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Low-Cost Neutron and Gamma Sensitive Plastic Scintillator Detectors

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Volume I

BAA Number: *HSARPA BAA 04-02*

Technical Topic Area 3: *Passive Primary Portals (PPP)*

Part: *C*

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II. Abstract

This proposal addresses enabling technologies (Part C) for Technical Topic Area 3, Passive Primary Portals. However, radiation detectors (x-ray, gamma, and neutron) are essential components in all systems that address the 6 Technical Topic Areas in this BAA and thus the detectors described in this proposal, once fully optimized, are applicable to ALL technical topic areas in this BAA. Our scientific and technical approach is to develop a new family of radiation detectors based on plastic scintillator fabricated using an extrusion process. Plastic scintillators sensitive to both neutrons and gammas (x-rays) will be demonstrated. They can be configured in combination systems (neutron and gamma detection with a high level of discrimination capability) or separately. This work will involve an extension of our work on extruded plastic scintillator, Escint, (patent #5,968,425). Neutron-sensitive plastic scintillator has already been demonstrated in our laboratory and preliminary measurements indicate that these early prototypes **ALREADY MEET ANSI N42.35** specifications for neutron sensors. Plastic scintillator with enhanced gamma sensitivity is under development. The technical goal for our enhanced-gamma sensitivity plastic scintillator is the development of a plastic scintillator with high-Z elemental loading so that the scintillator will exhibit photoelectron peaks for gammas. This will allow some level of energy discrimination and thus give potential isotope identification. Although detectors for the above mentioned radiation species do exist, our technology is unique in its large-scale production possibilities and potential **COST REDUCTIONS** of up to a **FACTOR OF 10** over existing commercial products. Successful development of the detectors described herein will lead to advances in:

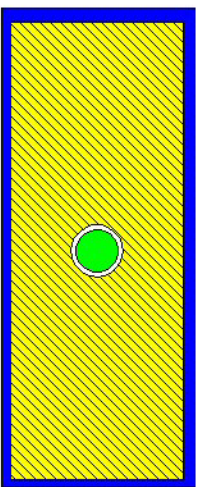
1. Advanced Passive Imagers
 - a. Development of low-cost high efficiency neutron and gamma detectors
 - b. Neutron and gamma detectors that can be configured in almost arbitrary geometry
 - c. Environmentally robust and stable neutron and gamma detectors with long lifetime.
2. Gamma Detectors
 - a. Low cost plastic scintillator with good energy resolution.
 - b. Robust, light weight, with the potential for isotope identification
3. Neutron Detectors
 - a. Dramatically reduced cost over conventional neutron detectors with equivalent sensitivity
 - b. High Neutron sensitivity with very low gamma sensitivity
4. Combination Detector Systems
 - a. Combination of our neutron and gamma sensors yields a robust, light weight system with very high neutron sensitivity, very good gamma sensitivity, and excellent n/ γ discrimination.

In Phase I of this work we will purchase laboratory-scale extrusion equipment that will allow us to further develop the neutron and gamma plastic scintillators and begin optimization studies. Phase II of this work will perform a full optimization study of production of the scintillators, manufacture prototype detectors, measure detection efficiency, radiation-type discrimination, noise rate, and isotope identification capability. Success in Phase II would then lead to Phase III which would be an industrial scale demonstration of production of the scintillators using the Fermilab extrusion facility.

COST SUMMARY:

Phase I	\$662.18k
a) Equipment	470.0
b) Sub-contract	75.0
c) Manpower	83.68
d) Consumables	33.5
Phase II	\$163.60k
a) Manpower	138.6
b) Sub-contract	25.0
Travel	\$ 10.0k
Total	\$835.78k

