Physics and Technology of Electromagnetic Calorimeter

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A key instrument for the high impact Jefferson Lab experiment investigating the nucleon structure via the study of a proton elastic electric form factor is the electromagnetic calorimeter. An electromagnetic shower calorimeter measures the energy of a particle. This is done by generating a particle shower, which is the result of alternating pair-production and Bremsstrahlung radiation in the detector. The calorimeter proposed to be constructed is composed of lead glass with photomultiplier tubes connected via Borosilicate +33 light guides. The novel approach for electromagnetic calorimetry being developed is based on operating according to a high temperature regime and requires technological advances to resolve two remaining problems with the calorimeters construction. First, a number of the Borosilicate +33 cylinders have developed strain after being glued to lead-glass. Second, the epoxy attaching the lead-glass and Borosilicate +33, Eccobond F202 Bipax, is extremely difficult to remove. In order to prevent strain from developing in the Borosilicate +33 cylinders, the glass is annealed. In order to disconnect lead-glass and light guides which were improperly adhered, the material is heated to 340°C and a razor blade and hammer are applied to chip off the residual adhesive. The development of these techniques will allow the construction of the electromagnetic shower calorimeter to continue more efficiently.

1. INTRODUCTION

The purpose of this experiment is to use calorimetry to measure the energy of particles. One method of measuring the energy of particles with a calorimeter is based on particle showers, which multiply the number of particles in the system. There are two types of calorimeters used in particle physics: electromagnetic and hadronic. The calorimeter being constructed at Jefferson Lab is an example of an electromagnetic calorimeter. In an electromagnetic calorimeter, high energy photons, electrons, or positrons interact with a dense material within the calorimeter. Photons with high energies interact with the material via pair-production, changing into an electron-positron pair which reacts with the material's atoms. High energy electrons and protons emit photons via Bremsstrahlung, or braking radiation. The intensity of the radiation is proportional to the acceleration squared, a^2, which is inversely proportional to the mass of the particle, m. To increase the intensity of the radiation, a high electric field is needed to accelerate the the particles. A target with a high atomic number, Z, must be used.

The result of the alternating pair-production and Bremsstrahlung radiation allows the initial, high-energy particle to produce secondary particles with lesser energies. These particles then produce even more particles with still less energy until the energy of the particles drops below what is needed for pair-production and Bremsstrahlung radiation. The process results in a particle shower within the calorimeter, the energy of which is collected and measured (Fig. 1).

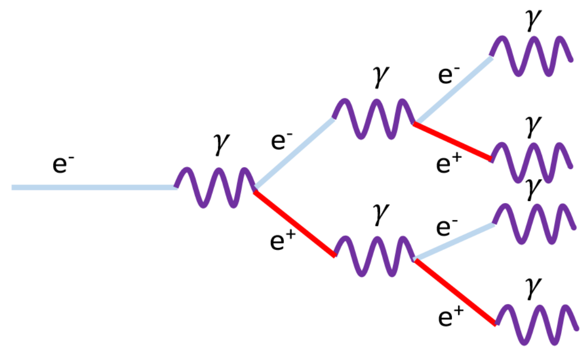

FIG. 1: Particle shower produced by alternating Bremsstrahlung radiation and pair-production.

The amount of matter over which electromagnetic particle showers traverse is characterized by the radiation length. The radiation length of a material can be found using the equation

$$X_0 = \frac{1432.8 \times A}{Z(Z+1)(11.319 - lnZ)} \frac{g}{cm^2} \quad (1)$$

where

X_0 = radiation length

A = mass number of the nucleus

Z = atomic number

The radiation lengths of some materials are listed in Table I.

