Studies of Doped Scintillator at BNL
A Generic Method for Neutrino Experiment

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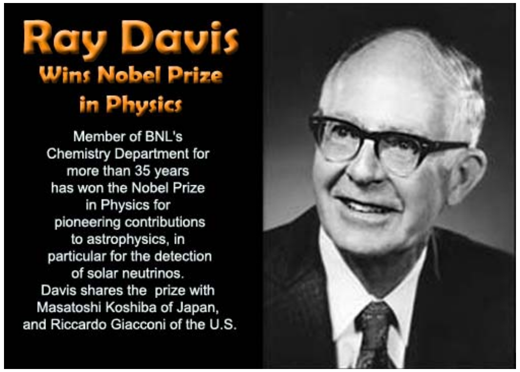
40 Years of BNL Chemistry and Neutrinos



- **HOMESTAKE** Radiochemical Detector
  615 tons of C_2Cl_4; $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$ (~40 years)
- **GALLEX** Radiochemical Detector
  30 tons of Ga; $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$ (1986 - 1998)
- **SNO** Water Čerenkov Detector (SNOLab)
  1000 metric tons of ultra-pure D_2O (1996 - ≥ 2006)
- **LENS** Real-time Detector (R&D)
  ^{115}In in Liquid Scintillator (~2000 - ?)
- **BNL-AGS NEUTRINO FACTORY**
  Very Long-Baseline Experiment- Neutrino Beam from BNL (~2002 - ?)
- **THETA-13** Real-time Detector (R&D)
  Gd in Liquid Scintillator (~2003 - ?)

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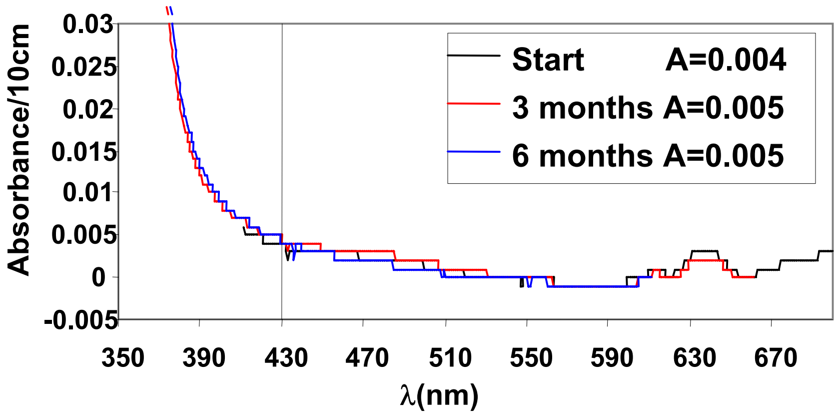
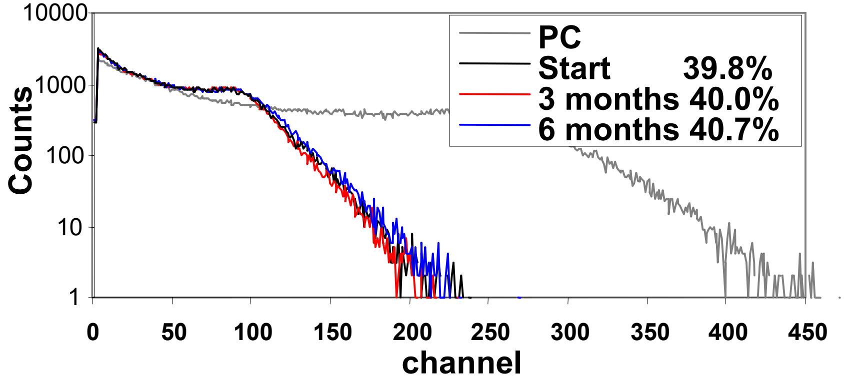
In-doped Scintillator for LENS-Sol



Stability: The UV-VIS absorbance (430 nm) with time over six months (BNL#115, In%=6.77)



Light yield with time over six months (BNL#115, 3g PBD/L , 15mg bis-MSB/L)

Bell Lab/Brookhaven National Lab developed a very consistent In-LS chemical synthesis method for LENS-Sol:

- high In content (~7%)
- good light yield (~40% of PC)
- long attenuation length (L(1/e) ~9 m without shifter)
- chemical stability for over 11 months since synthesis

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Gd-doped Scintillator for θ_{13} Reactor ν

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Advantages of adding Gd into LS for neutrino detection:

- enhance neutron capture.
- at 0.1% Gd by weight, it reduces the capture time from 200 μs on H to 30 μs on Gd $\rightarrow$ accidental background reduced by ~ 7.
- energy release of a neutrino capture on Gd is about 8 MeV (a cascade of 3-4 γ-rays), compared to 2.2 MeV for H $\rightarrow$ target volume is better defined and low energy backgrounds from other sources can be excluded.