III. Quad Chart

<p>BAA Number: BAA-04-02 TTA: 3 Part: C Title: Low-Cost Neutron and Gamma Sensitive Plastic Scintillator Detectors</p>	<p>Alan D. Bross Fermi National Accelerator Lab 5/6/2004 White Paper Control Number: 06EU Registration Number: 536</p>
<p>Diagram of scintillator extrusion for neutron detection</p>  <p>Neutron-sensitive scintillator - 40-500 micron thick Gamma-ray light absorbing plastic light collector Wavelength shifting fiber</p>	<p>Operational Capability:</p> <ul style="list-style-type: none"> • Optimization of our neutron and gamma sensitive extruded plastic scintillator detectors can lead to systems capable of scanning very large objects for nuclear material. • Integrated system for neutron and gamma detection with integral background rejection. • Neutron detection with excellent gamma rejection. • Gamma detection with energy resolution sufficient for isotope identification a possibility. • Very low cost radiation detectors compared to other technologies. • Scalable in size from tens of cm² to 10,000 m² in area. • Can scan intermodal carrier containers looking for both radiation signature and the presence of high-Z materials. • Robust detector technology.
<p>Proposed Technical Approach:</p> <p>We plan to use commercial extrusion processes to incorporate ⁶Li compounds (neutron scintillator) and high-Z compounds (gamma scintillator) into plastic scintillator. Prototype neutron sensitive extruded plastic scintillator has been fabricated and light yield and sensitivity compare favorably to commercial standards. Key technical problems are the optimization of the extrusion processes and production of the ⁶Li compounds</p> <p>Phase I</p> <ul style="list-style-type: none"> • Purchase extrusion equipment to allow optimization of neutron and gamma sensitive plastic scintillator • Acquire Lithium and high-Z compounds for scintillator production • Setup equipment and produce first samples of scintillator and measure scintillator properties <p>Phase II</p> <ul style="list-style-type: none"> • Optimize scintillator performance, manufacture prototype detectors and test neutron and gamma sensitivity, background and noise rates <p>Phase III</p> <ul style="list-style-type: none"> • Augment existing Fermilab industrial-scale extrusion facility to allow for full-scale production of neutron and gamma sensitive scintillators. Setup and test full scale production 	<p>Cost and Schedule:</p> <ul style="list-style-type: none"> • Phase I Cost - \$662,000 (9 months) • Phase II Cost - \$164,000 (10 months) • Phase III - ROM Cost of \$300,000 (9 months) <p>Deliverables:</p> <p>Phase I & II</p> <ul style="list-style-type: none"> • Prototype neutron – sensitive plastic scintillator detector • Prototype gamma – sensitive plastic scintillator detector • Technical reports describing detection efficiency, false positive, and false negative rates, production costs. <p>Phase III</p> <ul style="list-style-type: none"> • Production grade neutron and gamma sensitive scintillators • Technical report as in phase I & II <p>Corporate Information:</p> <ul style="list-style-type: none"> • Fermi National Accelerator Laboratory, Dr. Alan D. Bross, Wilson Road, Batavia, IL 60510 • Phone: (630)840-4880 • Email: bross@fnal.gov

IV. Proposal

A. Ability of proposed work to meet the program goals.

The work that is described in this proposal is based on our continuing research on extruded plastic scintillators. We are taking advantage of both our technological base for extruded plastic scintillator and the emerging commercialization of nano-technology for industrial and consumer applications. Our process can be applied to plastic scintillators for both the detection of neutrons and the detection of gammas. We introduce nano-particles into our extruded scintillator that either contain ${}^6\text{Li}$ (in the neutron case) or a high Z (atomic number) element (for the gamma case). The neutron detector is based on the ${}^6\text{Li}$ reaction. In our initial prototypes, the ${}^6\text{Li}$ has been introduced into our extruded scintillator in the form LiF nano-particles. We are investigating other Li containing compounds for this application, however. For the enhanced gamma sensitivity plastic scintillator, the introduction of the high-Z element increases the effective photoelectric cross section for the plastic scintillator, thus increasing gamma detection efficiency. This process provides the potential for observation of a photoelectric peak (characteristic gamma energy) for gammas in the MeV range in an inexpensive plastic scintillator. Although conventional plastic scintillator does detect high-energy gammas via the Compton Effect, photoelectron peaks are not normally detectable. Our work meets key aspects of the desired attributes and functionality goals specified in this BAA.

1. **Improved sensitivity radiation sensors.** We have already demonstrated a neutron sensitive scintillator that meets or exceeds ANSI N42.35 detection specifications. See data in Technical Approach section. The prototypes have given us high detection efficiency and good light output from the scintillator. In addition, this use of the ${}^6\text{Li}$ reaction allows us to fabricate efficient neutron detectors that are extremely thin. In this way we provide an **efficient neutron detector that has very low sensitivity to gammas**. This will be described in more detail in the technical approach section.
2. **Cost of ownership** – The neutron scintillator that we have already demonstrated has an extrapolated cost up to 10 times less than conventional neutron detectors. See detailed cost analysis in technical approach section.

Successful development of our technology can impact the following TTAs.

1. **TTA-2 Area Search Devices with Radioisotope Identification.** Our neutron sensitive plastic scintillator already meets ANSI N42.35 and would provide a low cost, light weight, robust detector for neutrons. Success in development of our gamma-sensitive plastic scintillator would address ANSI N42.34 requirements.
2. **TTA -3 Passive Primary Portals.** Our primary focus has been on PPPs. We know from applications in high-energy physics (HEP) that very large area arrays of plastic scintillator detectors can be fabricated in a cost effective manner. These applications provide the technology foundations to build scanning system for inter-modal cargo containers. Once the neutron and gamma sensitive plastic scintillators are optimized, applying the HEP techniques to PPPs is relatively straightforward. Combining neutron and gamma sensitive plastic scintillator extrusions with conventional scintillator extrusions would allow for the detection of both a radiation signal and a signal for the presence of high-Z materials. Cost of ownership is dramatically reduced due to the low cost per unit area of detector coverage afforded by this technology and its robustness, long life, and very-low running costs.
3. **TTA-4 Advanced Radiography for Cargo.** TTA-3 goals also applicable here. Application to large scan volumes (8 X 10 X 40 ft cargo container, for example) is well within the capabilities of the technology we wish to develop/optimize.
4. **TTA-5 Advanced Radiography for Parcels.** Same argument as for TTA-4.
5. **TTA-6 Advanced Active Imaging and Screening Systems.** Our technology offers large area coverage for neutron and gamma detection. This is particularly useful for systems that interrogate with high energy gammas. See for example Transfer Ready Technology 5 “**FIGARO: High Energy Gamma Rays for Nuclear Material Detection**” ANL. Our technology could deploy in a cost-effective way large area

neutron detectors for the signal generated by this technique. This would lower the required intensity of the interrogation radiation source and have a positive impact on total system costs.

