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Results of Reflectivity Measurements for the Muon Layer

1. Introduction

Here I report on measurements I've made on the reflectivity of materials considered for use in the muon layer. The materials examined were:

1. Tyvek: Type 10 Style 1073B
2. Liner
3. Komatex: A PVC foam, 1/8" thick
4. Kydex
5. PVC type 2, 1/8" thick
6. Polypropylene, 1/8" thick

It will be shown that all materials except Tyvek have a sharp drop-off in reflectivity for wavelengths below 400 nm.

2. Setup

I used a device built by a group here at LANL to perform optical biopsies. A schematic of the setup is shown in figure 1. There are 3 optical fibers bunched together. One brings light into the sample and the other 2 take it out to the detector. The detector consists of a diffraction grating and a CCD; this allows the entire spectrum to be taken at once. Wavelength calibration is performed using a mercury source and identifying the emission lines with their known frequencies.

First, measurements are taken of a standard diffuse reflector, Spectralon. All subsequent measurements are relative to the Spectralon measurements. Spectralon

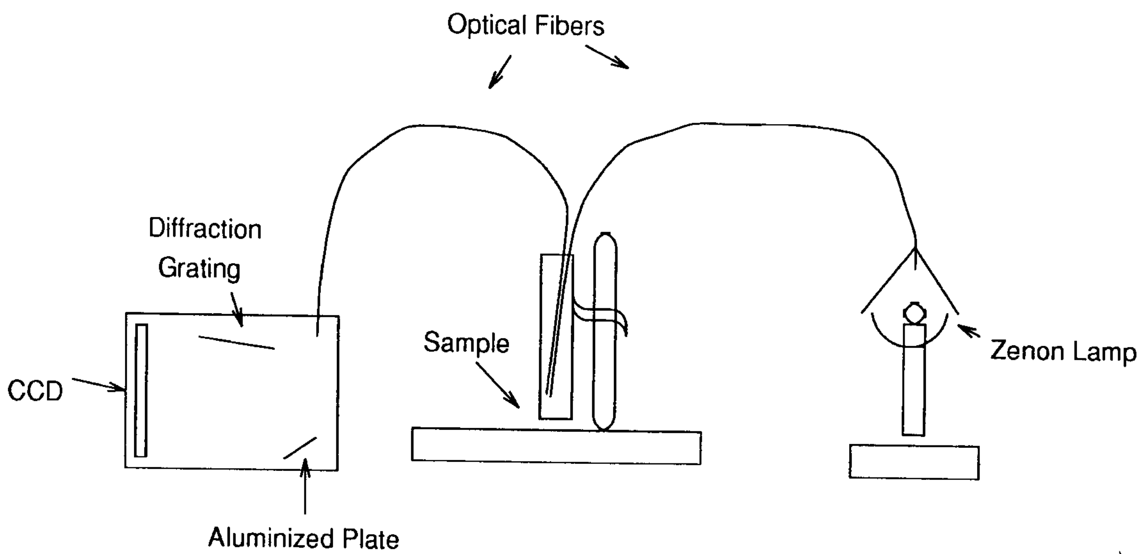

Figure 1. Schematic of the experimental setup to measure reflectivity.

is reported to have a reflectivity of 99% above 400 nm and 95% below 400 nm. However, the Spectralon sample has been out in the open in the lab for a while so it is possible that its reflectivity will be degraded somewhat.

I was quite impressed with this system. You simply place the sample under the fibers, press a button on a laptop computer, and within a few seconds a relative reflectivity spectrum from 250 nm to 750 nm appears on the screen and is saved in a file.

3. Results

Results of the measurements are shown in figures 2 and 3. There is a sharp drop in reflectivity below wavelengths of 400 nm for all materials except Tyvek. Tyvek's reflectivity does drop in this region also, but not as sharply. The peak of the PMT quantum efficiency convoluted with the Cherenkov spectrum is at about 350 nm so this drop in reflectivity is quite damaging.