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CHOOZ

5t 0.1% Gd-loaded scintillators

- Not stable Gd-loaded scintillator (*L* ~ 2 - 5 m) ➔ turned yellow after few months of deployment (0.4% degradation per day)
- Homogeneous detector ➔ *n* capture peak at 8 MeV
- Detector Efficiency ~70%

Palo Verde

12t 0.1% Gd-loaded scintillators

- Good Gd-loaded scintillator (*L* ~ 11 m) ➔ slight deterioration with time (0.03% degradation per day)
- Segmentation detector ➔ *n* capture peak < 6MeV
- Detector Efficiency ~10%

Loading Gd into LS is not trivial

- difficult to add *inorganic* salts of Gd into *organic* liquid scintillator → extracting agents required
- Gd-LS must be long attenuation, good light yield and stable for several years → chemical and material selections…
- purifications required to remove
  - Radioactive species that mimic the neutron-capture signal
  - Chemical species that affect the attenuation and stability

Gd-LS Chemistry and Preparation

- **Considerations of Gd-LS for θ_{13} Measurement to 1% or better**
  - C/H of the liquid scintillator must be well determined
  - concentrations of Gd and mass of the organic LS need to be identical in Near and Far detectors $\rightarrow$ special care for batch-wide preparation
- **Scenarios of Gd-LS Preparation at BNL**
  - to develop a reproducible procedure for Gd-LS synthesis
  - to dope Gd into different scintillators (PC and mix of PC and mineral oil)
  - synthesize concentrated Gd-LS (1~2 %) first, then dilute to (0.1~0.2%)
  - to establish chemical assays to remove and measure chemical and radioactive impurities

Status of BNL Gd-LS for θ_{13} Experiments

Measurements of:

- Purification
- Attenuation Length
- Light Yield
- Long-term Stability

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Purification of Radioactive Impurity

	^{238}U	^{232}Th	^{40}K
Gd_2O_3 [ppb] (IHEP)	<13	440±32	< 2.3
$GdCl_3$ [ppb] (BNL)	in preparation		

- Require purity of Gd powder < 1 ppb → 10^{-12} g/g → 0.3 Hz for 10-ton, 0.1% Gd-LS + 45 cm γ-catcher.
- Purification of Water (positive/negative ion exchange).
- Purification of Gd (ion exchange vs solvent extraction).

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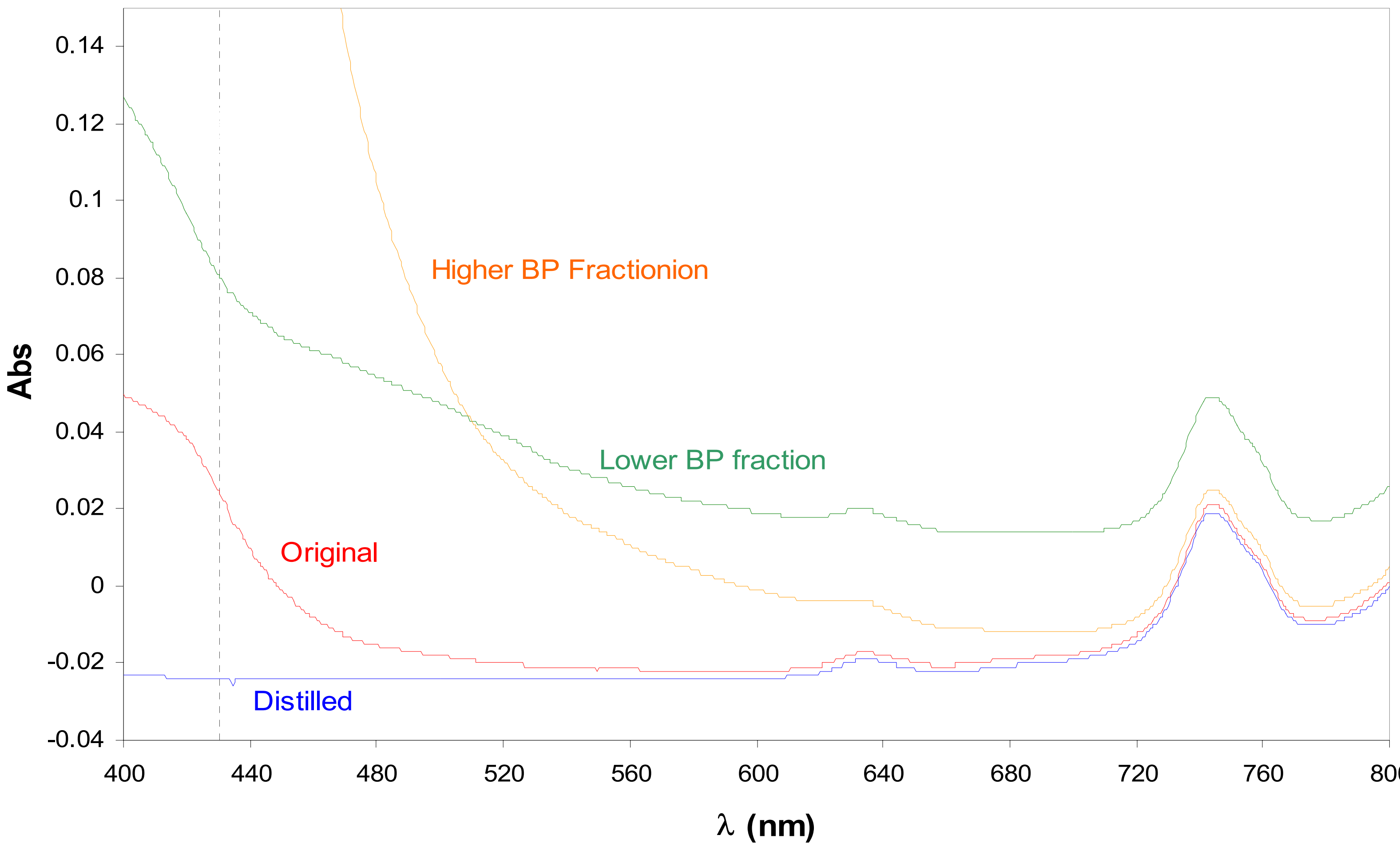
Purification of Chemical Impurity

- Purify Aqueous $GdCl_3$ separately.
- Purification of Aqueous Phase (NH_4 – carboxylate) by mixtures of organic solvents.
- Purification of Organic Phase (carboxylic acid, liquid scintillators) by dry column and temperature-dependent, vacuum distillation.
- Measure by attenuation.

