Evaluation of ‘first-article’ lead for the GlueX Barrel Calorimeter

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Abstract

The quality of Vulcan Resources Inc. lead was evaluated herein, based on overall condition, dimensional uniformity, response to plastic deformation and chemical composition. The lead was in relatively clean condition and free of flakes or large particulate matter. The thickness of the lead sheets was measured to be (0.494 ± 0.030) cm, a number that falls within the 10% tolerance specification. A material analysis scan indicated 100% purity with accuracy of $\pm 0.63\%$. The results of all tests confirm that the lead meets the GlueX specifications as contracted to Vulcan and, therefore, signal the start of production of lead towards the construction of the GlueX BCAL Calorimeter.

Key words: lead sheets, electromagnetic calorimeter
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1 Introduction

The study in this paper was undertaken in the context of determining whether the lead provided by Vulcan Resources Inc. to GlueX meets the specifications as layed out in the contract [1]. To this end, sample lead, termed ‘first-article lead’, was shipped to Regina for evaluation. The characteristics tested and

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reported herein are a) overall condition (cleanliness, oxidization), b) dimensional uniformity (thickness and width), c) response to plastic deformation (linearity, elongation and lateral expansion), and d) element purity.

The dimensions of the lead were specified in Article 3.1 of the contract [1]. Specifically, all lead strips shall have a thickness of 0.5 ± 0.05 mm (0.0197 ± 0.002 inches). The width tolerance is to be ± 2.5 mm (± 0.100 inches) and the length tolerance shall be ± 5 mm (± 0.200 inches). For the production phase, the lead shall be cut in strips, to the following sizes:

- 1000 strips, $13 \times 400 \times 0.05$ cm^3 (even number for 50 modules)
- 3000 strips, $12 \times 400 \times 0.05$ cm^3 (even number for 50 modules)
- 3000 strips, $11 \times 400 \times 0.05$ cm^3 (even number for 50 modules)
- 2000 strips, $10 \times 400 \times 0.05$ cm^3 (even number for 50 modules)

Finally, the lead shall be 99.94% pure minimum, conforming to the BS EN 12659:1999, material number PB970R or ASTM B29-03 UNS number L50049.

The first-article lead was shipped as purchase order 3849, part 542, Lot 90707 and Spec ASTN B29-03 L50049, in a single crate with gross weight of 557 lbs, and cleared Customs with harmonized code 780419. The shipment consisted of nine (9) coils (rolls), each wrapped around a cardboard core and packaged in a transparent plastic bag, some of which contained desiccate pouches. The specifics follow:

- LEAD 0.020"T x 3.940"W x 50 LB coils, shipped 5 coils, 248 lbs net, 250 lbs gross. Approximate metric dimensions: 0.5 mm thickness x 10 mm width.
- LEAD 0.020"T x 4.334"W x 56 LB coils, shipped 4 coils, 227 lbs net, 228 lbs gross. Approximate metric dimensions: 0.5 mm thickness x 11 mm width.

The material details are shown below, in Table 1, reproduced here from the information provided by Vulcan with the shipment bill of lading. The thickness was determined as being (0.0201 ± 0.00018) inches or (0.511 ± 0.005) mm (median $\pm$ standard deviation), well within the contracted tolerance. The lead is certified to be free of mercury (Hg) contamination.

2 Project Background

The lead will be used in the construction of the electro-magnetic barrel calorimeter (BCAL) for the GlueX project [2,3]. The BCAL is a sampling calorimeter based on scintillating fibres and will be deployed inside the GlueX detector's super-conducting solenoid, operating at a central field of 2.2 T.