The measured relative reflectivity often goes above 1. Thus the standard, Spectralon, must not be as reflective as claimed—probably more like 85%. In addition,

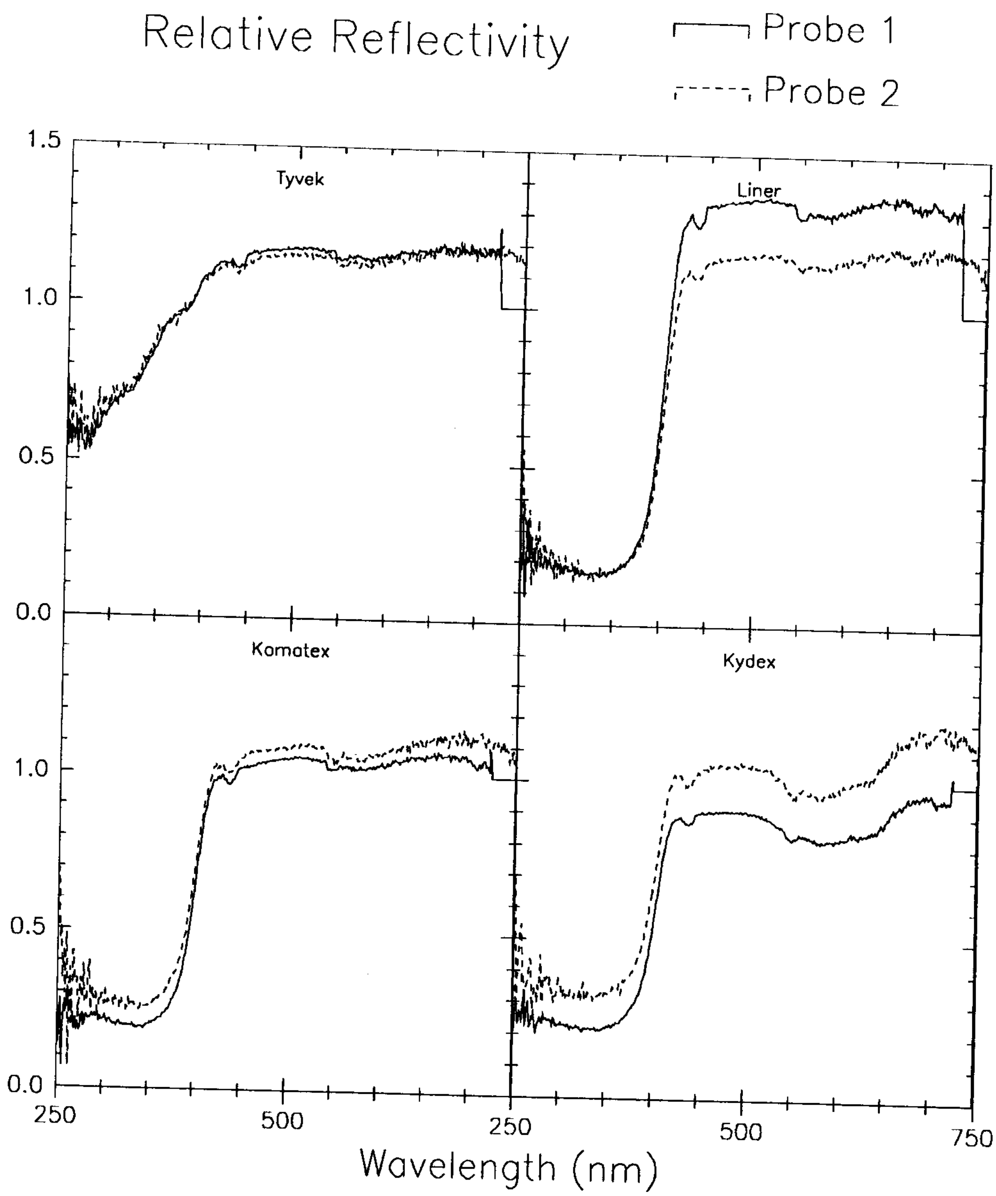

Figure 2. Results of measurements.