The usefulness of a calorimeter is also partially determined by the geometry of the calorimeter; different calorimeters have different advantages and disadvantages due to their design. Calorimeters can generally be categorized as either a sampling calorimeter or a homogeneous calorimeter. A sampling calorimeter consists of alternat-

TABLE I: Radiation Lengths (Taken from Reference 1)

Material	X_0 (g/cm^2)	X_0 (m)
Polyethylene	44.8	0.459
Air	36.6	299
Water	36.1	0.361
Borosilicate Glass	28.2	0.126
Lead Glass	15.4	0.0400

ing layers of a dense material to act as an absorber to degrade the energy of the incident particle and an active medium that provides the detectable signal. Some examples of sampling calorimeters include spaghetti calorimeters and shashlik calorimeters. Spaghetti calorimeters consist of dense absorbers with grooves, with scintillating fibers inserted into the grooves to act as the active material. Spaghetti calorimeters have good energy resolution, and allow for any granularity to be chosen. Shashlik calorimeters are made of stacks of alternating slices of absorbers and scintillators penetrated by a wavelength shifting fiber perpendicular to both. The wavelength shifting fiber absorbs photons with too much energy and releases multiple, lower-energy photons. Shashlik calorimeters provide a fast response of approximately 25ns, stable operation under high radiation rate, and small lateral segmentation.

For homogeneous calorimeters, the entire detector volume is filled by a high density material that serves as both an absorber and an active medium. Homogeneous calorimeters provide optimal energy resolution but are expensive and exclusively electromagnetic calorimeters.

The calorimeter used in this research is a homogeneous calorimeter made with lead glass and is designed to take advantage of Cherenkov radiation. Cherenkov radiation is produced when a particle moves through a matter faster than light can. Since glass has an index of refraction of 1.6, light moves through glass at a speed of

$$v_0 = \frac{c}{n} = \frac{3.00 \times 10^8 m/s}{1.6} = 1.9 \times 10^8 m/s \qquad (2)$$

where

c = speed of light in a vacuum

n = index of refraction

This calorimeter is a novel idea because it operates at a high temperature. Lead glass becomes discolored when exposed to high amounts of radiation, compromising the ability of the calorimeter. When the lead glass is treated at high temperatures, it becomes clear. This lead to the idea of keeping the lead glass heated while the calorimeter is running. The EM calorimeter being built will operate with the lead glass being heated according to the temperature profile in Fig. 2.

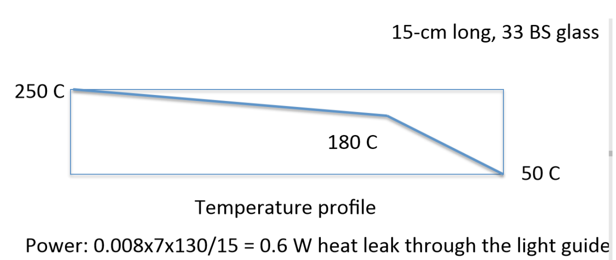

FIG. 2: Temperature profile for lead-glass in new high-temp EM calorimeter. Taken from Reference 2.

2. OBJECTIVES

The construction of the EM shower calorimeter for the GEP experiment has encountered two problems. The light guides develop strain after being glued to the lead-glass, resulting in 1/10 of the glued products breaking. Due to the Borosilicate light guides breaking from the lead glass after being glued, there is residual adhesive on the materials. The objective of this research is to resolve these problems in the construction of the calorimeter. The first objective is to find a method of preventing strain from developing in the light guides without compromising the flatness of the ends of the cylinders. The second objective is to find a method of removing Eccobond F202 Bipax. Due to the adhesive's strength and resistance to heat up to 265°C, it cannot be removed easily.

3. METHODS AND MATERIALS

In order to prevent strain from developing in the Borosilicate +33, the glass was annealed. Ten light guides were labeled and had the flatness of each end measured using a microscope; the microscope was used to plot 20+ points on the end of each cylinder and calculate the closest distance two parallel planes could be that contained all of the points. The ten Borosilicate +33 light guides were then placed in an oven with the following parameters:

Ramp Rate = 2 °C/min

Temperature = 340 °C

Soak Time = 4 hr

Cool Down Time = 6 hr

After the light guides were removed from the oven, the flatness of each end of the cylinders was measured again to determine the degree of glass deformation from the heating. Eight Borosilicate +33 light guides were annealed by soaking at the temperatures listed in Table II.