The BCAL will be comprised of a lead and scintillating fibre matrix, consisting

Elements	Spec/ASTM	Lot No 90707	SPC DATA	Lot No 90707
Tin	0.001 max	< 0.0001	Mean	0.0201
Antimony	0.001 max	< 0.00009	Median	0.02014
Copper	0.0015 max	< 0.0001	Mode	0.020015748
Lead	99.94 min	BALANCE	Std Dev	0.00018
Arsenic	0.001 max	< 0.00009	Range	0.00076
Zinc	0.001 max	< 0.0001	Minimum	0.01971
Bismuth	0.05 max	< 0.0001	Maximum	0.02048
Iron	0.001 max	< 0.001		
Nickel	0.001 max	< 0.00009	Count	45
Silver	0.005 mX	0.0009		
SB AS & SN	0.002 MAX	< 0.002		

Table 1
Lead specifications as provided by Vulcan resourses. The SPC DATA statistical information on the right refers to the thickness in units of inches. This lead is free of mercury contamination.

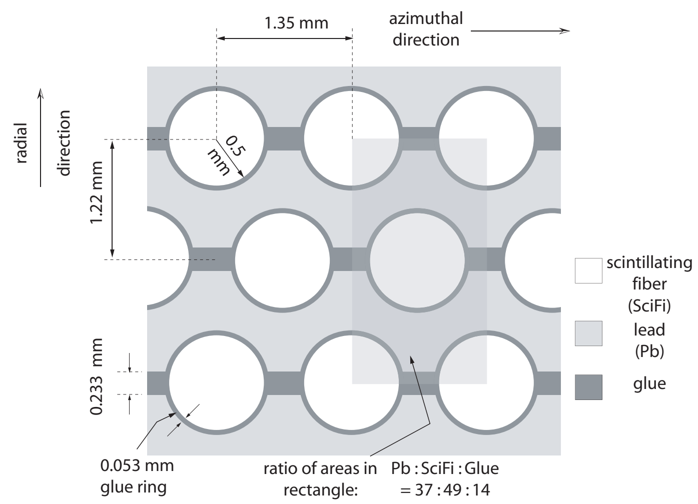

Fig. 1. A close up of the lead matrix is shown.

of ∼200 layers of corrugated lead sheets, each of 0.5 mm thickness, and 1-mm-diameter, multi-clad, scintillating fibres (SciFi), bonded in place of the lead grooves using BC-600 optical epoxy [1]. This geometry is sketched in Fig. 1

[1] St. Gobain Crystals & Detectors, Hiram, OH 44234, USA (www.bicron.com)

and will result in ∼16 000 fibres per module, for a total number near 780 000 fibres. The detector will consist of 48 wedge-shaped modules, and will form a 390 cm long cylindrical shell with inner and outer radii of 65 cm and 90 cm, respectively, as shown in Fig. 2.