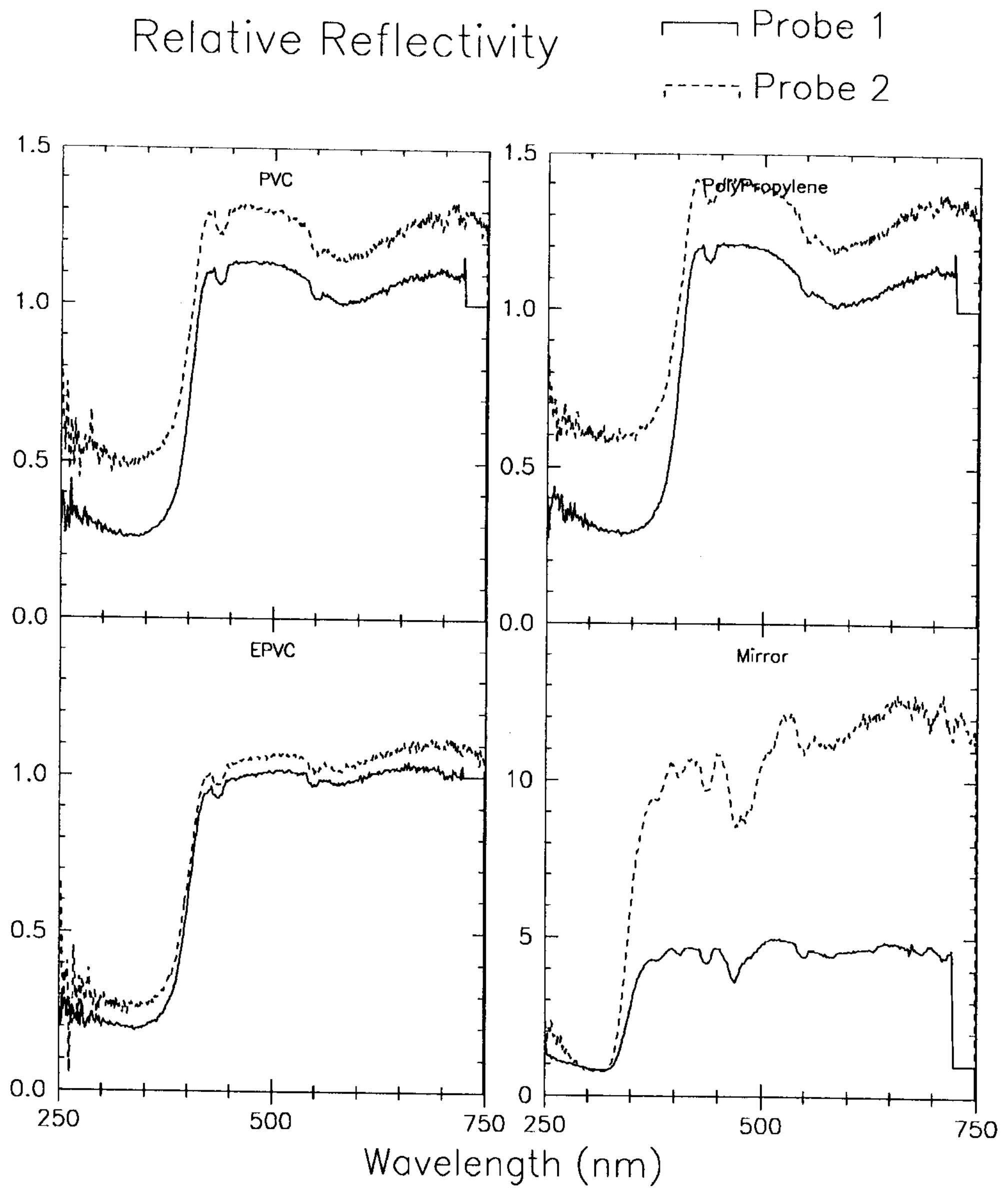

Figure 3. Results of measurements.

