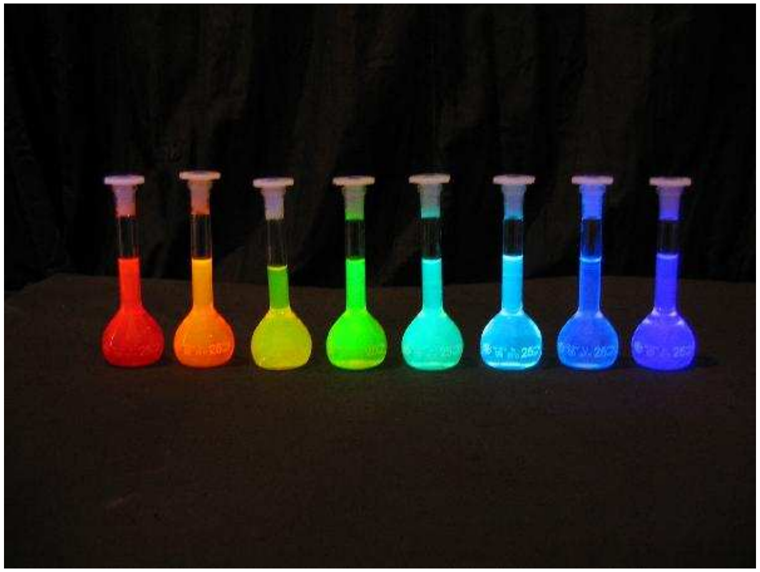
Liquid Scintillator Calorimetry for the Electron-Ion Collider



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May 9, 2011

Need for Diverse R&D Program on EIC Calorimetry

To build the best calorimetry detectors for the EIC, various technological options need to be thoroughly investigated. Utilizing knowledge gained by a multitude of calorimetry projects, one can design a new detector with good control and optimization of performance parameters, manufacturability and metrological limits.

In-depth understanding of a particular technology reduces a “research” component during development of a new detector and allows concentrating more on instrumentation aspects. A well-studied technology leads to timely design and construction of the calorimeter, even with limited resources.

Next generation calorimeters require an optimal performance/cost ratio. This can be achieved only by making several detector prototypes of different geometries and designs. The follow-up systematic comparison of the prototypes, with cost evaluation, will help make the right choice for what kind of calorimeters are better suited for the EIC detectors.

Studies of different technologies allow considering several alternative detector configurations. One configuration can become the main preferred choice, while others will be backup options for altered budget and construction schedule scenarios.

Eventually, few calorimetry technologies will be presented and outlined in Conceptual Design Reports.

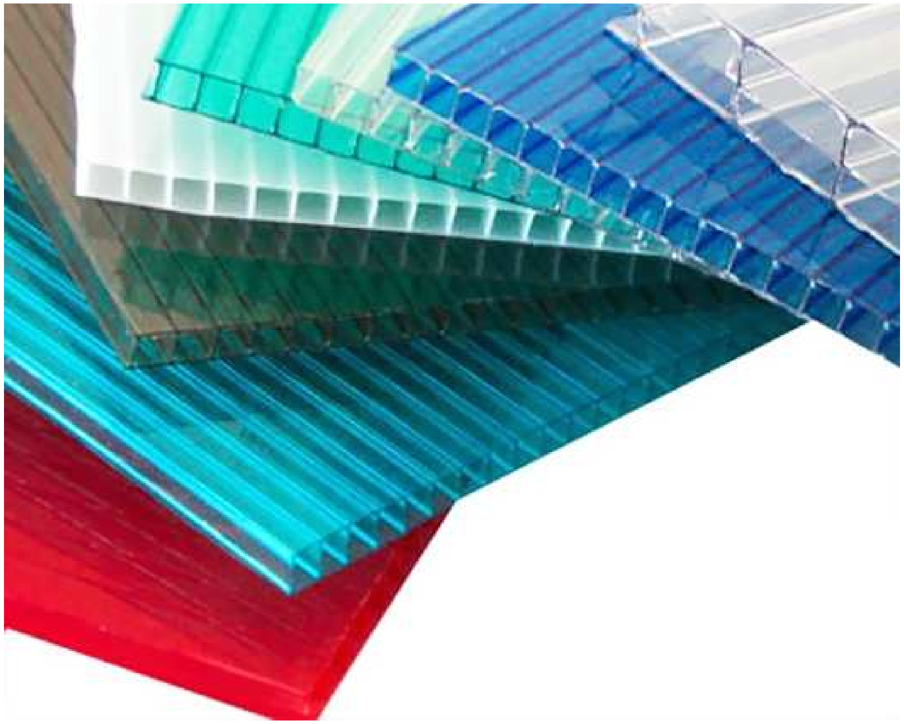
Objective of the Project

Develop inexpensive and radiation hard technology for forward calorimetry detectors at the EIC.

The technology will use liquid paraffin based scintillators contained in off-the-shelf commercially available cell polycarbonate panels.

Criteria for the technology:
- safety against explosion and fire hazards,
- low detector fabrication, operation and maintenance costs,
- easy upgrades, replacements and disposal.

Properties of a variety of inexpensive liquid scintillators will be studied.



Liquid Scintillators

Liquid scintillator solutions consist of a solvent and a fluor. A particle which passes through the liquid energizes molecules of the solvent; those molecules, in turn, excite molecules of the fluor that emit light. Sometimes, secondary (or even tertiary) fluors are added to absorb the light from the primary fluor and reemit the light at different wavelength to match maximum sensitivity wavelength of a readout device.