TABLE II: Annealing Process

Temperature (°C)	Time (hrs)
565	4
496	4.5
454	1
371	1
260	0.75

with an initial ramp rate of 10 °C/min. In order to anneal large quantities of light guides at once, a metal container was designed to place the light guides in during the annealing process (Fig. 3, Fig. 4).

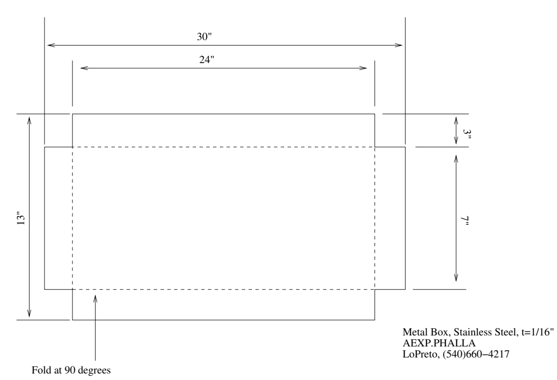

FIG. 3: Metal Container Bottom

Approximately fifty light guides were able to be placed in the metal container in horizontal rows, allowing for

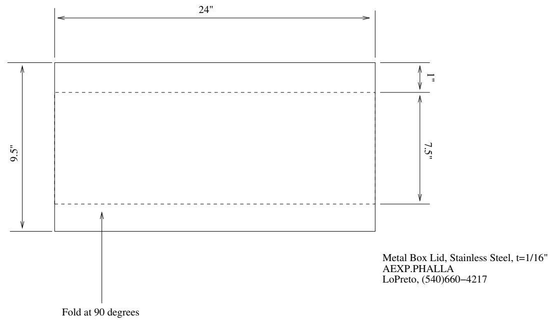

FIG. 4: Metal Container Top

large numbers of light guides to be placed in the oven for the annealing process at one time.

The first method attempted to remove the Eccobond F202 Bipax was to melt the epoxy by exceeding the maximum service temperature. Lead glass with residual adhesive was placed in an oven with the following parameters:

Ramp Rate = 2 °C/min.

Temperature = 340 °C

Soak Time = 6 hr.

Cool Down Time = 6 hr.

The second attempt to remove the adhesive was to soak the epoxy in a solution of baking soda at approximately 100°C. This was done for 30 minutes and then repeated for 4 hours.

The third method attempted to remove the Eccobond F202 Bipax was to use a razor blade and hammer to chisel the adhesive off of the lead-glass. This was attempted before and after heating the adhesive to 340°C.

4. RESULTS

Tables III and IV show the flatness (the distance between two parallel planes containing all the points registered by the microscope) of the end surfaces of ten light guides before and after baking at 340°C for 4 hours.

TABLE III: Flatness of Ends of Light Guides (near label)

Number	Initial Flatness (in.)	Final Flatness (in.)
1	2.4×10^{-4}	2.7×10^{-4}
2	6.3×10^{-4}	6.8×10^{-4}
3	2.3×10^{-3}	2.72×10^{-3}
4	4.8×10^{-4}	8.3×10^{-4}
5	1.4×10^{-4}	2.5×10^{-4}
6	6.3×10^{-4}	8.9×10^{-4}
7	1.6×10^{-4}	2.3×10^{-4}
8	5.0×10^{-4}	6.1×10^{-4}
9	2.1×10^{-4}	3.5×10^{-4}
10	3.0×10^{-4}	3.2×10^{-4}

TABLE IV: Flatness of Ends of Light Guides (far from label)

Number	Initial Flatness (in.)	Final Flatness (in.)
1	2.4×10^{-4}	2.5×10^{-4}
2	5.5×10^{-4}	6.4×10^{-4}
3	2.7×10^{-4}	3.4×10^{-4}
4	2.66×10^{-3}	2.77×10^{-3}
5	5.8×10^{-4}	6.3×10^{-4}
6	2.9×10^{-4}	3.9×10^{-4}
7	2.08×10^{-3}	2.70×10^{-3}
8	2.26×10^{-3}	5.88×10^{-3}
9	2.6×10^{-4}	3.2×10^{-4}
10	2.4×10^{-4}	3.3×10^{-4}

After annealing light guides, there have been no instances of strain developing between the Borosilicate +33 and the lead glass after being glued.