the results of probes 1 and 2 are different for most of the materials. I believe that this is indicative of some fraction of a specular reflection being detected. Spectralon is a highly diffuse reflector so a purely diffuse sample should yield the same results between probes 1 and 2. This is the case for Tyvek. However, as is shown in figure 3 for the mirror, a purely specular reflector yields very different results between probes 1 and 2. Indeed, the PVC and PolyPro samples obviously have some specular component just from looking at them; and the difference between probes 1 and 2 is relatively high for these samples. The Liner sample, however, has the results from probe 1 being higher than those from probe 2; this is the opposite of that expected for a specular reflector. I believe this is due to the macroscopic texture or pattern on the Liner which could cause the specular component to be directed in a different angle—in this case, one which puts probe 1 in more of the specular beam than probe 2.

3.1. Estimating the Total Reflectivity

I've tried to estimate the total reflectivity by separating out the diffuse and specular components using the difference between the results of the two probes. The algorithm is the following. Let the measured reflectivities be $r_i = s_i + d_i$, where s is the specular reflectivity and d is the diffuse reflectivity (i is 1 or 2, denoting probes 1 and 2). Because the measurements are compared to Spectralon, a diffuse reflector, $d_1 = d_2$. In contrast, for the specular component we see from the Mirror sample that $s_2/s_1 = 2.41$. Combining these equations yields $s_1 = (r_2 - r_1)/1.41$ and $d_1 = r_1 - s_1$. The specular component has a higher gain which we can normalize by dividing s_1 by the average r_1 of the mirror in the visible—a value of 4.56. The total reflectivity is then $R = d_1 + s_1/4.56$ which can be written $R = 1.554r_1 - 0.554r_2$. Finally, I also divide by 1.2 in order to normalize the resulting reflectivities to a maximum value of 1. This algorithm obviously does not apply to the Liner, for which I simply normalize r_2 to a maximum value of 1. Figure 4 shows the resulting values for the relative total reflectivities. The relatively low reflectivity of the Kydex is consistent with visual observation; it looks about as dark as the