Very convenient for making detectors of a variety of shapes. Low costs allow building large volume detectors (popular in neutrino physics).

Higher transparency to its own emitted light, compared to crystals or plastic organic scintillators.

Light yields of best liquids are 60-70 % of anthracene's.

Short component of a decay time is equal to 3-5 ns.

Etalon mixture (the one that is considered to have 100 % scintillating efficiency for liquid scintillators):
toluene +
p-terphenyl (primary fluor) (4 g/l) +
1,4-bis(5-phenyl-2-oxazolyl)benzene (POPOP) (secondary fluor) (0.1 g/l)

Active Detection Material Cost

Homogenous calorimeters:

$PbWO_4$:	8 million U.S. dollars per m^3
Lead-Glass:	>1.5 million U.S. dollars per m^3

Sampling calorimeters*:

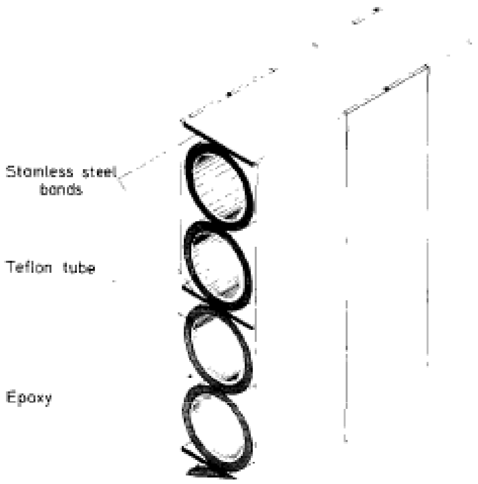
Polystyrene-based scintillator:	700 thousand U.S. dollars per m^3
Liquid scintillator** in polycarbonate containers:	~25 thousand U.S. dollars per m^3

* Costs for absorber material are not included

*Least expensive liquid scintillator in the proposal

WA-70 Lead-Scintillator EMCal

Fine grained sampling EMCal installed at OMEGA spectrometer at SPS primarily to study direct photons.



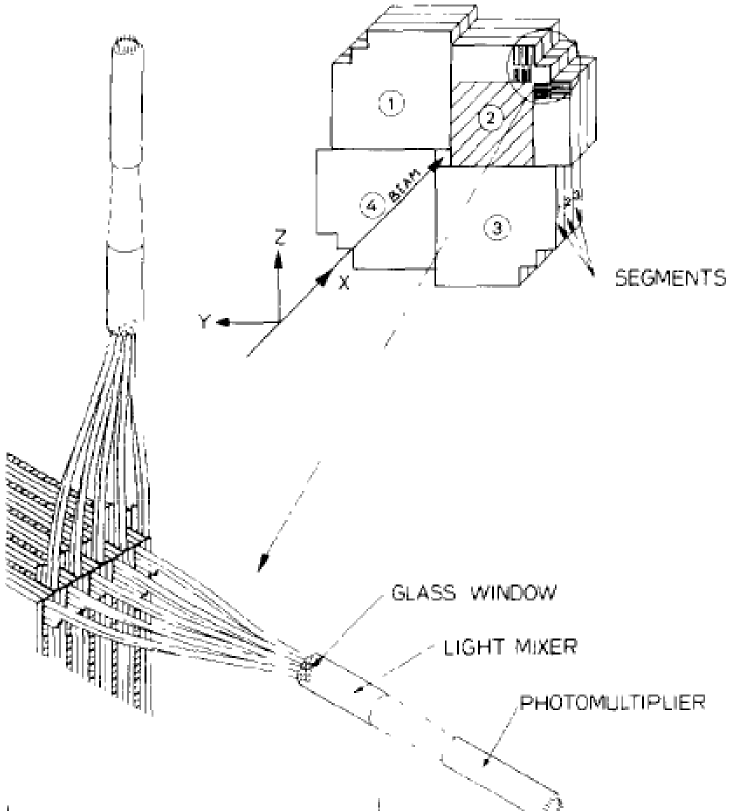
Active layers assembled from stacks of sheets. The sheets were made from extruded teflon tubes embedded in epoxy and steel skin.

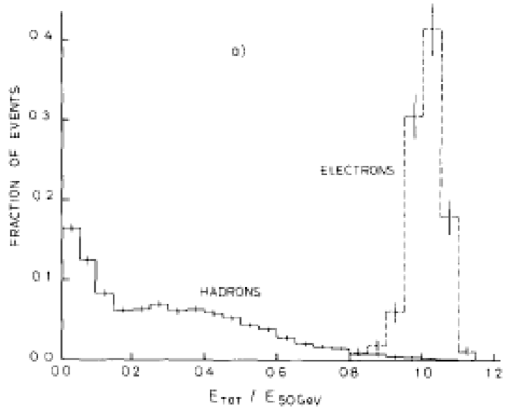
Every tube filled with oil-based scintillator from Nuclear Enterprises and read out by PMTs. 4.4 mm internal diameter and 2.4 m length.

Lateral geometry of 2 x 2 segments and thickness of 3 segments. Every segment made from 10 layers of lead and 10 layers of teflon tubes with orthogonal readouts.

EM energy resolution = $12.6\%/\sqrt{E} + 3.2\%$
Ability to identify hadrons, as well as to measure longitudinal shower development.

Physics: π^0, η, direct γ with 280 GeV hadron beams.



