fermilab Procurement Section

2. Saint-Gobain Crystals. Bicron of USA belongs to SGC. Meeting with SGC representatives on 3rd Nov. 2005. The meeting was attended by:
   1. Mike Kusner – Product Manager – Scintillation Products
   2. Timothy J. Parker – Sales Manager for Midwest Region
   3. Ron Ray – Fermilab - NOβA Depty Project Manager
   4. Carl Bromberg – MSU - NOβA L2 Fiber Manager
   5. Brajesh Choudhary – Fermilab - NOβA L3 Fiber Procurement Manager
   6. Anna Pla-Dalmau – Fermilab
   7. Stefano Zucchelli – Univ. of Bologna & INFN Bologna – By Phone
   8. Joseph Collins, & Leonard Mack – Fermilab Procurement Section

3. PolHiTech of Italy - No Response after repeated attempt to contact the company President by our Italian collaborator Stefano Zucchelli. – DROPPED AS A POSSIBLE VENDOR.

This questionnaire investigates issues relating to the production of 26,000 km of wave shifting fiber for the NO$\nu$A experiment. NO$\nu$A is designed to measure neutrino interactions in 30 kT of liquid scintillator. The liquid scintillator, primarily mineral oil (~90%) and a scintillating hydrocarbon (pseudocumine, ~10%), is contained in thin-walled PVC tubes, 15 m long with a 3.87 cm x 6 cm cross section. Particles generated in the collisions pass through the liquid scintillator and generate blue light (~425 nm peak).

A wave shifting fiber immersed in the liquid scintillator captures the blue light, shifts the wavelength to green (~500 nm peak), and transmits the light to photo-detectors. Each wave shifting fiber is 0.8 mm in diameter and 32 m long, bent at 16 m into a narrow loop (~7.14 cm diameter curvature) to fit into the 15 m long tubes. The two free ends of the fiber, each 1 m long, guide the light to an avalanche photodiode.
QUESTION TO VENDORS FOR DISCUSSION

1. What is the production capacity of your company? Will it be possible for the vendors to produce 26,000 Km of 0.8mm WLS fiber in 4 years (approximately 2008-2011)?

2. What is the dimensional tolerance on 0.8mm fiber supplied on a spool?

3. Bend radius - What is the minimum bend radius for 0.8mm diameter fiber to maintain a transmission efficiency of =>95%? Is there a choice of fiber type with different minimum bend radius that meets this requirement? Can you provide measurement of bending loss as a function of the bend radius?

4. Wavelength shifter K27 dye or equivalent - If you use a different wavelength shifter what properties does it have?

5. The concentration of the wavelength shifter may be in the range of 100ppm to 500ppm to maximize the light output. Is the concentration of dye a cost driver?

6. Do you produce multiclad fiber? What is the thickness of various layers and what they are made of? What are the refractive index and density of the various layers?

7. What is the trapping efficiency of your multiclad fiber?

8. What is the numerical aperture of the fiber?

9. What data do you have describing the light output and attenuation length for the WLS fiber with various concentrations of dye and if it is possible to improve upon it? Can you provide us with this data? NOνA will prefer fiber with high light output and longer attenuation length.
1. Kuraray representatives promised that they can produce 26,000 Km of 0.8mm diameter fibre needed for NOνA in 4 years. Kuraray can produce 7,000 Km of 0.8mm diameter fibre/year with two shifts/day. At present Kuraray employs a total of 3.5 FTE, one shift/day, in fibre production. They will have to hire new people and train them which usually takes about six months. They would like to have 6-12 months advance notice in case NOνA decides to use Kuraray fibre.

2. They also discussed the possibility of producing ~26,000 Km of fibre in 3 years. Although that depends on the funding profile, the very idea suggests that Kuraray can produce fibre needed by NOνA well within the time limit of detector production.

3. Till today, MINOS has been the single largest vendor for Kuraray. MINOS bought ~2,200 Km of 1.2mm diameter WLS+CLEAR fibre.

4. At present SGC can only produce 4,500 Km of 1.0mm fibre/year, working 3 shifts/day, 6 days/week. To meet the NOνA schedule SGC will need to add pulling towers and oil baths for preform curing. They have adequate space, and any minor expansion of the facility would not be a problem. – 3 shifts/day, 6 day/week could put some constraint. Not much margin left.

5. Usually SGC produces about 300-400Km of 1mm diameter scintillating fibre every year for nuclear gauges. These fibre does not require to have long attenuation length.