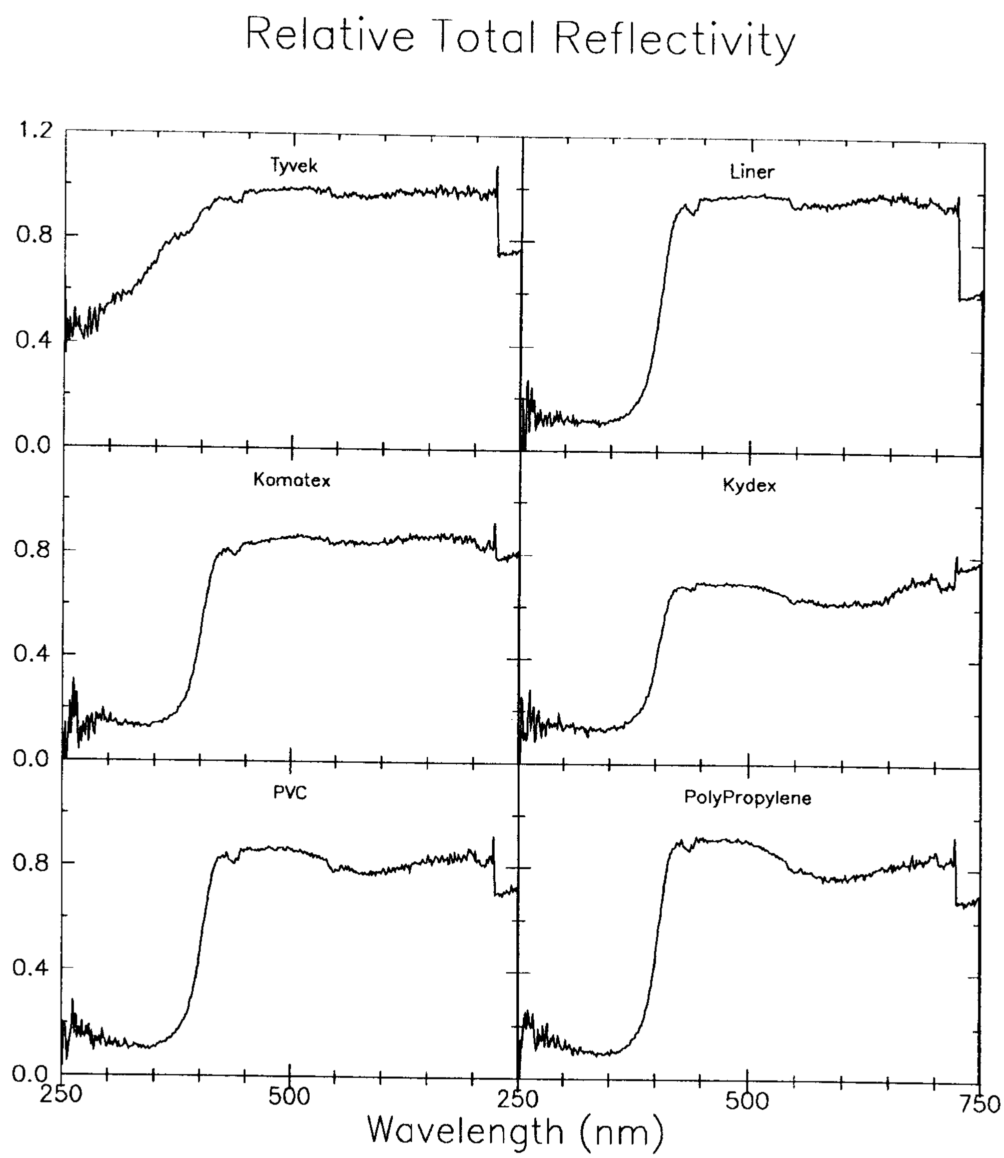

Figure 4. Estimated total reflectivity.

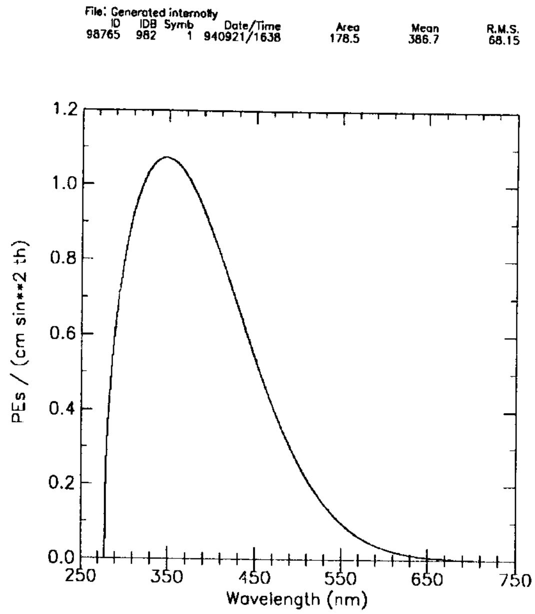

Figure 5. Detectable Čerenkov light distribution.

PVC and PolyPro but lacks the specular component which brings up the total reflectivity of the PVC and PolyPro.

3.2. Convolving with Quantum Efficiency and Čerenkov Spectrum

I've fit data from a spec-sheet for the quantum efficiency of a Hamamatsu R1408 PMT to a Gamma distribution and convolved this with the $1/\lambda^2$ Čerenkov spectrum. The resulting detectable Čerenkov light distribution is shown in figure 5. The integral under this curve yields 77.4 PEs/cm; however, it should be noted that this does not include the collection efficiency of the PMT. In order to get the detectable Čerenkov light distribution after 1 reflection I multiply the curve in figure 5 with those in figure 4. The resulting distributions are shown in figure 6. Figure 7 shows the detectable Čerenkov light distribution after 2 reflections and finally figure 8 shows the average fraction of detectable light left after 1 and 2 reflections. It is clear that Tyvek should yield significantly more light.