B. Technical Approach

1. Introduction

Plastic scintillation detectors have been used in nuclear and high-energy physics for many decades¹. They exhibit good light yield, fast response time, ease of manufacture and versatility. During the late 1980s and early 1990s, wavelength-shifting (WLS) fiber became commercially available and was utilized in numerous scintillation detector applications. The concept of WLS fiber readout of scintillator is illustrated in Figure 1.

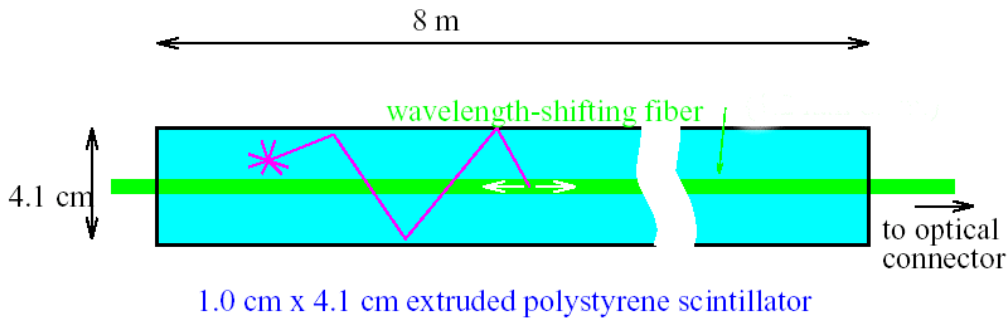
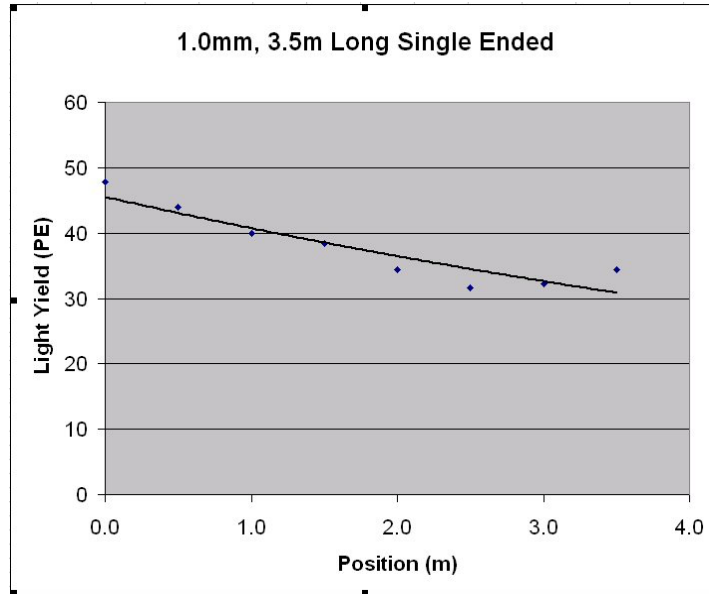


Figure 1 Extruded Scintillator Strip readout with WLS fiber²

Light produced in the scintillator by ionizing radiation is absorbed by the WLS fiber. The fiber re-emits light isotropically and approximately 5% of this light is captured within the fiber and piped to a photodetector. This concept allows a relatively small photodetector to readout a large active area. In the case above, a 1 mm diameter photodetector coupled to the 1 mm WLS fiber reads out a scintillator area of approximately 0.3 m². In addition light collection efficiency is primarily determined by the WLS fiber, not the transparency of the scintillator, since the WLS absorbs light from the scintillator locally. The use of WLS fiber readout of plastic scintillator thus makes the requirement for a low attenuation in the scintillator less important. With this in mind, our group at Fermilab began investigating the possibility of using commercial polystyrene pellets as the base material for extrudable plastic scintillators. Extruded plastic scintillator (Escint) based on our technique (patent # 5,968,425) has now been used in large-scale high-energy physics applications³. Escint is 5-10 times less expensive than conventional cast plastic scintillator sheet and with WLS readout has approximately the same light yield. The largest detector⁴ made to date that uses this technology employs approximately 20,000 m² of Escint of the type shown in Figure 1. Figure 2 gives the light yield of this extruded scintillator strip read out using a 1 mm WLS fiber coupled to a solid-state photodetector⁵ with a quantum efficiency of approximately 80%. We show data for both double-ended readout of an 8m long strip and single-ended readout of a 3.5m long strip. An extension of this technique allows us to fabricate Escint that is sensitive to neutrons and whose gamma and ionizing particle sensitivity is low. In addition the extrusion technique can also produce scintillator with higher gamma sensitivity than normal plastic scintillator. The low cost and high light yield (as shown in Figure 2) makes very-large-area and highly sensitive systems for detection of nuclear material economically feasible. The photo-yield shown here corresponds to approximately 2 MeV of deposited energy. This is what we expect to see with an optimized ⁶Li based plastic scintillator. 40 detected photoelectrons is a signal well above the noise. For this reason we believe that the WLS fiber technique can be applied to large area neutron detectors based on our concept. Development of Escint was funded by the U.S. Department of Energy.