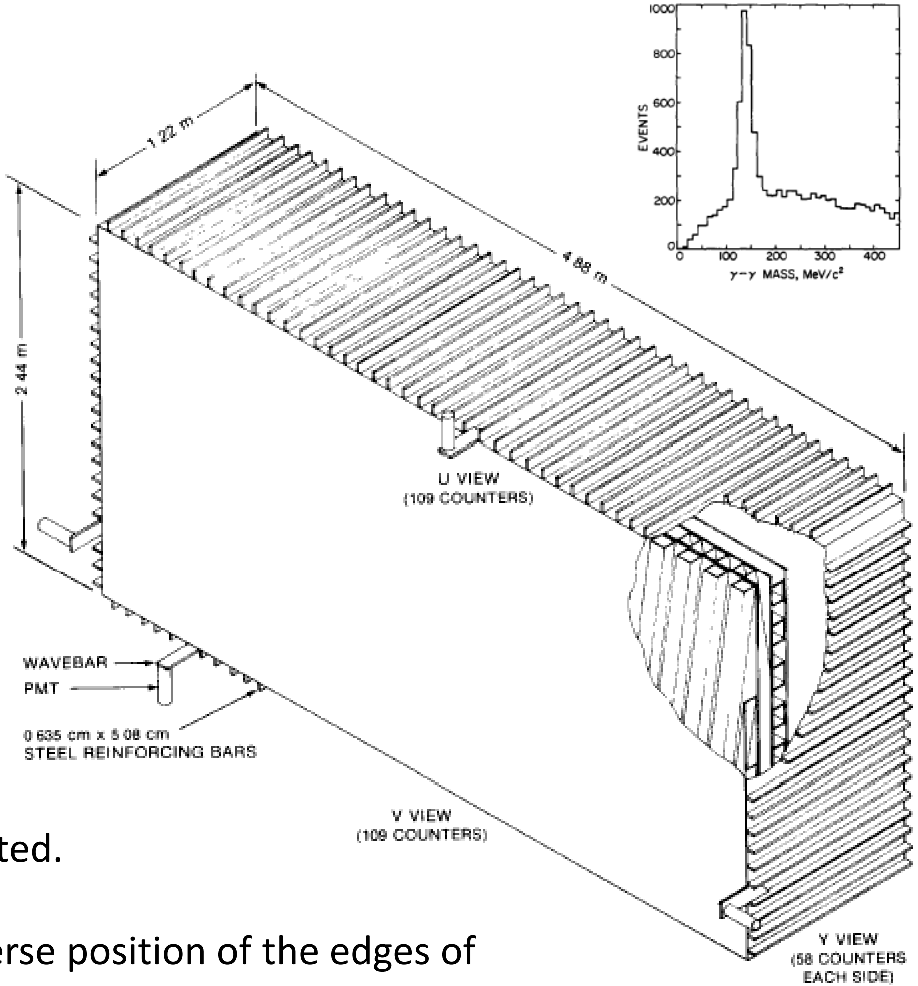


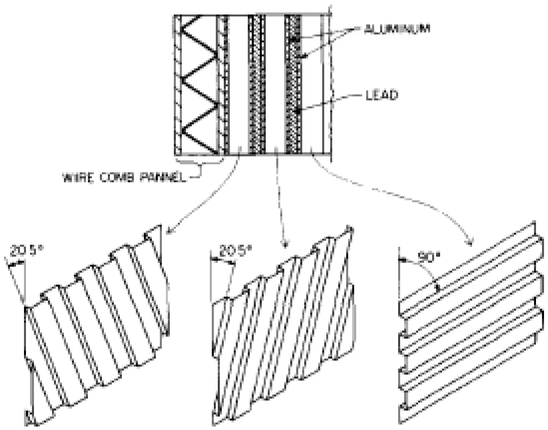
Excellent rejection of electrons from hadrons.

FNAL SLIC Lead-Scintillator Calorimeter

Multiphoton shower detector SLIC installed at FNAL tagged photon spectrometer.

60 layers of lead and scintillator. Active layers made of corrugated teflon-coated aluminum sheets. Corrugation had square-wave patterns with 3.17 cm widths to form 1.27 cm thick conduits filled with mineral oil based scintillator, thus making scintillating counters. The counters had 3 possible orientations, giving 3 coordinates for the transverse position of each shower.





Design allowed longitudinal segmentation, but it was not implemented.

For the same transverse position of the edges of the counters, light collection was done by a single wavebar.
Sampling EM energy resolution of 15%. Position resolution of ~3 mm.

Physics: used in studies of D^0->K$^-\pi^+\pi^0$ decay, as well as for e and μ identification in J/ψ->e$^+$e$^-$ and J/ψ->$\mu^+\mu^-$ and π^0 identification in γp->J/$\psi\chi$.

Forward SDC Calorimeter

Forward calorimeter of the SDC detector was supposed to be built with rapidity acceptance of $3<|\eta|<5$. In the SSC environment, the EM radiation dose at $\eta=5$ would have reached few Gigarads annually.

A “spaghetti” calorimeter was proposed as a forward detector. In that calorimeter liquid scintillator fibers contained in Pyrex borosilicate tubes were supposed to be embedded in a metal matrix and oriented along the beam.

During a short R&D period several prototypes were made and tested. The tubes had 2 mm internal diameters. Different scintillators from Nuclear Enterprises, Bicron and Nuclear Diagnostics were studied for the light yield and attenuation, using 50 mCu ^{90}Sr source.