3.3. If You Don't Believe My Normalization ...

For those of you who don't believe my algorithm for getting the total reflectivity, I've simply taken the results of probe 2 for the different materials and divided them by their average value between 450 nm and 525 nm. This attempts to equalize the reflectivities of the different materials in the visible range. Then the major effect is that of the decrease in reflectivity below 400 nm. The average fraction of detectable light left after 1 and 2 reflections in this case is shown in figure 9. Here PVC and PolyPro are closer to Tyvek than with the previous normalization, but Tyvek is still the clear winner.

4. Conclusion

It appears that Tyvek is the material of choice in terms of reflectivity. For those of you wondering what Tyvek looks like, you've probably seen it in the form of white package mailing envelopes or as haz-mat suites. It has the feel of thick paper and can be torn if a rough edge is present. However, it is fairly difficult to tear from a clean cut. It is also not completely opaque, so we would need to have an additional light-barrier material on the top of the muon layer. I've obtained a price quote for 2 rolls of tyvek, each 39" wide and 2200 yards long, of $0.882 per linear yard. This totals $3880 plus about $400 for shipping. This price is 6 to 8 times cheaper than that of the other materials tested.

I am ordering enough samples of Tyvek for testing and prototyping. If we do want to go with Tyvek the main open questions in my mind are: will it hold up in water over time, and how do we build the cells with it? I will attempt to contact experts regarding the first question. Regarding the second, I've been told that Tyvek can be glued and heat-bonded to itself or to other plastics; but we should test this ourselves.