6. In last few years they have produced a total of about 40-50Km of BCF12 WLS fibre for CERN, and University of Regina in Canada. Not much by NOνA standard.
MATERIALS & STRUCTURE DETAILS – KURARAY & SGC

**Round Fiber**

- Core
- Inner Cladding
- Outer Cladding

- T = 3% of D
- NA = 0.55
- Trapping Eff. = 3.1% (Kuraray)
- Trapping Eff. = 3.4% minimum SGC

- T = 3%(To) + 3%(Ti) = 6% of D
- T = 3%(To) + 1%(Ti) = 4% of D for SGC
- NA = 0.72
- Trapping Eff. = 5.4% (Kuraray)
- Trapping Eff. = 5.6% minimum SGC

**Square Fiber**

- Core
- Inner Cladding
- Outer Cladding

- T = 3% of SQ – 4% of SQ for SGC
- NA = 0.55 – 0.58
- Trapping Eff. = 4.2% (Kuraray)
- Trapping Eff. = 4.4% minimum SGC

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<table>
<thead>
<tr>
<th>Materials</th>
<th>Material</th>
<th>Refractive Index</th>
<th>Density [g/cm³]</th>
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<tbody>
<tr>
<td>Core</td>
<td>Polystyrene (PS)</td>
<td>1.59</td>
<td>1.05</td>
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<tr>
<td>Inner Cladding</td>
<td>Polymethylmethacrylate (PMMA)</td>
<td>1.49</td>
<td>1.19</td>
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<tr>
<td>Outer Cladding</td>
<td>Fluorinated Polymer (FP)</td>
<td>1.42</td>
<td>1.43</td>
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**Operating Temperature** -20°C to +50°C

In principle the thickness of the outer cladding should not have an effect on the trapping efficiency provided it is at least several times thicker than the wavelengths of light being propagated in the fiber. In practice, this is something I'd like to see us investigate over the next couple of months to better understand the effect on light transmission and to improve the robustness of the fibers.

Mike Kusner, SGC
Non-S TYPE vs. S-TYPE – POLYMER ORIENTATION OF THE PS CORE

- Standard Type (Non-S Type) from Kuraray – The PS core has almost no oriented polystyrene chain and is optically isotropic and very transparent. This conventional standard type has good attenuation length, but it showed weakness against cracking caused by bending or handling during assembly.

- S Type from Kuraray – The PS core has molecular orientation along the drawing direction. This fiber is mechanically stronger against cracking at the cost of transparency. The attenuation length of S-type is nearly 10% shorter than the non-S type.

- There is no difference between S-type and non-S type fiber in chemical composition or material used, but only the way fiber is drawn from the preform. S-type is drawn by setting a particular drawing parameter value to 25, and for non-S type the parameter value is 70. Fiber somewhere in between S-type and non-S type, for example S50, with longer attenuation length than S-type and stronger than non-S type, can be drawn by setting the particular drawing parameter to 50. But the control of fiber drawing is rather difficult and the variation of mechanical property is larger. – From Osamu Shinji of Kuraray. – Is it worth the risk??

- SGC does not have S-type or non-S type fibers like Kuraray, but by pulling the fibers at different tension they can produce fibers more or less flexible, akin to Kuraray’s S-type and non-S type.

- WHICH FIBER TYPE SHOULD WE CHOSE????
MINOS experience showed that Kuraray Non-S fiber gave respectively 4%, 8%, and 12% (extrapolated) more light than S type fiber at a distance of 1m, 8m and 12m.
Minimum Bending Diameter recommended by Kuraray - On safety side and long term reliability.

Bending Loss of all the samples <= 5%.

<table>
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<tr>
<th>Type/Fiber Diameter</th>
<th>2mm</th>
<th>1mm</th>
<th>0.8mm</th>
<th>0.5mm</th>
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<tbody>
<tr>
<td>S* Type</td>
<td>200 mm</td>
<td>100 mm</td>
<td>80 mm</td>
<td>50 mm</td>
</tr>
<tr>
<td>Non-S Type</td>
<td>400 mm</td>
<td>200 mm</td>
<td>160 mm</td>
<td>100 mm</td>
</tr>
</tbody>
</table>

* S type – Stronger against cracking, but has 10% shorter A.L.

- Below the minimum bending diameter there is rapid increase in bending loss for non-S type fiber due to cracking of the core. S-type fiber does not show such cracking.

- NO$
u$A cells are 3.87cm wide and 6.00 cm deep. The allowed bend diameter is 7.14cm.