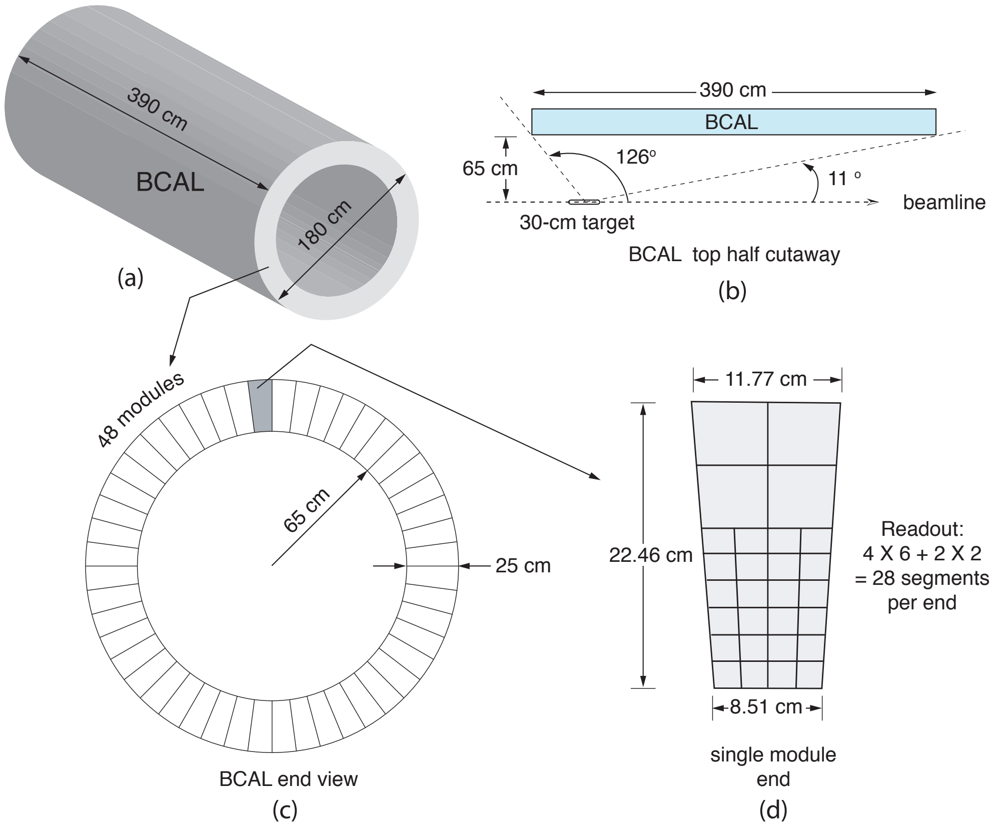

Fig. 2. The GlueX BCAL calorimeter. (a) overall schematic; (b) top-half cutaway showing the placement of BCAL with respect to the beamline and liquid hydrogen target; (c) end view showing 48 modules; and (d) end view of a module showing readout segmentation.

The lead sheets are plastically deformed ('swaged'), following passage through a custom-built machine, termed the 'swager', resulting in lead sheets with a corrugated profile. During construction, the top surface of each sheet is 'painted' with optical epoxy before fibres are layed into each of its $\sim$ 100 grooves. Each BCAL module will be built upon a $1\frac{1}{4}$ inch aluminum base plate and will be assembled in the shape of a Mayan pyramid comprised of four steps having progressively decreasing widths: 13 cm, 12 cm, 11 cm and 10 cm. This explains the precut widths described in Section 1. Following construction, each module will be machined to its final wedge-shaped form, namely with a trapezoidal cross section: $8.5 - 12.5$ cm taper from narrowest to widest.

In order to test the fabrication procedures, it was decided to build a 49^{th} module, termed the "Construction Prototype". Roughly 30% of this module will be constructed using the first-article lead evaluated herein. The remainder will be made with surplus lead from a previous prototyping exercise.

3 Evaluation

3.1 Overall condition

The first-article lead was shipped to Regina in nine lead rolls, five of which were pre-cut to a width of 10 cm and the remaining four to 11 cm. Surplus lead existed in Regina from a past prototype construction as mentioned above and that was prepared to equip the two lower (13 cm and 12 cm), wider rungs of the pyramid, and part of the 11 cm stage. For this reason that it was decided to request enough first-article lead to complete a full-scale BCAL Construction Prototype, which had to be in rolls of 11 cm and 10 cm width.

The crates and contents were examined and there were no visible signs of abuse. A few of the lead rolls had minor dents along their edge that disappeared after swaging. The rolls were unrolled and inspected. The overall condition of the lead was very good with no flakes or large foreign particles present, and only slight dust and discoloration, possibly due to oxidation. The first-article lead was scrubbed gently using a Brillo pad (TM) and then sprayed with ethyl alcohol and wiped with a soft cloth. This procedure thoroughly cleansed the lead and possibly scoured it somewhat, which may improve the bonding of the epoxy to it. Before and after images of a sample are shown in Fig. 3.