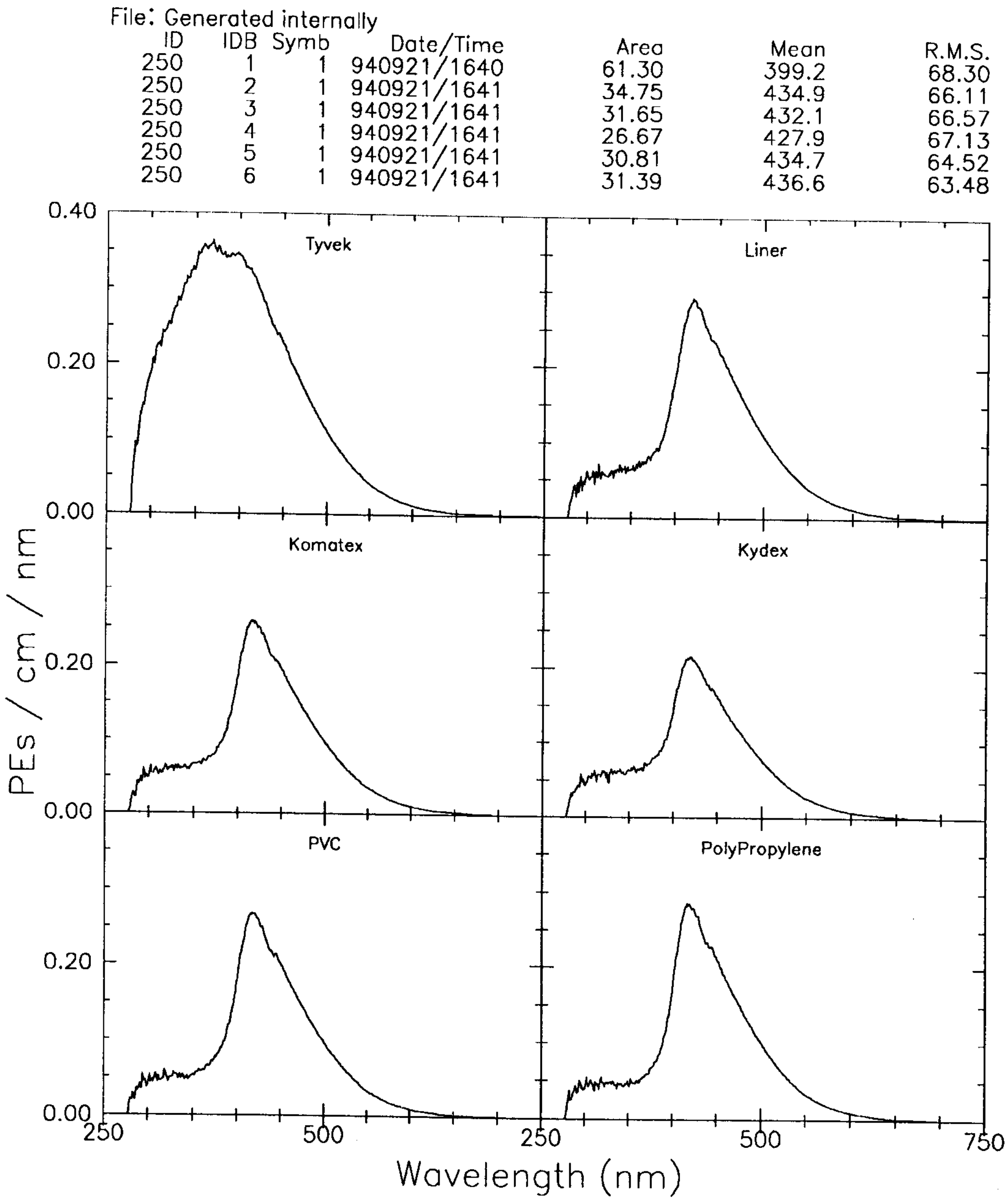

Figure 6. Detectable Čerenkov light distribution after 1 reflection.