B)

Figure 2 Light yield from 4 X 1 cm scintillator extrusion with 1 mm single-ended WLS fiber readout

2. Extruded Scintillator (Escint) - Background

In an extrusion process, polymer pellets are typically used. Commercial polystyrene pellets are readily available and their optical properties are adequate in applications where WLS fiber readout is used. The process for manufacturing extruded polystyrene based scintillator is shown schematically in Figure 3.

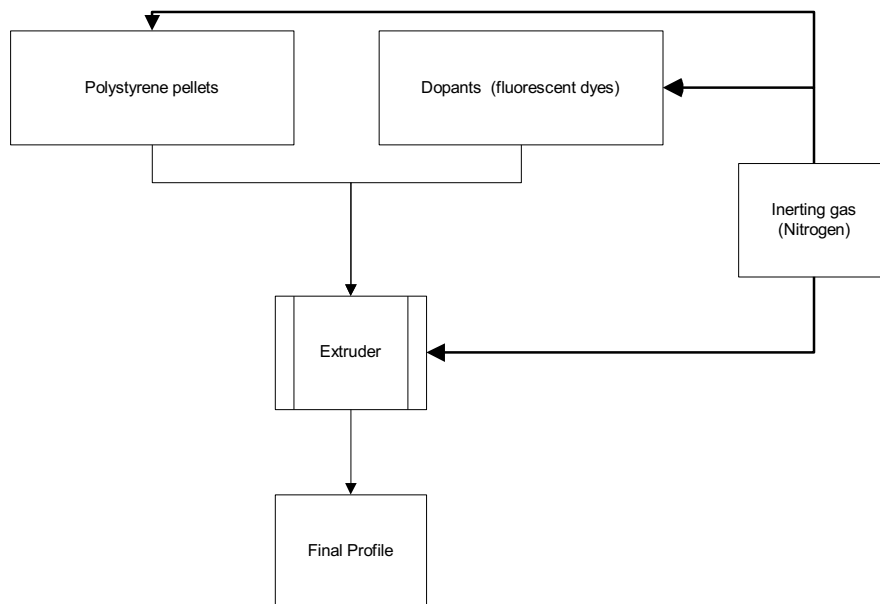


Figure 3 Process schematic for production of extruded plastic scintillator

This process is a continuous in-line compounding and extrusion process. The process is inherently low cost.

3. Neutron Sensitive Escint

Following this concept a neutron sensitive scintillator can be produced by introducing a ${}^6\text{Li}$ containing compound into the scintillator. [Note: ${}^6\text{LiF}$ powder has been used to date]. The reaction:



deposits energy in the scintillator which in turn is converted into light with an efficiency of approximately 3% (for the case of a polystyrene-based plastic scintillator). The process mixes the lithium containing powder in the polymer matrix as opposed to introducing it via chemical reaction. This powder does not go into solution in the polymer matrix in the conventional sense. [Note: The scintillator dopants (organic compounds) have high solubility in the polymer matrix and thus go into solution.] However, in order to produce an efficient scintillator, as much of the reaction particle energy as possible must be deposited into the polymer matrix. If the particle size of the powder is large compared to the range of the reaction particle, 5-40 micron for the neutron reaction given in (1) above, the energy released in the interaction is primarily deposited in the powder particle and not in the polymer matrix (scintillator). Therefore very little light is produced. If the particle size is small compared to the range most of the energy is deposited in the scintillator.

The light produced in the scintillator can still be affected by the particle size of the powder. Scattering of light by small particles is described by MIE theory and by Rayleigh scattering. If the scattering intensity is large, then the detection of the scintillation light will be made less efficient. The scattered light intensity as a function of position r from the scattering site and angle θ is described by:

$$I_s = 8\pi^4 \frac{Na^6}{\lambda^4 r^2} \frac{(m^2 - 1)^2 (1 + \cos^2 \theta)}{(m^2 + 1)^2} I_i \quad (2)$$

Which when integrated over all r and θ becomes:

$$I_s \propto \frac{Na^6}{\lambda^4} \frac{(m^2 - 1)^2}{(m^2 + 1)^2} I_i \quad (3)$$

In these expressions a is the radius of the particle, N the number per unit volume, m the ratio of the index of refraction of the particle to the index of refraction of the polymer λ is the wavelength of the incident and scattered light, I_s the intensity of the scattered light, and I_i the intensity of the incident light. From these expressions we immediately see two things. First as m goes to 1 (index of the particle equal to the index of the polymer) the intensity of the scattered light goes to zero. Also for fixed concentration of the powder in the polymer or wt. percent (fixed Na^3), the intensity of the scattered light goes as a^3 . So the smaller the particle size in the powder, the smaller is the intensity of the scattered light. For these reasons we want to work with particle size as small as possible and want to try to match the index of refraction of our powder additive as closely as possible to that of the polymer. The process for fabrication of neutron sensitive plastic scintillator is shown schematically in Figure 4. This process is the same that of Figure 3 except that we now allow for the possibility of the Lithium compound between introduced into the via in solution.