It is worth to note that in WA-70, SLIC, SDC projects, as well as in neutrino or other lower energy, or generic R&D projects, physics groups were dealing with liquids supplied by industry. In most cases, user did not know exact formula of the solution, thus he could only give recommendations/requests to vendor, and later measure performance characteristics of the scintillators.

Compositions of the scintillators in most cases were proprietary information, thus physics groups did not have complete control of optimization and costs.

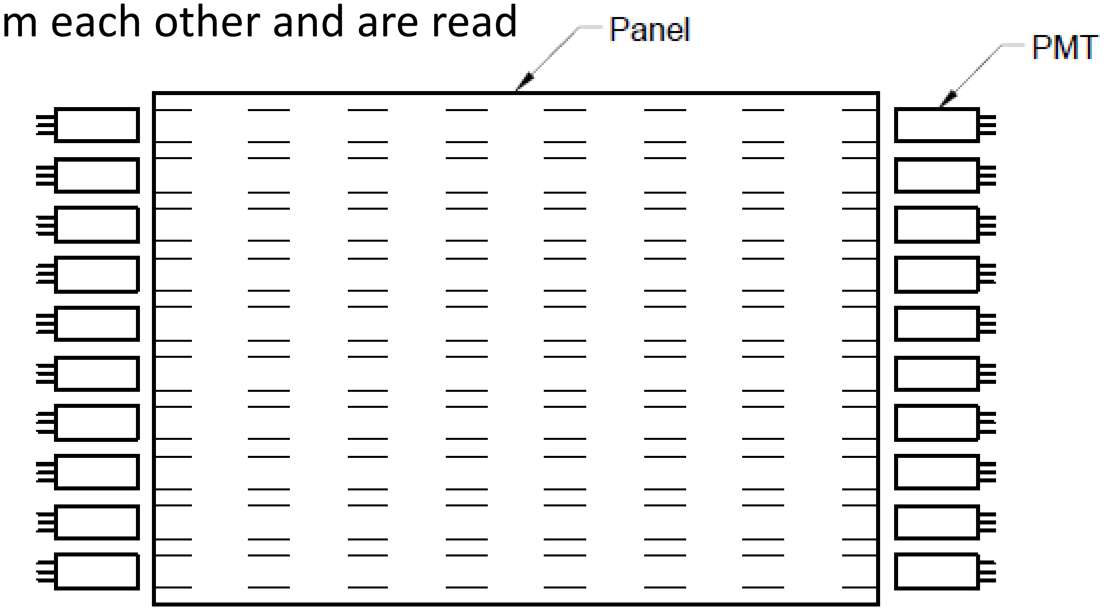
Forward Calorimeters at the EIC

Adaptation of WA-70 and SLIC design concepts.

Make active detector layers from commercially available mass-produced cell polycarbonate panels. Low cost, easily maintained or/and disposed, non-hazardous.

Cell polycarbonate panels have “already built within” conduit-cells, to be filled with liquid scintillator.

Cell-conduits are optically isolated from each other and are read out by PMTs.



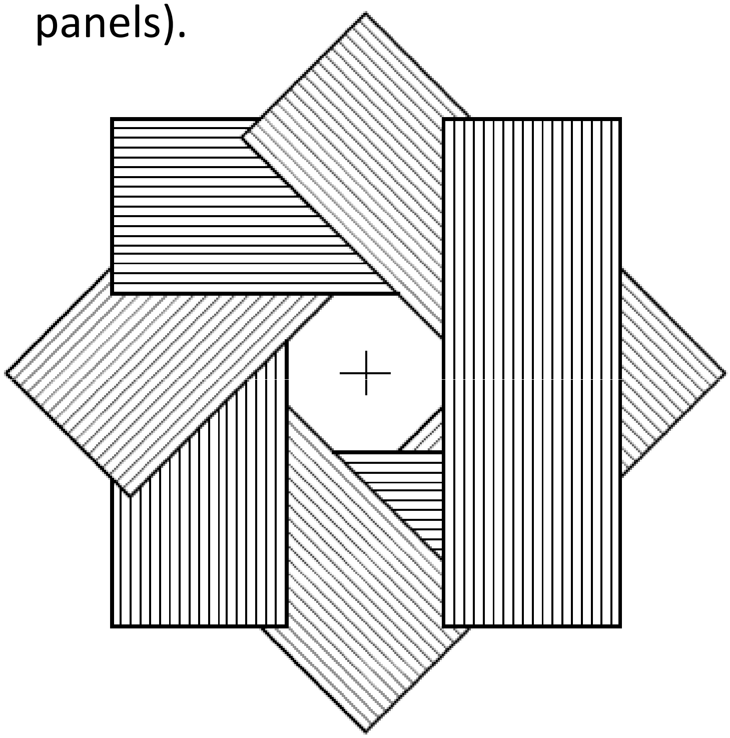
Later identify what kind of forward detectors: EMCals, HCals, hybrid calorimeters, etc.

Individual per-cell PMT readout, or bundling from several cells and panels.