Purification of carboxylic acid



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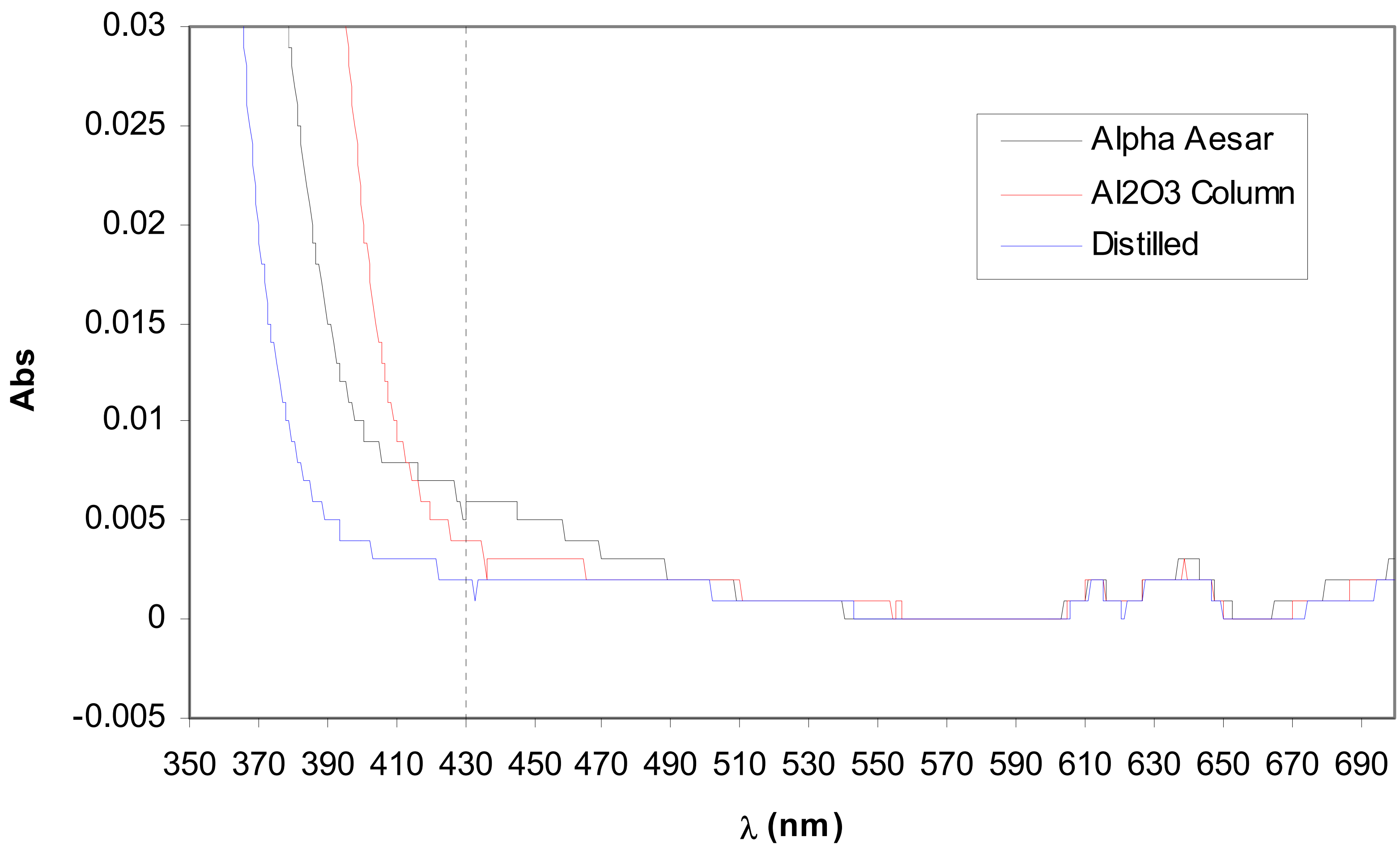
Purification of Pseudocumene, PC