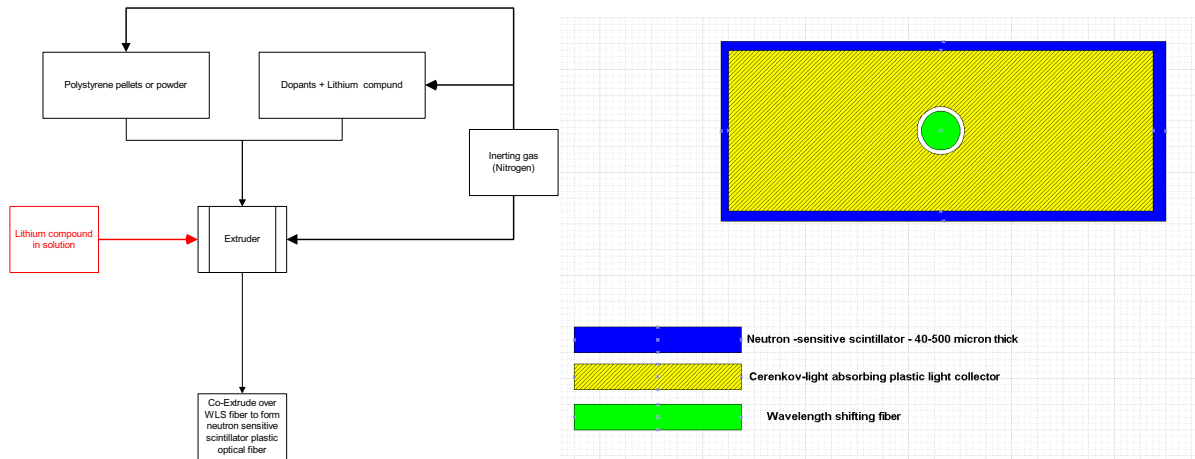


Figure 4 Process schematic for neutron scintillator. Figure 5 Extrusion optimized to only register detection of neutrons

Often the detection of neutrons is done in an environment that has other types of ionizing or interacting (x-ray) background. A neutron detectors performance is often measured against its ability to detect neutrons while at the same time rejecting (or not registering) other types of radiation. We can use our neutron-sensitive scintillator in the extruded configuration shown in Figure 5 in order to accomplish this task. As stated above the neutron reaction shown above (1) produces ionizing species that have a very small range in plastic. Therefore all the scintillation light from the reaction can be produced in a very thin layer. It is almost impossible for an x-ray or ionizing particle (cosmic-ray muon, for example) to produce the same amount of light in such a thin layer. Therefore one can set a tight threshold under which only neutron events are registered. For the extrusion shown in figure 5, a thin layer of neutron –sensitive scintillator covers a non-active plastic core. Light from the scintillator is guided by the plastic core to a hole in the middle that contains the wavelength shifting (WLS) fiber. The plastic light collector can also incorporate dyes that absorb light from cerenkov radiation from ionizing particles while not absorbing light from the neutron scintillator. In this way the extrusion maintains its detection efficiency for neutrons while further rejecting non-neutron originating events. The design of this system is very flexible. The neutron scintillator light wavelength distribution can be tailored to match the absorption of the WLS fiber while at the same time not overlapping the cerenkov light region. The extrusion technique allows for almost any shape, rectangular, triangular, multi-faceted, etc.

To date we have not had the equipment to produce the extrusion shown in Figure 5, but have produced ${}^6\text{LiF}$ loaded Escint and compared its light yield from thermalized neutrons from a ${}^{252}\text{Ca}$ source to two of the most common solid neutron scintillator standards: GS20⁶ (neutron sensitive glass scintillator) and BC702⁷ (neutron sensitive $\text{ZnS}(\text{Ag})\text{-}{}^6\text{LiF}$ scintillator). A 4" lead shield was used to stop gammas for these measurements. Disks of each scintillator (Escint: 30 mm diameter X 1mm thick - 2.5 mg ${}^6\text{Li}/\text{cm}^2$, GS20: 25 mm diameter X 2 mm thick – 17.2 mg ${}^6\text{Li}/\text{cm}^2$, BC702: 50 mm diameter – 11 mg ${}^6\text{Li}/\text{cm}^2$) were placed directly on a Hamamatsu R669 PMT and the PMT was connected to a Lecroy qVt pulse height analyzer. The R669 PMT has a QE that is constant over a wide wavelength range (400-550 nm). Therefore we do not have to apply a wavelength correction to the measured pulse heights. The pulse height distributions for these three scintillators are given in Figure 6.