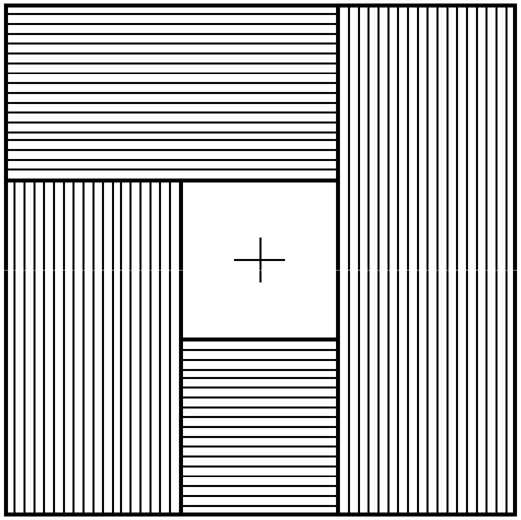
Longitudinal segmentation from the start-up or as upgrade implementation.

Assembling Active Layer

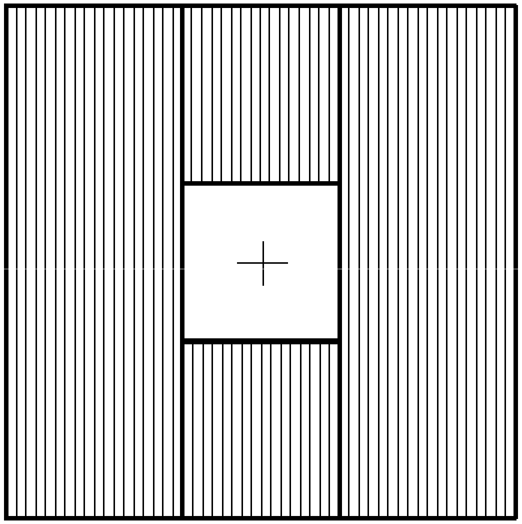
PMTs can be placed away from the beamline. In cases of identical panels, light can be read out from both opposite ends of the cell-conduit (1 PMT per cell in short “non-identical” panels).



“Wheel” assembled from 8 identical panels



“Wall” assembled from 4 identical panels



“Wall” assembled from 4 non-identical panels

Simulations will find the optimum number of “wheels”/”walls” per active layer, the number of layers, sampling fraction/frequencies, cell orientations, absorbers, etc.)

Radiation Damage

If collision products are thought to have a fixed transverse momentum,

the energy deposited in the calorimeter: $dE = (p_T/\sin\theta)\cdot d\eta d\phi$,

while for small θ: $\sin\theta = \theta$ and $d\eta = d\theta/\theta$.

For the detector element dA at distance R from the vertex: $dE = D\cdot dA\cdot dz\cdot\rho$,

where D is the dose, dz is the EM shower max depth, ρ is the mass density of the detector.

Thus, the dose from one collision: $D = p_T\cdot(\theta^3\cdot R^2\cdot dz\cdot\rho)^{-1}$

Accumulated dose: $D = t\cdot f\cdot p_T\cdot(\theta^3\cdot R^2\cdot dz\cdot\rho)^{-1}$,

where f is the event rate, and t is the duration of data taking.

Doses at Forward Rapidities

Rapidity acceptances of forward calorimeters can reach $\eta = 5$
(see, for example, “A detector for forward physics at eRHIC: Feasibility Study”, hep-ex/0407053v1)

Hypothetical sampling calorimeter made of equally thick iron and organic scintillator layers:
ρ= 4.5 g/cm^3,
f = 100 MHz,
t=10,000,000 sec (which is ~116 days of 24/7 data taking per year),
p_T = 0.1 GeV.

η	θ	linear segmentation for $\Delta\eta$=1.0 at 4 m from vertex	Radiation dose accumulated over 5 years
3.0	5.70^0	-	0.8 Mrad
4.0	2.10^0	25.1 cm	16 Mrad
5.0	0.77^0	9.3 cm	220 Mrad

Note: shower max depth increases from 4X_0 (η=3.0) to 6X_0 (η=5.0).

Radiation Hardness

- Liquid scintillators are inherently less sensitive to radiation damage than solids. A toluene-based scintillator with PPO fluor starts manifesting degradation of performance after absorbing a dose of 3 Gigarads from ^{60}Co source
- The calorimeter can be constructed in such a way that allows circulation or replacement of liquids
- If active layer materials are inexpensive and costs of production, assembly and installation are low, the active layers can be disposed and replaced with newly made

Liquid Scintillator Solutions

Traditional scintillators based on toluene or white spirit have low flash temperatures, thus posing fire or explosion hazard (in part, that prevented wide-spread applications in physics experiments).

To make the liquid less hazardous, while keeping high scintillating efficiencies and high optical transparencies, one needs to mix by-products of petroleum distillation with certain aromatic hydrocarbons.

Inexpensive scintillator can be made from such easily accessible components as

- liquid paraffin, as a main solvent,
- naphthalene, methylnaphthalene, or xylene (xylol), as added aromatic hydrocarbons,
- fluors:

PPO: 2,5-diphenyloxazole
BPO: 2-phenyl-5-(4-biphenyl)-oxazole
TPP: 1,3,5-triphenyl-2-pyrazoline

these three were found to work well with naphthalene, methylnaphthalene and xylene.

Wave-shifters can be added, if necessary.

Hazard Categories

Hazard Materials Identification System (HMIS) defines hazards ratings as

Flammability:

3: Materials capable of ignition under almost at normal temperature conditions. Includes flammable liquids with flash points below (23 ^{0}C), as well as liquids with flash points between 23 ^{0}C and 38 ^{0}C;

2: Materials which must be moderately heated or exposed to high ambient temperatures before ignition will occur. Includes liquids having a flash point at or above 38 ^{0}C but below 93 ^{0}C (e.g. diesel fuel);

1: Materials that must be preheated before ignition will occur. Includes liquids, solids and semi solids having a flash point above 93 ^{0}C (e.g. canola oil).