- According to Kuraray expert Osamu Shinji – S-type fiber can be safely bend into a 7.14cm diameter, but for non-S type the diameter seems to be rather severe. The center part of 32m fiber curved diagonally at the bottom end of the PVC tube, as the strength of material tells us, will not have uniform curvature of 7.14cm diameter, but will have partially smaller diameter of curvature than 7.14cm in the middle of the curved part. So the problem is much more serious with non-S fiber.

- **THE CHOICE IS OBVIOUS – S-TYPE!!!**
1. Measurement made almost every 5-10 cm. 50,000 points for 2,500 meter (?) fiber on spool.

2. Average Diameter = 0.8mm ± 0.008mm

3. Standard Deviation RMS =< 0.007mm

4. Tolerance $3\sigma/D=2.5\%$ ($\sigma = \text{rms}, D = 0.8 \text{ mm}$)

5. SGC’s tolerance for round fiber is 2% of the fiber diameter. On request they can quote tighter tolerance.
ECCENTRICITY OF THE FIBER – FROM KURARAY

Measure 2 points by micrometer

D_{max} – D_{min} < 3\% of D

\frac{D_{max} – D_{min}}{D_{max} + D_{min}} < 1.5\%

SGC must meet similar tolerance too.
Number of 2% bumps =< 50 per km
Number of 4% bumps =< 15 per km

The number, position, diameter, and the length of the bumps can be specified. Bumps can also be marked with a red marker.

I am sure SGC can do the same.
1. About 5000 gm of fibers can be made from one preform.

2. For 0.8mm fiber:
   - ~7,500m of fiber from one preform
   - ~3 spools of 2,500m ± several 100m each. Fiber with diameter >= 0.6mm is delivered on 900mm diameter spool. Fiber with diameter <=0.5mm is delivered on 300mm diameter spool.

3. NOνA fiber will be produced from ~3500 preforms and delivered on ~10,500 spools.

4. For R&D purpose the minimum amount of fiber Kuraray can produce with varying dye concentration is 500gm or 750m of 0.8mm diameter fiber.

5. This is consistent with the way fiber was produced and delivered for MINOS.

6. SGC produces ~1 Km of 1.0mm diameter fiber (~1,500 m for 0.8mm fiber) from individual preforms. Fiber pulled from one preform will be supplied on 1meter circumference spool. NOνA fiber will be produced from ~17,400 preforms and delivered on ~17,400 spools. Larger (X5) number of preforms means chances of more variation in fiber from one preform to another.

7. For R&D purpose, SGC can produce a minimum of 500m to 750m of fiber with varying dye concentration. For one dye concentration, two ~750m lengths of fiber with different diameter can be pulled from the same preform by adjusting the pulling speed during the production.
Usually Kuraray measures 2, 3m long samples from every spool.
Kuraray Y-11(200), 0.8mm diameter, MC, S, J, On-Spool
- Attenuation Length for all fibers > 3.5m
- The A.L is sampled throughout the whole order. RMS/Ave <= 10%

ATTENUATION LENGTH & LIGHT OUTPUT (HOW DO THEY DO IT?)

SGC usually tests 1m-3m long fibers for AL and LO measurement, but they can always optimize the system to measure properties for a longer fiber.
1. 10.5m long fiber on test apparatus. LO measured at 21 points.
2. Light measured at all 21 points must be > 85% of the “Reference Fiber”.
3. Can we use something like this for NO\(\nu\)A? – Possibly not – Too tedious.
4. May have to develop new test apparatus to QC 32 meter long fiber or just test only 10-12m long fiber. If light is consistent over 12m fiber, it should be consistent for longer fibers too.
5. Try to test fibers randomly from different spools – or believe in the vendors.
1. The fibers will be bent for a long time. Can heat processing of fiber be a solution for smaller bend diameter? In that case can one use non-S type fiber?

2. KURARAY does not have any systematic data or information to give fiber a permanent curvature by heating. All they have is - that one should treat fiber to less than 60-70C temperature to avoid fiber shrinkage, and the fiber should not be kept for long time in high temperature to avoid additional increase of light absorption loss due to chemical damage of polystyrene oxidation.

3. Kuraray business representative visiting FNAL told us that they have bent 0.8mm diameter non-S fiber to a minimum bend diameter of 70mm, instead of the suggested 160mm, but they were not sure about its long term effect. Technical expert not very comfortable.

4. Here personally I will go with Osamu Shinji’s advice and if we decide to heat treat the fiber – we should do our own R&D on heat treatment.