Scintillator Response - Moderated ^{252}Cf neutrons

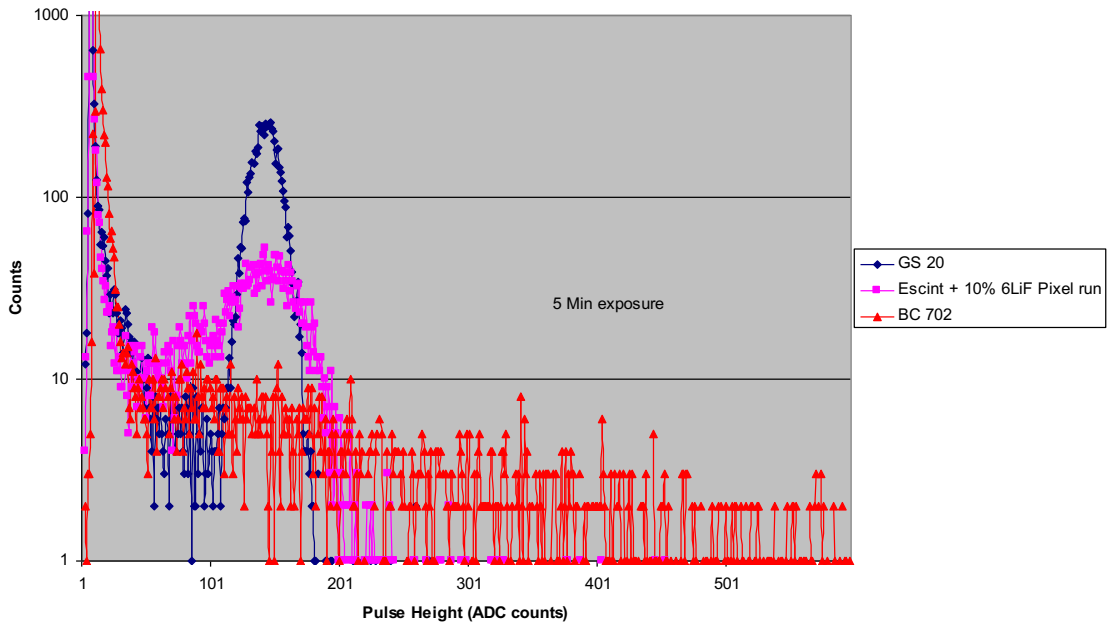


Figure 6 Pulse Height Spectra for neutron scintillators

The light yield of our ^6LiF loaded plastic (Escint +10% ^6LiF Pixel run in the above plot) compares quite favorably to GS20. The pulse height from BC702 shows much larger ADC value hits, but shows no clear peak (exponential tail only) which is true for most $\text{ZnS}(\text{Ag})\text{-}^6\text{LiF}$ detectors. With optimization we believe that we can increase the yield of our extruded scintillator by as much as a factor of two. In addition the low-pulse height shoulder on the distribution for the Escint above is likely due to large ^6LiF particles and should disappear with a proper particle size distribution and proper mixing.

We have also made preliminary measurements of light yield from an Escint+10% ^6LiF 1" square pixel detector readout with WLS fiber. Using the same photodetector as was used for the data in Figure 2, the mean signal for detection of thermal neutrons from ^{252}Ca would be approximately 12 photoelectrons for a WLS fiber of 2 m length.

4. X-ray enhanced sensitivity scintillator

Although plastic scintillator detects x-rays and gammas quite readily through Compton scattering, the photoelectric cross section is quite small above an energy of 100 keV. We can increase the photoelectric cross section (X-ray enhanced sensitivity scintillator) by compounding heavy element nano-particles into the plastic along with dopants that make the plastic scintillate. High-Z compounds that we are considering include: CeO , ZnO , SnO , and PbWO_4 . X-rays interact with the heavy elements producing electrons which deposit energy in the scintillator which, in turn, produces light. This flow process is the same as that used for the neutron-sensitive plastic scintillator. Again, the High-Z nano-particle compounds can be introduced into the extruder either with the scintillator dopants as dry powder or via liquid injection (powder solvent solution) directly into the extruder. X-ray sensitive scintillators have to be thicker than scintillators used for neutron detection since the converted x-rays produce electrons that can travel distances up to a few cm in the plastic before losing all their energy. The heavy metal compound must be in the range of 20 nm to 100 nm in order to allow for good light collection from samples this thick. Optimum performance will be obtained if the particle size is near 20 nm. Our initial trials on an x-ray enhanced sensitivity scintillator used CeO . These trials were not successful due to a reaction involving the Ce that occurred in our equipment. ZnO

appears to be a better choice at this point. We have recently successfully incorporated ZnO nano-particles into a plastic scintillation and are now evaluating its performance. ZnO with particle size of 20 nm is now a commercial product (used in sun screens) and quite inexpensive.