Flash temperature of liquid paraffin is equal to 98 ^{0}C.

Health:

2: Temporary or minor injury may occur;

1: Irritation or minor reversible injury possible.

Saint Gobain Liquid Scintillators: Properties

Product	Ingredients other than fluors	Formula	Flash point	Flamma-bility	Health hazard
BC-501A	xylene (>90%)	$C_6H_4\,(CH_3)_2$	29 ^{0}C	3	2
BC-505	1,2,4-trimethylbenzene (>97.5%)	C_9H_{12}	49 ^{0}C	3	2
BC-509	hexaflurobenzene (>99.75%)	C_6F_6	10 ^{0}C	3	2
BC-517H	1,2,4-trimethylbenzene (<30%), mineral oil (>70%)	proprietary	81 ^{0}C	1	1
BC-517L	1,2,4-trimethylbenzene (>30%), mineral oil (<60%)	proprietary	102 ^{0}C	1	1
BC-517P	1,2,4-trimethylbenzene (<10%), mineral oil (>90%)	proprietary	116 ^{0}C	1	1
BC-517S	1,2,4-trimethylbenzene (<60%), mineral oil (>30%)	proprietary	54 ^{0}C	2	1
BC-519	1,2,4-trimethylbenzene (<40%), mineral oil (<60%)	C_9H_{12} + petroleum distillate	63 ^{0}C	1	2
BC-521	1,2,4-trimethylbenzene (>85%)	proprietary	44 ^{0}C	2	2
BC-523A	1,2,4-trimethylbenzene (>30%), trimethylborate (<60%)	proprietary	1 ^{0}C	3	2
BC-525	1,2,4-trimethylbenzene (>50%), 2-ethoxyethanol (<6%)	proprietary	81 ^{0}C	1	2
BC-531	linear alkylbenzene (95%), 1,2,4-trimethylbenzene (5%)	proprietary	93 ^{0}C	2	1
BC-533	isoparaffinic solvent (>75%), aromatic hydrocarbons (<25%)	proprietary	65 ^{0}C	1	1
BC-537	benzene-d_6 (>98%)	proprietary	-11 ^{0}C	3	2

Hazardous Materials Identification System (HMIS) for flammability and health hazard

Saint Gobain Liquid Scintillators: Performance

Product	Light output (anthracene)	Attenuation length in bulk	Applications	Comments
BC-501A	78 %	N/A	γ, fast n	pulse shape discrimination
BC-505	80 %	N/A	γ, fast n	large volume detectors
BC-509	20 %	N/A	γ	n-insensitive, H-free
BC-517H	52 %	>5m	γ, fast n, cosmic, charged	acrylic plastic compatible, large tanks
BC-517L	39 %	>5m	γ, fast n, cosmic, charged	acrylic plastic compatible, large tanks
BC-517P	28 %	>6m	γ, fast n, cosmic, charged	acrylic plastic compatible, large tanks
BC-517S	66 %	>4m	γ, fast n, cosmic, charged	acrylic plastic compatible, large tanks
BC-519	60 %	N/A	γ, fast n	pulse shape discrimination, large tanks
BC-521	68 %	>4m	n spectroscopy, ν	gadolinium loaded
BC-523A	65 %	>4m	total absorption n	boron loaded, pulse shape discrimination
BC-525	55 %	>4.5m	n, ν	gadolinium loaded, acrylic compatible
BC-531	59 %	>3.5m	fast n, cosmic	acrylic and PVC compatible
BC-533	51 %	5m	γ, fast n, cosmic	for low temperatures, large volumes
BC-537	61 %	N/A	fast n	pulse shape discrimination

This Project Reference Mixtures (1)

Solutions developed and patented (now public domain) by the Institute of Single Crystals of the National Academy of Sciences of Ukraine:

N	liquid paraffin	naphthalene	α-methyl-naphthalene	η-xylol	PPO	λ_{max}	scintillating efficiency	transparency at λ = 400 nm
1	94.5 %	5 %	-	-	0.5 %	370 nm	54 %	90 %
2	89.5 %	10 %	-	-	0.5 %	365 nm	64 %	90 %
3	89.5 %	-	10 %	-	0.5 %	370 nm	66 %	90 %
4	79.5 %	-	-	20 %	0.5 %	370 nm	60 %	90 %
5	79.5 %	10 %	-	10 %	0.5 %	370 nm	70 %	90 %

N	liquid paraffin	naphthalene	α-methyl-naphthalene	η-xylol	BPO	λ_{max}	scintillating efficiency	transparency at λ = 400 nm
6	94.5 %	5 %	-	-	0.5 %	390 nm	72 %	90 %
7	89.5 %	10 %	-	-	0.5 %	395 nm	90 %	90 %
8	89.5 %	-	10 %	-	0.5 %	390 nm	88 %	90 %

*Mixtures with 2-phenyl-5-(4-biphenyl)-oxazole (BPO) will not be investigated due to high costs of BPO.