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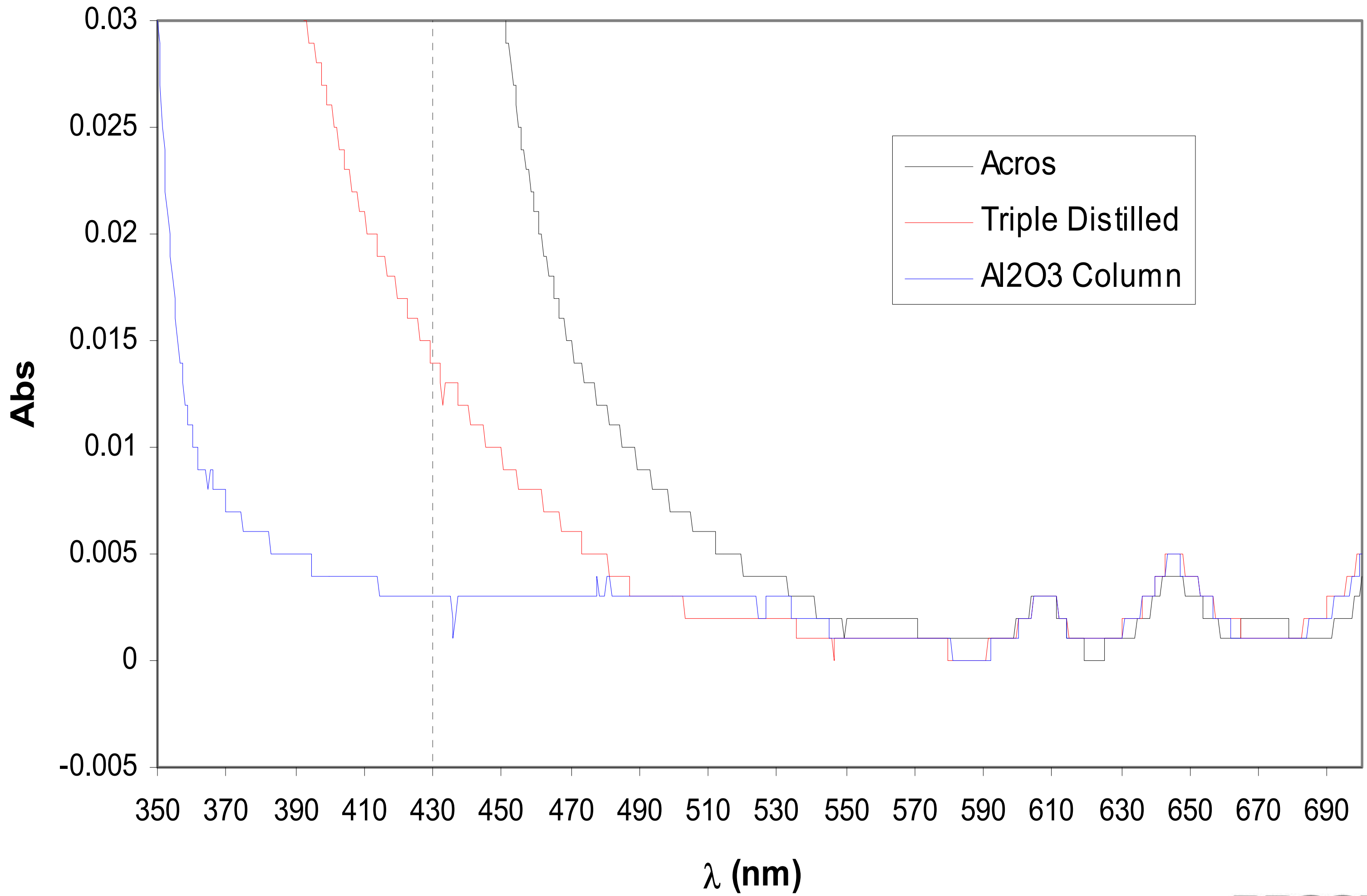
Purification of Phenyl Cyclohexane, PCH



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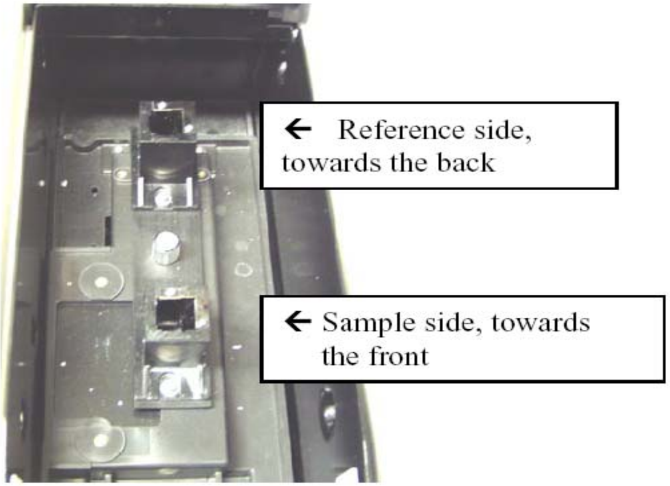
Attenuation by Shimadzu UV-1601

- 1-cm/10-cm cell
- scanning wavelengths from 190 nm to 1100 nm
- silicon photodiode
- 50W halogen lamp and deuterium lamp
- Spectrum/Quantitation/Photometric/Kinetics modes