5. Cost of Ownership - Cost Performance Analysis

Since neutron detection is a performance requirement of many of the TTAs in this BBA as is lowering the system cost of ownership, we will address in this section our estimation of cost savings of our neutron scintillator over commercially available neutron scintillators. All the solid scintillators that we will discuss in the section can be read out using the WLS fiber technique (see section above), we will assume the same readout architecture can be applied to each and our cost comparison will be for the scintillator alone. [Note: Plastic Escint is the only detector that gives flexibility in tailoring the fluorescence light distribution to match available WLS fiber. This can have a very positive effect on signal level and readout costs.] The costs for Escint are based on our known production costs of \$10/kg from the 20,000 m² production for the MINOS experiment. In our cost comparisons in this section, the actual extrusions costs (non-⁶Li materials and manpower) are approximately \$100/m². The dominant cost is for the ⁶Li carrying compound (we have assumed a D.O.E. cost of approximately \$2.50/g for lithium carbonate (the starting material) and a \$3.50/g cost for processing. The ⁶Li loading for cost comparison was scaled from our measured data to give equivalent detection efficiency for ⁶Li loaded plastic Escint and GS20 glass. The performance numbers are based on the data shown in Figure 6. A pulse height cut of 55 was used and all hits above that cut were counted. The exposure time was 300 sec in all cases. The numbers were corrected for area but not for mg ⁶Li/cm², which is also given. Although a Pb shield was used for the measurements in Figure 6, there still may have been some gamma-ray background. No gamma subtraction was applied to the data. The comparisons are given in Table 1.

Table 1 Cost – Performance Comparisons of neutron scintillators

Scintillator	Cost (k\$/m ²)	⁶ Li (mg/cm ²) [Loading at proj. Cost]	Measured Relative Detection Efficiency (Efficiency)/(mg ⁶ Li/cm ²)
Escint (plastic)	1.6	7 ⁸	0.40/2.5
GS20	100 ⁹ (1 mm)	9	1/17.2
ZnS(Ag)- ⁶ Li	6.0 ¹⁰	11	0.13/11 (BC702)
BC454 ⁷	14.0	N.A. (Boron loaded)	N.A.

[Note: the fully instrumented cost (Scintillator(no ⁶Li) + WLS fiber + optical coupling hardware + PMTs + power supplies) is \$2k/m² for the MINOS experiment.

At this time we are not in a position to estimate the cost of gamma-enhanced sensitivity Escint and there are no commercial products that we are aware of that have High-Z element loading at the 10-30% by weight target that we wish to reach. The cost would, however, be dominated by the High-Z compound. Our current estimate is in the range of \$300-\$500/m² for the loading compound.

Extruded plastic scintillator has many advantages over other technologies including cost, robustness, versatility etc.

6. Phase 1 Task Plan

The task plan effort and critical issues for Phase I are the following:

Task 1. **Purchase new extrusion equipment.** Our present equipment is not capable of producing an extrusion such as that shown in Figure 5. In addition the equipment that we have been using to date does not provide the thorough mixing we need, does not allow for liquid injection of additives, nor does it control environmental conditions (oxygen and moisture) during processing at the level we feel is required for optimum performance of the scintillator. In this task we will: 1) Set final specifications, 2) Bid, Procure,

install, setup, and commission the equipment. All the equipment that we have specified in this proposal is standard commercial equipment. No special modifications are required. We see no risk for this task.

- Task 2. **Acquire ${}^6\text{Li}$ and High-Z nano-compounds from our industrial partner.** We plan on working with an outside company (Advanced Powder Technology (APT) of Australia) that has extensive experience in nanopowder development. This work will include producing ${}^6\text{LiF}$ nanopowders (<100 nm particle size). In addition we will have them continue R&D of the development of other ${}^6\text{Li}$ containing compounds such as ${}^6\text{LiAlO}_2$ and ${}^6\text{Li}_4\text{SiO}_4$. The index of refraction of ${}^6\text{LiAlO}_2$ is 1.61, for ${}^6\text{Li}_4\text{SiO}_4$ it is 1.60. Both have a better index match to polystyrene (1.59) than does LiF (1.39). They also have High-Z nanopowders such as ZnO and SbO which we will test. In parallel with this work, at Fermilab we will investigate the production of nanopowders of PbWO_4 and lead glass using conventional ball-mill grinding techniques. (See task 4). If APT's process does not work, we can use conventional grinding processes to produce the required compounds. Given our current level of performance of our neutron scintillator, we believe that using conventional processes can still lead to improvements. In order to mitigate this risk, we have completed a pilot project with APT to produce a non-enriched sample of LiAlO_2 . Technical data on the results are this project are given in Volume II.
- Task 3. **Scintillator Production.** We will produce first samples of neutron and gamma scintillator in order to perform critical tests of the new equipment and procedures. These samples will be studied to determine their basic scintillation properties, neutron and gamma sensitivity.
- Task 4. **Inorganic Compound Preparation.** We will process commercial PbWO_4 powder utilizing the ball-mill grinder. This material will be characterized for particle size and particle size distribution utilizing the laser diffraction particle size analyzer. Other High-Z candidates will also be identified at this time and processed. Initial samples of scintillator will be produced using High-Z material produced in this task.

C. Deliverables

Phase I

- Task 1. Report describing installation and commissioning of the equipment.
- Task 2. Technical report describing particle size characterization of compounds produced.
- Task 3. Technical report describing basic scintillator properties and neutron and gamma sensitivity of initial samples produced with the new nano-compounds and using the new equipment. At this point we will be able to provide some detector samples to potential part B performers.
- Task 4. Technical report describing the particle size characterization and results from preliminary measurements on the gamma-sensitive scintillator produced in this task. At this point we will be able to provide some detector samples to potential part B performers.