This Project Reference Mixtures (2)

N	liquid paraffin	naphthalene	α-methyl-naphthalene	η-xylol	TPP	λ_{max}	scintillating efficiency	transparency at λ = 400 nm
9	94.5 %	5 %	-	-	0.5 %	435 nm	52 %	92 %
10	89.5 %	10 %	-	-	0.5 %	440 nm	64 %	94 %
11	89.5 %	-	10 %	-	0.5 %	440 nm	64 %	95 %
12	89.6 %	-	10 %	-	0.4 %	440 nm	62 %	94 %
13	89.4 %	-	10 %	-	0.6 %	435 nm	64 %	93 %
14	89.7 %	-	10 %	-	0.3 %	435 nm	45 %	95 %
15	89.3 %	-	10 %	-	0.7 %	440 nm	50 %	94 %
16	79.5 %	-	-	20 %	0.5 %	440 nm	58 %	94 %
17	79.5 %	10 %	-	10 %	0.5 %	435 nm	70 %	94 %

The reference mixtures will be the baseline liquid scintillators to be tested with polycarbonate containers. However, we might investigate how modifications of the solutions from their baseline equations affect the light yields and light attenuation lengths.

Effects of adding POPOP to the mixtures, which use PPO fluor, will be studied, as well.

Cost Comparison

Available from industry and quoted as May, 2011:

BC-517L:	$230 per gallon
BC- 517P:	$220 per gallon
BC-525:	$355 per gallon
BC-531:	$390 per gallon

Proposed least expensive solution:

liquid paraffin (94.5 %) + naphthalene (5 %) + PPO (0.5 %) + POPOP: $60 per gallon

Polycarbonate

Polycarbonate sheet panels have been mass-produced mostly for construction and farming needs.

12-250 times stronger than glass. Density = 1.2 g/cm^3.
Non-flammable. Upper working temperature = 120 ^{0}C.

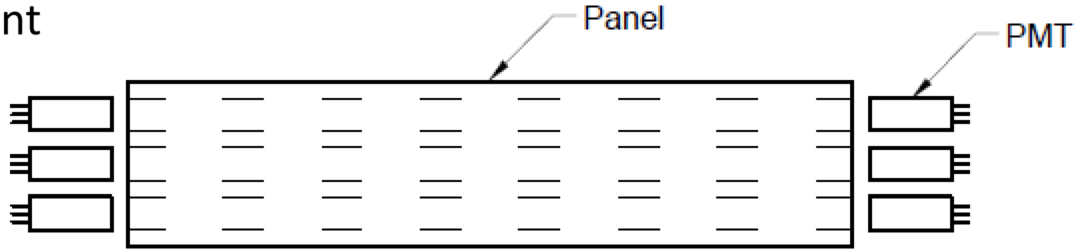
Transparent and non-transparent with different colors.

Cell polycarbonate has air gaps between panel sheets. The air gaps are mechanically separated by internal walls, which leads to high rigidity and low mass of the panel.
Cell polycarbonate usually achieves same performance parameters as monolythic polycarbonate, but with less amount of the material.

Thicknesses of cell panels: from 4 mm to 32 mm. Mass of 1 m^2 panel is equal to 1.5-3.5 kg.

Since it is not going to be a scintillator, but a container for liquid scintillators, attention to radiation damage is paid in regard to mechanical properties, e.g. the material may become brittle.
However, studies performed up to 100 Mrad dose showed no changes in Brinell hardness number.

Prototypes



Two prototypes made of non -transparent monolythic polycarbonate*. Each panel will have 3 cell-conduits.

Length: 2 m. Internal cell dimensions:
1 x 1 cm^2 and 2 x 2 cm^2. Thus the total internal volumes will be 0.6 liters and 2.4 liters.

End caps will be made of transparent polycarbonate for light read-out by PMTs. Direct optical coupling of the PMTs to the caps, no optical fibers are envisioned for light transfer. Mechanisms to attach PMTs to the panels will be designed and made. Special covers will protect PMTs from accidental environmental light.

The panels will be refilled with liquids rather frequently, mechanisms will be made to make refills easy, and keep the panels leakproof. The cells will be hydroisolated from each other so only one cell can be filled, when necessary.

PMTs: head-on Hamamatsu R3878 with a diameter of 10 mm and a photocathode active area size of 8 mm. Spectral response is from 165 nm to 650 nm with a peak at 420 nm. Quantum efficiency slowly changes when the wavelength increases from 370 nm to 440 nm.