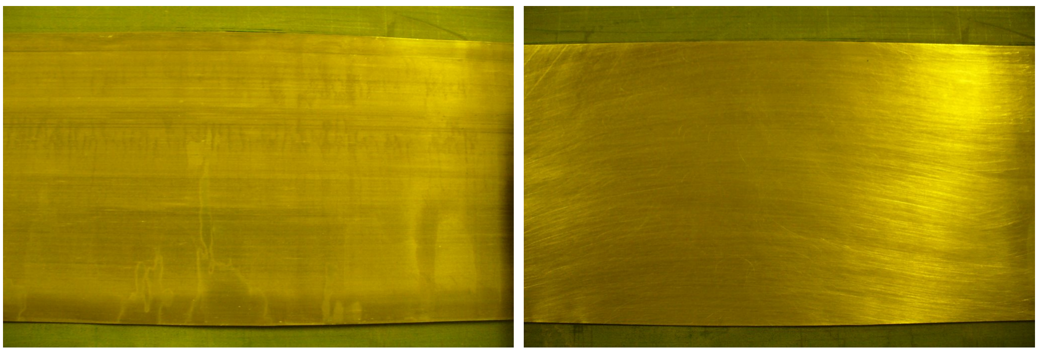

Fig. 3. Photographs of a lead sample before (left) and after (right) scrubbing and cleaning. The removal of discoloration is visible near the bottom quarter strip of the sheet.

Following the cleaning process, the lead rolls were cut to length, each approximately 396 cm long, resulting in 36 11-cm-long lengths and 44 10-cm-long ones. One 10 cm sheet was damaged by the swaging process and three other were not swaged and were kept as spares. The total length of the lead, calculated from the Vulcan information in Section 1 and assuming the standard density for pure (99.94% in our case) lead of 11.35 g/cm^3, comes to 19694 cm and 16042 cm for the 10 cm and 11 cm rolls, respectively. Details are shown in Table 2.

Cut Type	T×W (inches)	Wt. (lbs)	L/coil (cm)	No. coils	L_{tot} (cm)	L_p (cm)	L_u (cm)	L_r (cm)
10 cm	0.020×3.940	50	3939	5	19694	17434	395	1865
11 cm	0.020×4.334	56	4010	4	16042	14256	1609	177

Table 2
Length details are shown for the first article shipment. The thickness and width (T×W), as well as weight per coil (Wt.) are as quoted by Vulcan in their bill of lading. The density of lead was assumed to be 11.35 g/cm^3, since the lead is pure (99.94% purity, as quoted by Vulcan). L_{tot}, L_p, L_u, L_r refer to the total calculated length, the length processed through the swager, unused (spare) and rejected (remaining length too short) plus damaged (swager or handling), respectively.

All sheets were cut to an approximate length of of 396 cm, a number more precise than the 400 cm specified in the contract, so as to reduce waste. As will be explained below, the sheets elongate to give a final length slightly above 400 cm. As it turned out, the 11 cm rolls resulted in integer number of sheets with far less waste (lengths that were shorter than 396 cm from each roll) than the 11 cm rolls. Specifically, the waste from the three 11 cm rolls that were fully expended was 60 cm, 41 cm and 76 cm, respectively. On the other hand, there was considerably waste from four of the 10 cm rolls: 319 cm, 227 cm, 343 cm and 223 cm. The fifth one had no waste.

3.2 Dimensional uniformity

The width and thickness of each cut near one edge, at three positions along its length (approximately 50 cm, 200 cm and 350 cm) were measured using a Starrett 799 electronic caliper [2] and a Starrett 1015MA portable dial thickness gauge. The results are histogrammed in Fig. 4 and are presented in Table 3.

Based on 249 measurements – albeit by different individuals – the measured thickness was found to be (0.489 ± 0.030) mm, to be compared to the Vulcan result of (0.511 ± 0.005) mm. The Regina average is 4% lower than Vulcan's but within one standard deviation; the latter was 6% and within the contracted tolerance of 10%. A different measuring method, but using the same thickness gauge yielded averages of 0.494 mm and 0.513 mm for the 10-cm and 11-cm

[2] The L.S. Starrett Company, Athol, MA 01331, USA (www.starrett.com)