Phase II

- Task 5. Interim report on neutron scintillator optimization study. Neutron scintillator samples/profile extrusions made available to part B performers.
- Task 6. Interim report on gamma scintillator optimization study. Gamma scintillator samples/profile extrusions made available to part B performers.
- Task 7. None
- Task 8. Final report. Neutron and gamma scintillator samples (bulk, thin-film, and profile extrusion) available to Part B performers.

E. Management Plan

The work described in this proposal will be performed within the Scintillator Development Detector Laboratory (SDDL) at Fermi National Accelerator Laboratory (Fermilab). The SDDL is part of the Technical Centers Group with the Particle Physics Division at Fermilab. Dr. Anna Pla is head of the SDDL and will provide direct line management of the technicians and COOP students that will be involved with this project. Dr. Alan Bross will act as principal investigator for the project and will oversee the project plan and schedule. Drs. Bross and Pla will set all technical goals for the project and evaluate progress within the context of the project plan given in this Volume.

F. Requirements for Government Furnished Resources

None

G. Task Delineated Cost Summary

General comments: Equipment and material costs in bold are from vendor quotations. Otherwise they are budgetary estimates. No charges for scientific personnel effort (A. Bross, A.Pla-Dalmau) will be charged to this project (Fermilab contribution). Included is support for two COOP students. The COOP students will be chosen from chemical engineering or electrical engineering disciplines. Hourly rates are fully loaded. Equipment costs include 18% G&A.

Task 1. Procure extrusion equipment	
a. Twin Screw Compounding System	\$250.0 k
b. Single screw extruder	48.0
c. Co-extrusion die	15.0
d. Liquid Injection pump	22.0
e. Vacuum pyrolysis cleaning system	30.0
f. Ball-Mill grinder	27.0
g. Laser Diffraction particle analyzer	78.0
h. Develop final equip spec.	
i. COOP (120 hrs @\$15/hr)	1.8
i. Installation/Setup/Commissioning	
i. Electrician (112 hrs @\$60/hr)	6.72
ii. Tech Mechanical (136 hrs @ \$55/hr)	7.48
iii. Tech Electrical (120 hrs @ \$55/hr)	6.6
j. Consumables	1.0
Task 2. Materials/Consumables Procurement	
a. Subcontract to Advanced Powder Technologies - Nano compounds	75.0
b. ⁶ Li carbonate procurement	25.0
c. Technician procurement (16 hrs @\$55/hr)	0.88
d. Consumables	7.5
Task 3. Scintillator Preparation	
a. Tech Mechanical (360 hrs @ \$55/hr)	19.8
b. Tech Electrical (160 hrs @\$55/hr)	8.8
c. COOP (600 hrs @\$15/hr)	9.0
Task 4. Inorganic compound preparation	
a. Tech Mechanical (280 hrs @ \$55/hr)	15.4
b. COOP (480 hrs @\$15/hr)	7.2
Task 5. Neutron Plastic Scintillator Optimization	

a.	Tech Mechanical (400 hrs @ \$55/hr)	22.0
b.	Tech Electrical (60 hrs @\$55/hr)	3.3
c.	COOP (440 hrs @\$15/hr)	6.6
Task 6.	Gamma Scintillator preparation	
a.	Tech Mechanical (200 hrs @ \$55/hr)	11.0
b.	Tech Electrical (60 hrs @\$55/hr)	3.3
c.	COOP (240 hrs @\$15/hr)	3.6
Task 7.	Scintillator Performance Test and Evaluation	
a.	Subcontract to APT – Phase II	25.0
b.	Tech Mechanical (100 hrs @ \$55/hr)	5.5
c.	Tech Electrical (100 hrs @\$55/hr)	5.5
d.	COOP (200 hrs @\$15/hr)	3.0
Task 8.	Final Scintillator Optimization and Test	
a.	Tech Mechanical (640 hrs @ \$55/hr)	35.2
b.	Tech Electrical (480 hrs @\$55/hr)	26.4
c.	COOP (880 hrs @\$15/hr)	13.2
Travel		10.0
TOTAL		\$835.78k

¹ Birks, “Theory and Practice of Scintillation Counting”, Macmillan, 1964.

² MINOS Technical Design Report, MINOS Collaboration , October, 1998.

³ A. Pla-Dalmau, A.D. Bross, K.L. Mellott, *Low-cost Extruded Plastic Scintillator*, Nucl.Instrum.Meth.**A466**:482-491,2001.

⁴ MINOS

⁵ A. Bross et. al., *Characterization and Performance of Visible Light Photon Counters (VLPCs) for the Upgraded D0 Detector at the Fermilab Tevatron*. Nucl.Instrum.Meth., **A477**, 172-178, 2002

⁶ Applied Scintillation Technologies, Inc., Annapolis, Maryland.

⁷ Saint-Gobain Crystals, Newbury, Ohio.

⁸ For cost comparison the 6Li loading the plastic Escint was chosen to yield a detector with the same detection efficiency as 2 mm thick GS20 glass based on our data.

⁹ Based on extrapolation from 0.1m X 0.1m Anger Camera for ANL.

¹⁰ Commercial ZnS(Ag)-⁶LiF screen (BC702 equivalent) for POW-GEN3 experiment, ORNL.