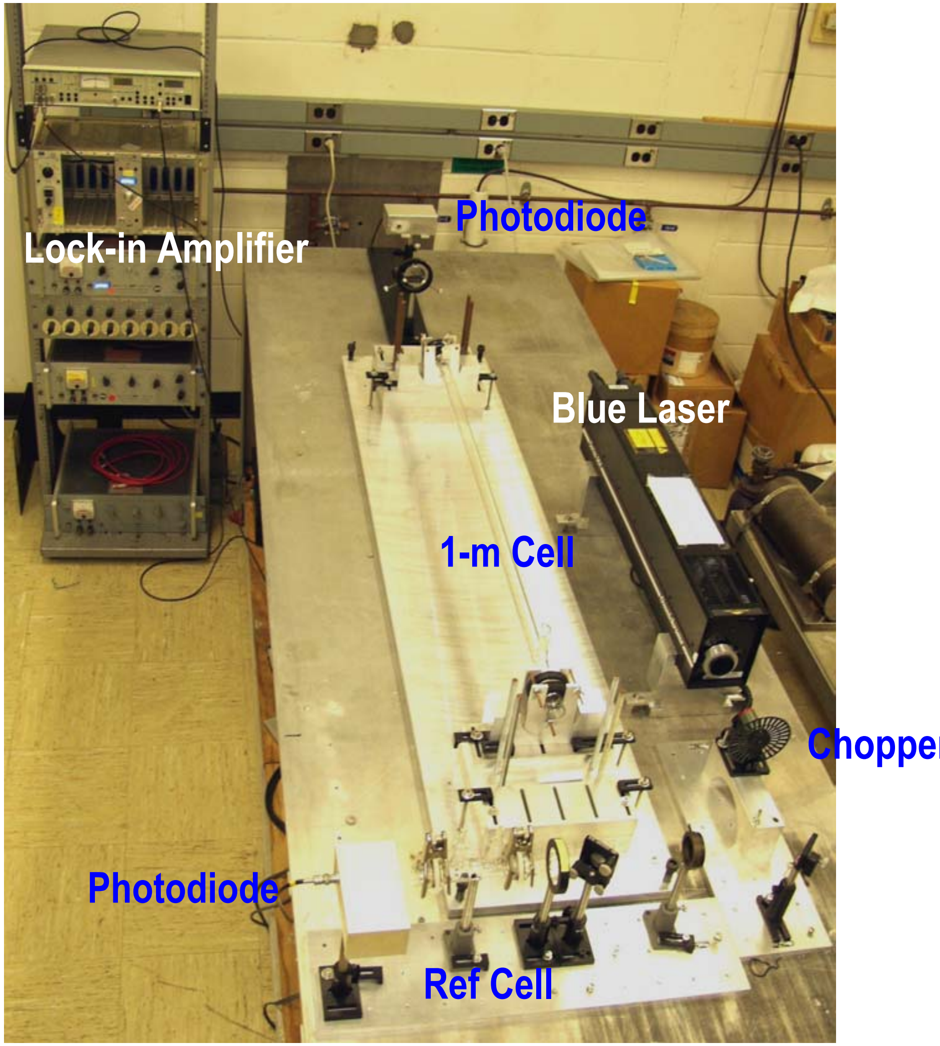


Attenuation by Long-path Optic System

- 48 mW HeCd blue laser
- single λ at 442 nm
- 2.5 mm blue beam
- ≥ 1-m horizontal cell
- silicon photodiode

$$A(\lambda) = -\log\left(\frac{I}{I_o}\right) = \varepsilon \times b \times c$$

$$L = \frac{\log(e) \times b}{A(\lambda)}$$



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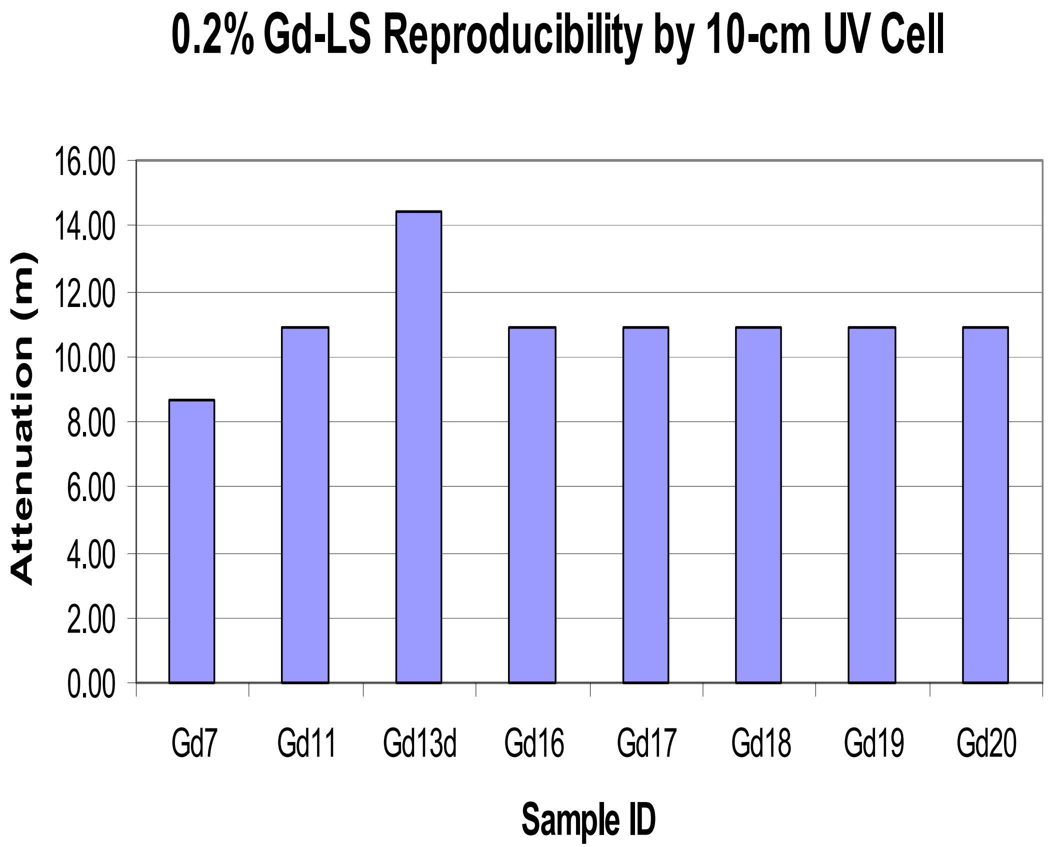
Reproducibility of Gd-LS Synthesis



Mixtures of Gd16 to Gd20 → L~16 m by 1-m Laser measurement.

- Samples are prepared from different batches under different conditions.
- The quality of PC is the main concern.
- The synthesis is very reproducible in terms of Gd extraction and physical properties.
- Need long-path laser measurement for attenuation length.