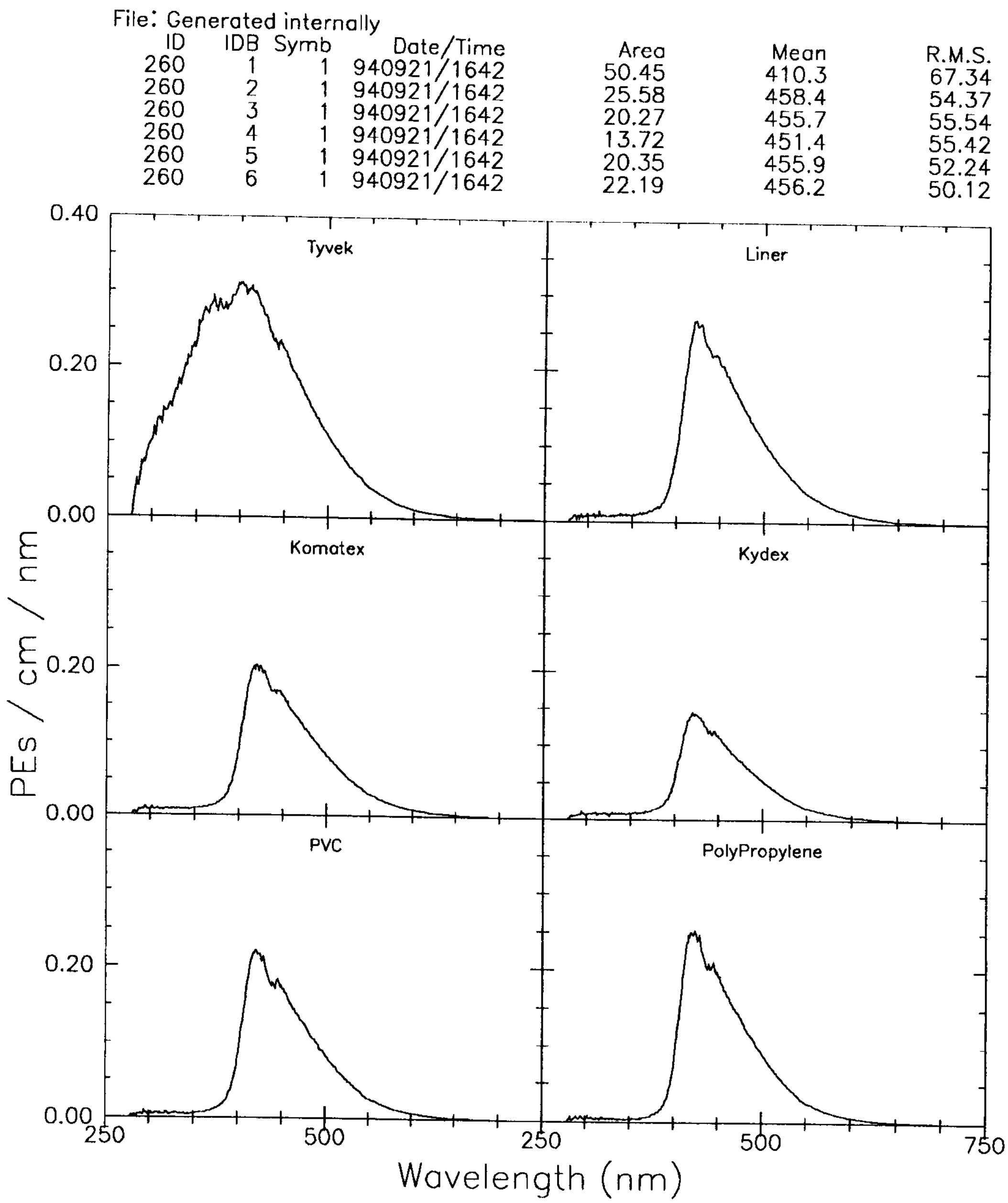

Figure 7. Detectable Čerenkov light distribution after 2 reflections.

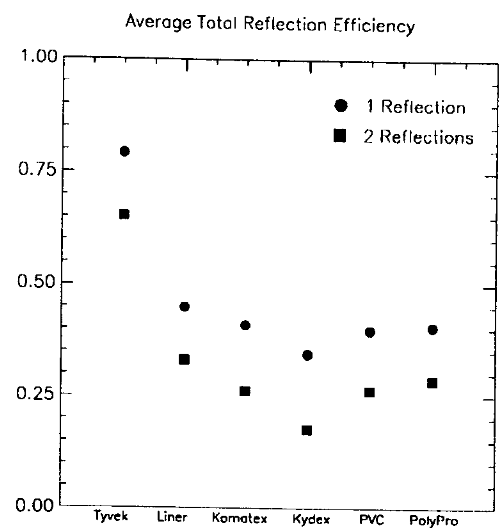

Figure 8. Average fraction of detectable light after 1 and 2 reflections.

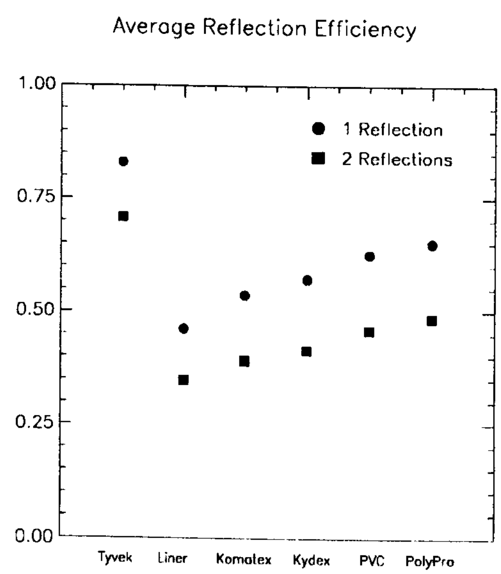

Figure 9. Average fraction of detectable light after 1 and 2 reflections, for equal reflectivity in the visible.