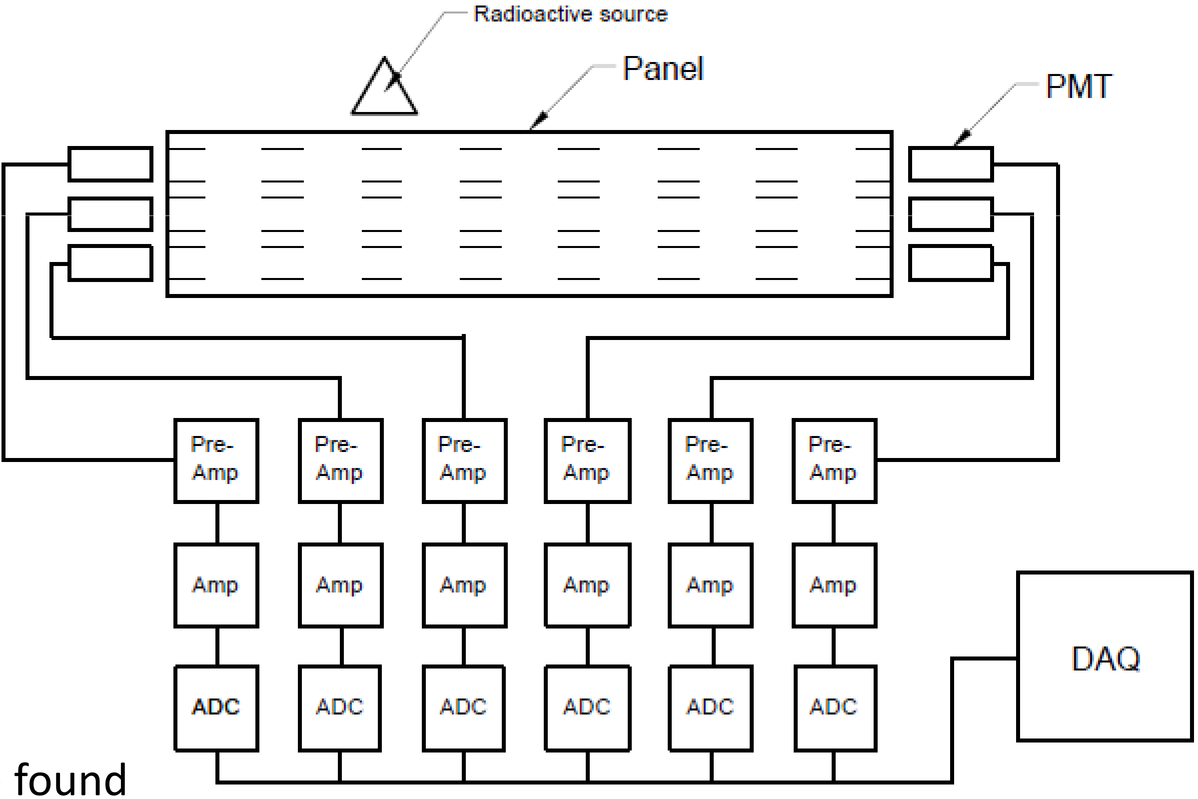
*Monolythic, to reduce production costs; industry mass-produces transparent cell polycarbonate.

Experiment

Method is similar to that of R&D project on liquid scintillator fibers for the SDC.

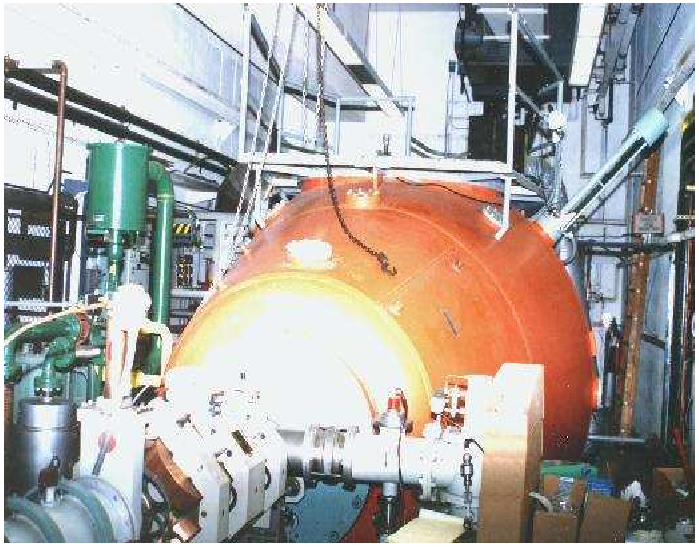
Measure light output as a response to irradiation from a radioactive source (^{137}Cs, ^{60}Co, ^{90}Sr, ^{252}Cf and other sources can be used).

Controls:
- Number of cells filled and read out;
- Number of PMTs per cell;
- Equations of liquids;
- Sources and their positions in regard to the cells;
- Use of reflective material at opposite end of the cell for single-PMT readout;
-Effects of the waveshifter;
-Etc.



Light attenuation lengths will be found by measuring light outputs as functions of distances from the radioactive source to the PMT.

Project Site, Personnel and Project Duration



The project will be performed at Edwards Accelerator Laboratory of Ohio University.

The Laboratory hosts 4.5 MV tandem Van de Graaf accelerator with multiple beam lines and experimental areas. The accelerator is used by several groups to conduct research on nuclear physics, astrophysics, materials science, and for development of new detectors.

Lab rooms, hardware assembly areas, an electronics testing lab, and a stockroom are available.

Access to various radioactive sources, measurement equipment, ADC modules, amplifiers, and to a few data acquisition systems.

Project will be conducted by the Principal Investigator and one post-doc. Assistance from electronic and computer engineer, who has DAQ expertise.

Duration of the project: 1 year.

Items to Purchase

Chemicals:

liquid paraffin:	25 gallons
naphthalene:	7 kg
a-methyl-naphthalene:	2 kg
PPO:	0.4 kg
POPOP:	0.05 kg
Xylol (xylene):	4 liters
1,3,5-triphenyl-2-pyrazoline (TPP):	0.5 kg

Equipment:	Qty
polycarbonate prototype panel with accessories:	2
Hamamatsu PMT R3878:	6
Hamamatsu Socket Assembly E1761-22:	6
Ortec 113 Preamplifier:	6

Potential Follow-Up Projects

- Use of optical fibers for light transfer from the scintillator to PMTs (bundling schemes, light attenuation studies, etc.)
- Other liquid solutions, different thicknesses of scintillator channels
- Test bench for cosmic muon measurements
- Tests at electron and hadron beams
- Studies of sampling fractions, sampling frequencies, different absorber materials in order to optimize performance
- Simulation studies
- Conceptual designs of the forward calorimetry detectors
- Transparent paraffin gel as an alternative to liquid paraffin