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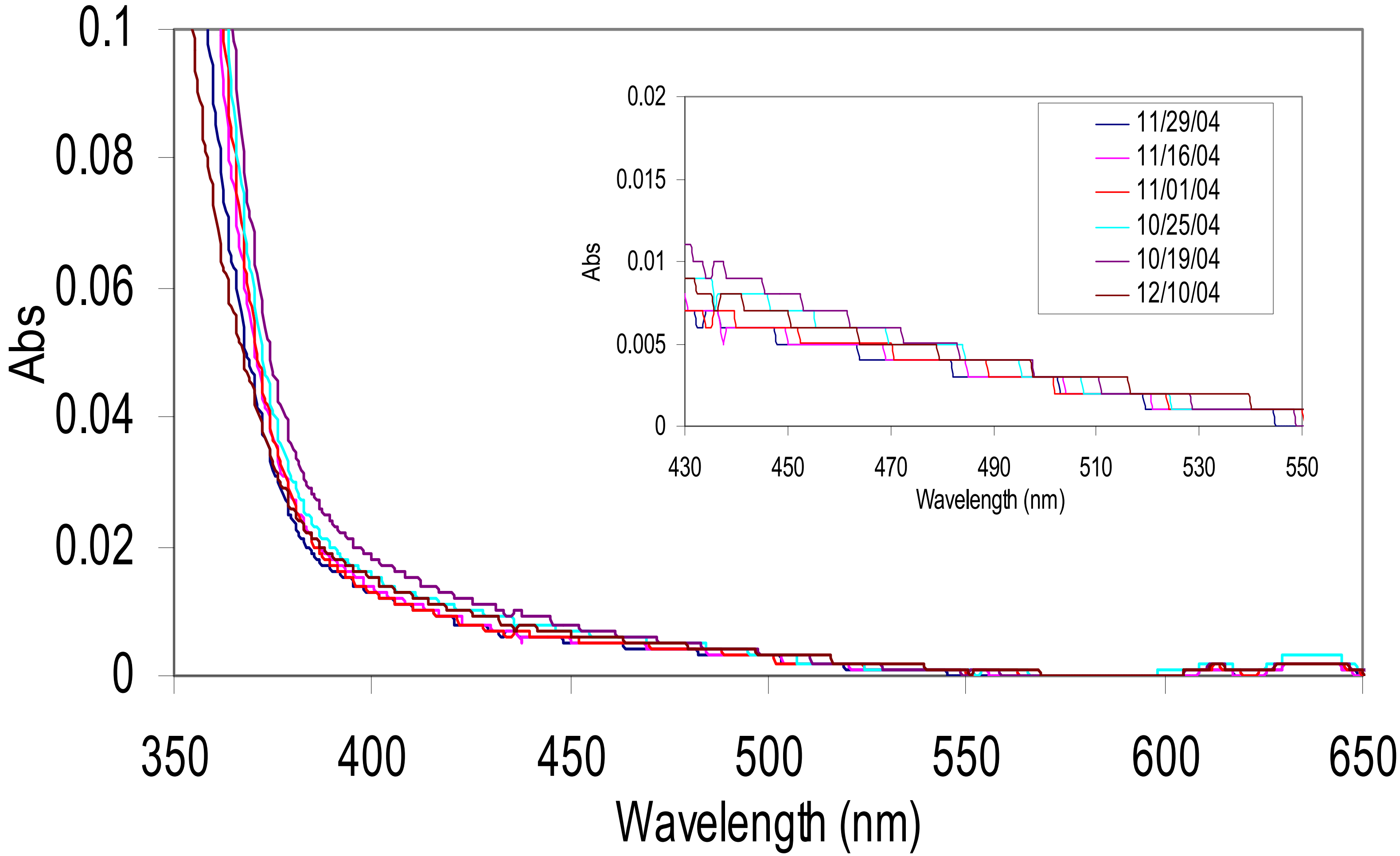
Long-term Stability Test: ~1.2% Gd-LS as a Function of Time



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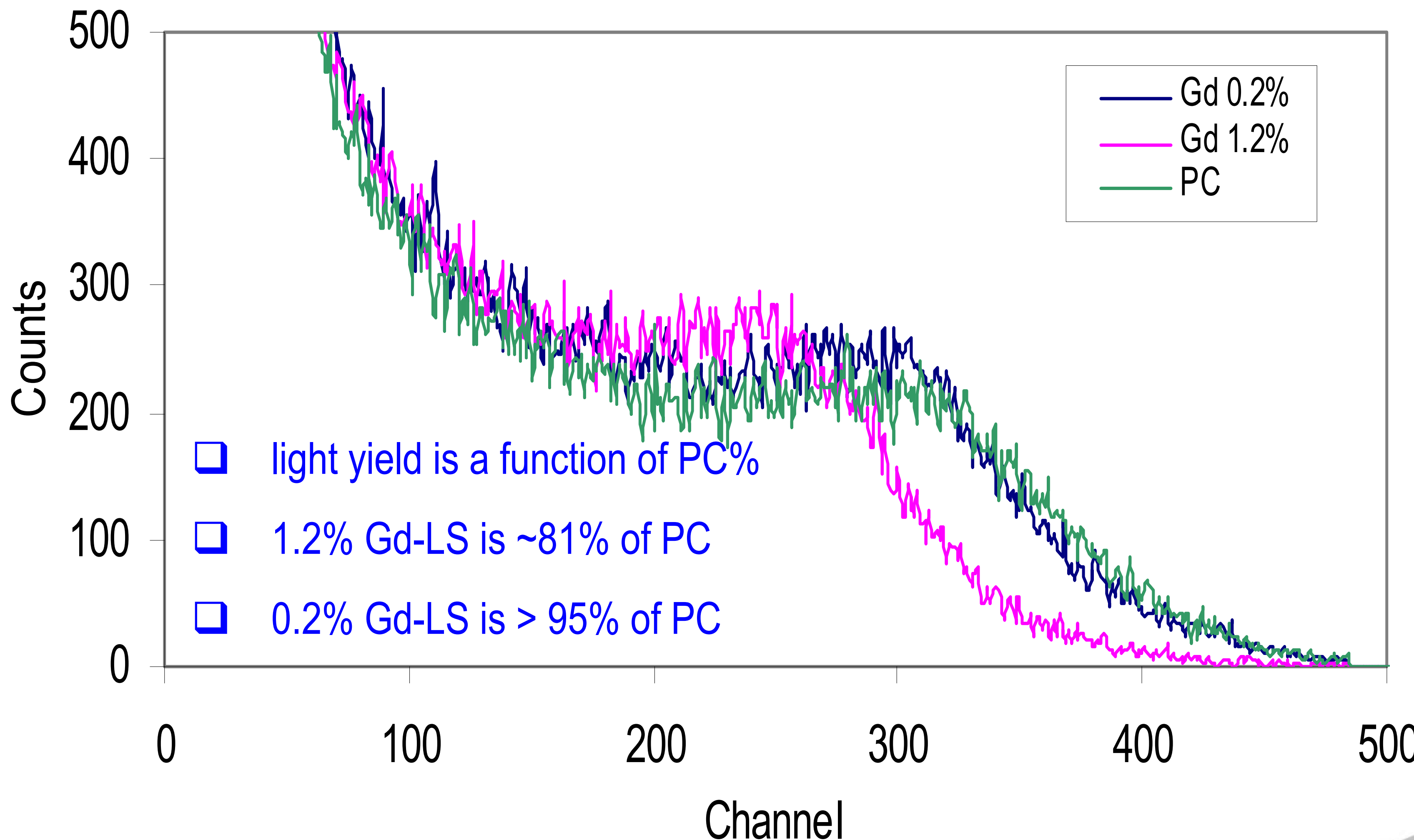
Light Yield: a Function of PC