5. SGC representatives told us that SGC has done R&D on bending the WLS fiber in a hot bath. This way they have made very sharp bends, and felt it was a safe procedure. They may have some data to back this up. But they also mentioned that sharp bend leads to light loss and they have tried this on small length fibers not used for serious scientific purpose.

6. Personally it is my opinion that it will be very hard to heat treat ~762K, 32m long fiber. Perhaps we should stick with 0.8mm S-type fiber for which 71.4mm bend diameter is fine.

7. Or one can study the heat treatment and its effect on fiber as another R&D feature.
MORE ON BENDING THE FIBER

From e-mail exchange between Leon Mualem & Edward Kistenev of BNL – dated 17th March, 2003.

- Bend 1mm diameter Bicron fiber to bend diameter of 3cm to preform the fiber in hot water bath at 60C for PHENIX experiment.
- Light gain 70-90%, not 100% for a perfect reflector.
- For “Accordion Calorimetry” fiber was heated to 80C but with larger bend diameter – no analyzed data available in 2003.

Courtesy – Leon Mualem
The most important anxiety Osamu Shinji has—whether KURARAY fiber will be OK in liquid scintillator or not. I have never known that our fiber was soaked in liquid scintillator. The fiber is made of PMMA and PS, and both material are not soluble in mineral oil, mixture of molecular structure of straight hydrocarbon chain. But in a solvent containing aromatic structure like benzene, toluene, pseudocumene (1,2,4-trimethylbenzene), fiber material will easily dissolve. So the larger the percentage of the pseudocumene in the liquid scintillator, the more risky is the experiment.

This question and anxiety, whether our fiber is safe for 5 or 10 years, is concerned to not only bended part but also whole fiber of 32 m. We at KURARAY will also start some test about it. Although it is very difficult to estimate 5-10 years phenomena, some accelerated test will be needed. For example, we should make fiber soak in liquid scintillator, changing keeping at temperature of 40, 50, 60 centigrade degree. We should measure the degradation of the attenuation length and the light output vs. the temperature. An Arrhenius plot of the degradation vs. absolute temperature will be helpful for estimation of 10 years degradation at the room temperature. We will need tests like this. By the way, I wonder if liquid scintillator itself would be stable enough for a long time. Especially are dye materials, PPO, bis-MSB, POPOP all long stable in the liquid solvent?

SHOULD WE BOTHER ABOUT THESE QUESTIONS? PERHAPS YES.

MORE R&D IS DEFINITELY NEEDED.
In MACRO, we expected no more than about eight years and there was empirical evidence that liquid scintillator lasted at least that long, but we never made any tests to verify this before the experiment.

However there was some talk about the issue in connection with how much antioxidant (vitamin E, I think) we ought to use. Greg Tarle was in charge of the oil and he argued that we had plenty; it was added to the oil by the oil's supplier. The argument, as I remember it, was that oxidation of the oil caused the long hydrocarbons chains to break and the newly created ends became color centers. Thus, with time, the oil yellowed. Vitamin E, as I recall the argument, was preferentially oxidized and so adding it slowed the yellowing process, until essentially all the antioxidant (E) was used up (a bunch of exponentials are clearly involved). Thus in principle, if you knew the appropriate constants, the lifetime of the scintillator for a given initial concentration of antioxidant could be estimated. I never did any such calculation (not being fluent in chemistry) but Tarle assured us that we had enough for our needs - and I expect that Greg (Univ. of Michigan) would be happy to talk to you about the matter.

On the empirical side, I don't think we ever did a systematic study of MACRO scintillator's light output as a function of time (we recalibrated on a regular basis about every month or so, however, so there is data, but it is probably unrecoverable); surely there was no big effect since that would likely have created comment which I would remember. Perhaps in Chris Walter's thesis there is a discussion of this, and maybe Chris (he's at Duke) can tell you about the matter.
Regarding MACRO scintillator, no, we had not observed any significant degradation after 10+ years of operation. I think degradation of the light yield is correlated to additives in the mix. I recall CHOOZ having serious problems in loss of light output that were attributed to the gadolinium added. Regarding detailed analysis of that data in MACRO, I don't know of others that might have, but Yiannis and I did look at historical data of calibration coefficients that were pointing towards the stability of the MACRO scintillator - however, we didn't put it in a note or something (and recovering any data now from disk is hopeless).