Heating the Eccobond F202 Bipax to 340°C for 4 hours causes the adhesive to become discolored from its clear state, but it remains slightly bonded to the lead glass (Fig. 5).

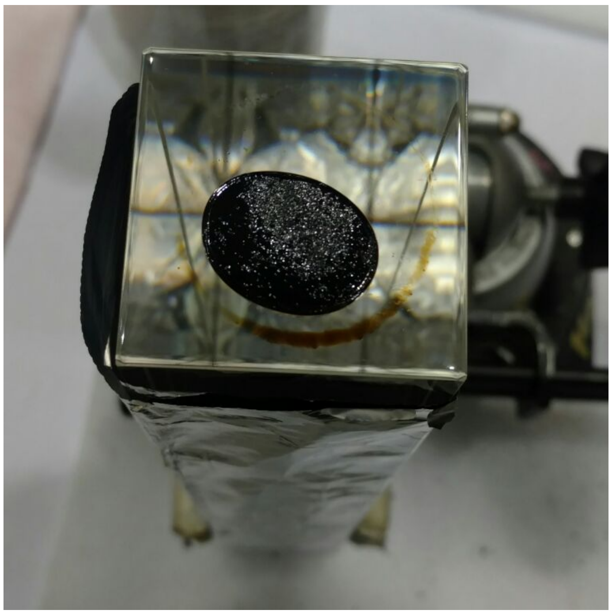

FIG. 5: Eccobond F202 Bipax on lead-glass after baking at 340 °C.

Soaking the adhesive in a solution of baking soda at 100 °C had no effect, regardless of time.

Using a razor blade and hammer (or other blunt object) to chisel the Eccobond F202 Bipax had little effect before heating the epoxy, but was able to remove the adhesive from the lead glass after it had been heated to 340°C for 4 hours (Fig. 6).

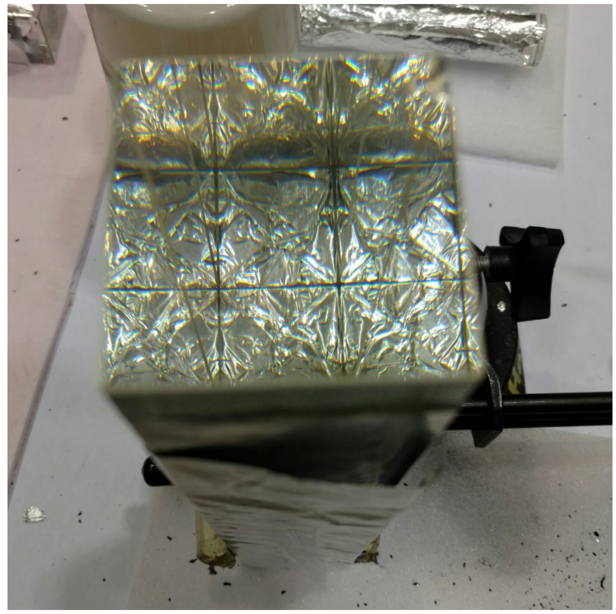

FIG. 6: Eccobond F202 Bipax on lead-glass after baking at 340 °C and scraping with razor blade.

5. CONCLUSION

Annealing is a successful method of preventing strain from developing in the Borosilicate +33 light guides. While the high temperatures can cause some slight degradation of the flatness of the end surfaces of the light guides, the change is generally negligible because the non-flatness does not exceed a magnitude of $10^{(} - 3)$in.

Although Eccobond F202 Bipax is more resilient than initially expected, it is can to be completely removed through a combination of heating and force. Heating the epoxy to 340 °C for 6 hours makes it brittle, making it possible to chip away the remaining adhesive with a razor blade and hammer (or other blunt object).

[1] Groom, D.E. (2015). Atomic and Nuclear Properties of Materials. Retrieved from http://pdg.lbl.gov/2015/reviews/contents_sports.html

[2] Wojteskhowski, B. (2013). ECAL Gep5. Retrieved from https://www.jlab.org/search/google/ECAL%20for%20GEp5

Appendix A: Acknowledgments

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