- light yield is a function of PC%
- 1.2% Gd-LS is ~81% of PC
- 0.2% Gd-LS is > 95% of PC

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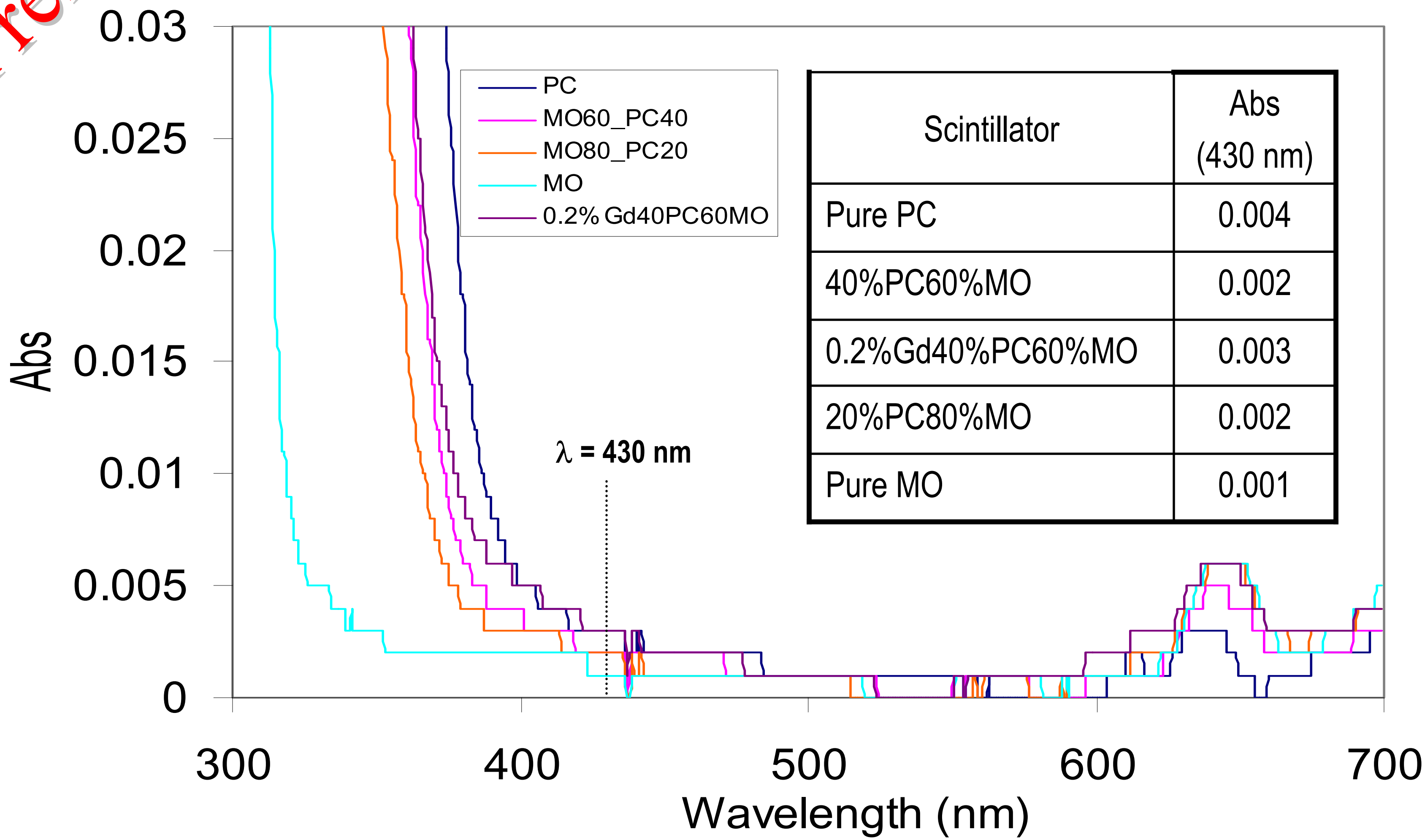
Comparisons of Different Scintillation Systems