2. MACRO test tank at U. Michigan loaded in July 1985 with 5% pseudocumene, 1.44g/l PPO, 12mg/l POPOP, and 40ppm BHT mixed in WITCO KLEAROL mineral oil. The final MACRO scintillator contained 3.6% pseudocumene, 1.44% g/l PPO, 1.44 mg/l BIS-MSG, and 40-80 ppm BHT in petroleum specialties mineral oil.

3. The memo describes a test of flowing dry nitrogen over the Michigan Macro scintillator tank in order to purge oxygen from the scintillator.

4. The light output of the tank was monitored during and after the flow to check the long term stability of the light output.

5. A 28±3% improvement in LO was seen after 13 days of flowing; this decayed to an 8.5±5.2% gain over the initial LO in 60 days following the stop of flow.

6. The absolute light levels and attenuation length of the scintillator were compared with those obtained when the tank was filled in July 1985. Photoelectron yields were found to have decreased by 25% though the attenuation length was essentially the same.
ON K27 DYE – MORE FROM OSAMU SHINJI

1. About K-27, in past we have searched for a better green shifter dye than K-27, and failed. K-27 dye has not so short decay time, but is excellent especially in the attenuation length. So if your project needs a long attenuation length, K-27 would be the best choice.

2. For a good attenuation length, the second problem is the purity of the dye. We at KURARAY have often experienced that the degree of dye purity seriously influences in uniformity of fiber property. The variation of dye impurity causes and effects the variation of attenuation length. Up to today we have made long and much efforts for obtaining K-27 dye of a high degree of purity.

3. And we succeeded in it a few years ago, but the cost have got rather high because the new preparation of K-27 was a laboratory scale production. Now this time, for the mass production we started to investigate a large scale production and will reduce the cost successfully.

4. The K-27 dye was long and widely used and has many and much achievements. I think the idea of a new choice other than K-27 is not very good, because a new materials needs a long time and a lot of know-how for the preparation. If we would have chosen a new dye that is a little better than K-27 and, we would take a large risk of unstable production or unstable purity.

K-27 will not be a cost driver. Although Kuraray’s representatives did talk about cost of K-27 going up, it seems for such a large order, it will not be a big problem.
1. MINOS R&D pointed out glaring problems with Bicron fiber produced in 1997-98.
   - The measured LO for “Old Bicron Fiber (Summer 97)” 1.0mm dia. and “New Bicron Fiber (9/97)” 1.0mm dia. respectively was 50% and 71% compared to Kuraray Y11(150), 1mm dia., MC, non-S, J type Dec. 97 batch.
   - Further on several spools with different dye concentration were ordered from Bicron. Usually after 3.5m the LO dropped precipitously.

2. The variation in LO could be due to
   - Dye purity – very important for uniform LO and AL of the fiber.
   - Dye concentration and uniformity (Kuraray controlled it to 0.5ppm)
   - Drawing process – Usually parameters like temperature and drawing speed need to be well controlled for uniform quality of fiber. These parameters may vary from preform to preform and also within the preform.

3. It is my understanding that Bicron fiber for MINOS R&D may have suffered because of all these problems, especially dye purity and uniformity. Bicron representatives promised to look into the matter but after a while they simply told me that Kuraray makes better fiber so they will not like to compete.

4. During 3rd Nov. meeting the SGC representative told us that some effort was put into understanding these problems but the scientist working on the problem was transferred to some other division, and after MINOS no one has ordered fiber with such stringent specifications. The SGC representatives were confident that with a few changes in the hardware and the drawing procedure they will be able to produce fiber that will meet NOνA specification.
SUMMARY AND CONCLUSIONS

- Both Kuraray and SCG are keen to provide fiber for NO$\nu$A.
- Representatives from both companies showed keen interest to develop some R&D to satisfy our scientific needs.
- Most likely NO$\nu$A fiber will be 0.8mm diameter, ~200ppm of K-27 dye, multi-clad, high-flex.
- Important open questions in my mind are:
  - Do we have adequate light for physics? Will we have adequate light for physics in 10 to 15 years? Or do we need to have larger diameter fiber? Should we go to 0.9mm S-type fiber? Perhaps NO. Cost goes up.
  - If we use non-S type (or low flex) fiber we will get more light. This will require bending 0.8mm fiber in a bend diameter of 71.4mm, instead of recommended 160mm. Do we need to do R&D on heat treatment of fiber, either in air or warm water? Definitely YES.
  - Do we know the long term effect of pseudocumene on fiber? YES & NO. Do we need to do our own R&D? Definitely YES.
- Some of these issues are not yet settled. You may disagree with me. Some people do. But I think definitely more R&D is needed.