- Pure PC
- 0.2%Gd + 40%PC + 60% MO
- 40%PC + 60% MO
- 20%PC + 80% MO
- Pure MO

UV-vis of PC/MO/Mix



Scintillator	Abs (430 nm)
Pure PC	0.004
40%PC60%MO	0.002
0.2%Gd40%PC60%MO	0.003
20%PC80%MO	0.002
Pure MO	0.001

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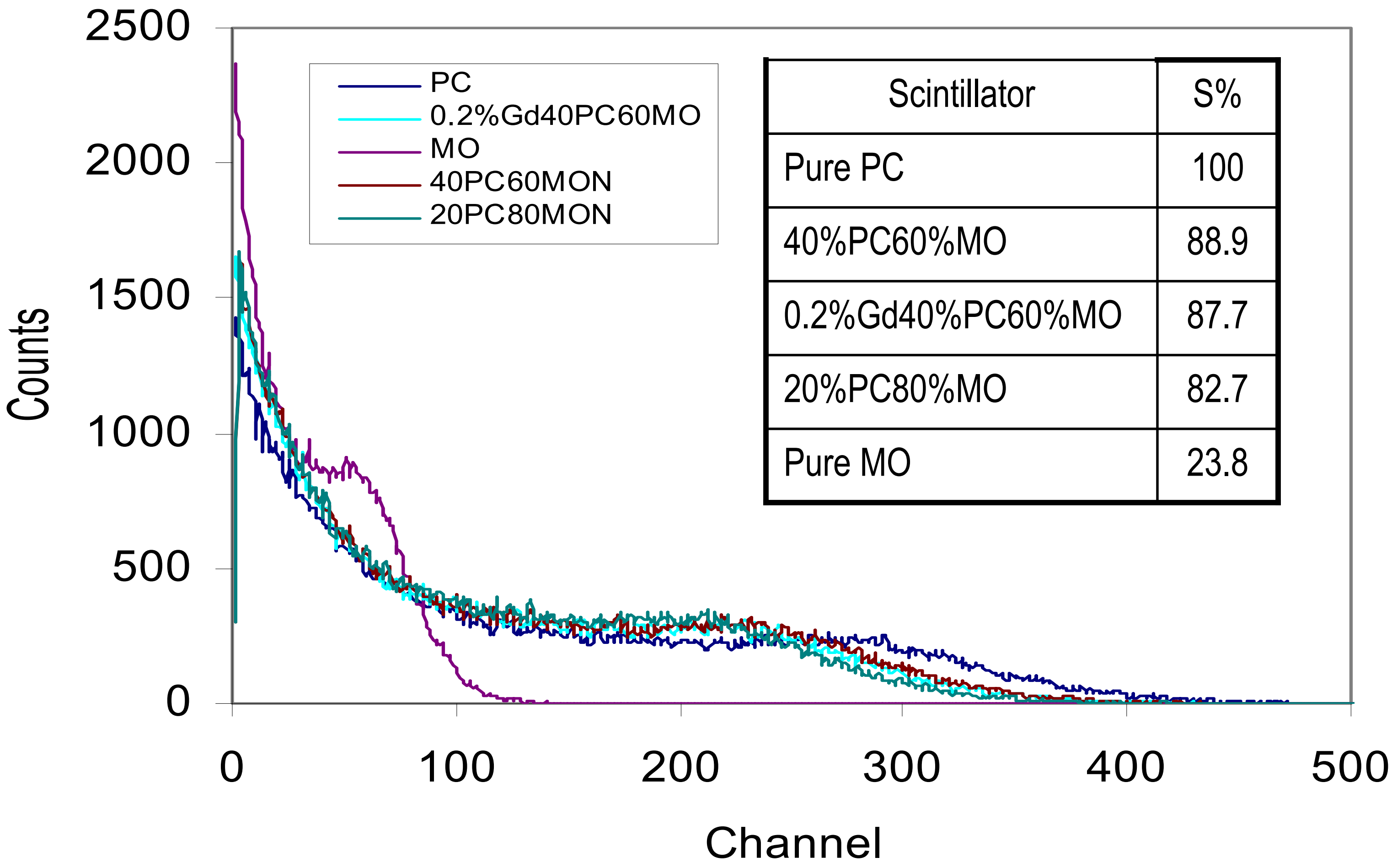
Preliminary

Light Yield of PC/MO/Mix



Scintillator	S%
Pure PC	100
40%PC60%MO	88.9
0.2%Gd40%PC60%MO	87.7
20%PC80%MO	82.7
Pure MO	23.8

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BNL Gd-LS vs BC-521 (Palo Verde)

	BNL Gd-LS	BC-521	
Measured by	BNL	BNL	Bicron
Gd %	~1.2%	~1%	1%
Attenuation Length (m)	13.5 (1-m laser) 6.23 (10-cm UV)	2.55 (10-cm UV)	> 4.00
Light Yield (s%)	81.9% PC	85% PC	57% anthracene
Stability	2 months and continuing	N/A	long term

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Summary

- The synthesis of Gd-doped scintillator is very reproducible in terms of Gd extraction (~85%), attenuation (~15 m for 0.2%Gd), and light yield (>95% of pure PC).
- Chemical purification is essential for attenuation and long-term stability.
- Mineral oil has better attenuation than PC.
- High concentrated Gd-doped scintillator has been stable for over 2 months in terms of attenuation and light yield.
- Long-Path Optical Measurement is necessary.

Future R&D at BNL

- Assays to remove radioactive impurities.
- Compatibility test of scintillator with acrylic.
- Aging test, temperature-dependent kinetics approximately doubles per $\Delta 10^{o}$ C.
- C/H ratio determination.
- Scale-up, closed-loop production.

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