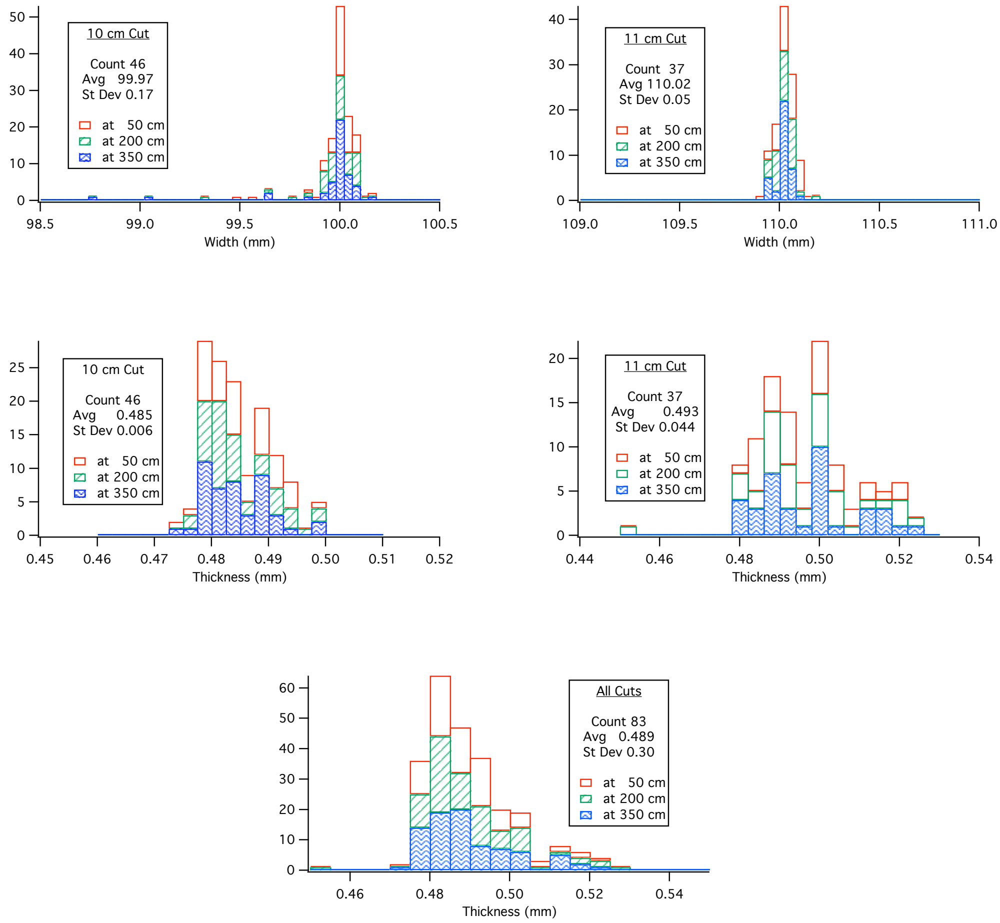

Fig. 4. The Regina histograms of lead width and thickness based on the two width cuts. Measurements were taken near the edge of each cut at approximately 50 cm, 200 cm and 350 cm from one cut end. The bottom panel combines the thickness measurements for both cuts.

sheets, respectively, after four measurements. These values are consistent with those in Table 3 and the differences vanish once the lead is swaged.

3.3 Response to plastic deformation

The lead cuts were passed through the swager. The lead swaged beautifully, on the sense that the extruded sheets came out nearly perfect in shape, that of a rectangle, having a width slightly expanded from the pre-swaged with and elongated by 1.7% on average. Specifically, the 10-cm cuts elongated by $1.60 \pm 0.09\%$, whereas the 11-cm cuts experienced a larger elongation of $1.98 \pm 0.17\%$. Histograms of the results and a plot of the elongation versus width are shown in Fig. 5.

Cut Type	Function	Width (mm)			Thickness (mm)		
		50 cm	200 cm	350 cm	50 cm	200 cm	350 cm
10 cm	Avg	99.98	99.98	99.94	0.486	0.485	0.485
	St Dev	0.12	0.13	0.24	0.006	0.006	0.006
	Avg±St Dev	99.97 ± 0.17			0.485 ± 0.006		
11 cm	Avg	110.03	110.02	110.01	0.485	0.497	0.497
	St Dev	0.05	0.05	0.04	0.074	0.014	0.012
	Avg±St Dev	110.02 ± 0.05			0.493 ± 0.044		
All cuts	Avg±St Dev	N/A			0.489 ± 0.030		

Table 3
Lead width and thickness statistical analysis is shown separately for the 10-cm and 11-cm cuts and for both cuts as far as the thickness is concerned.

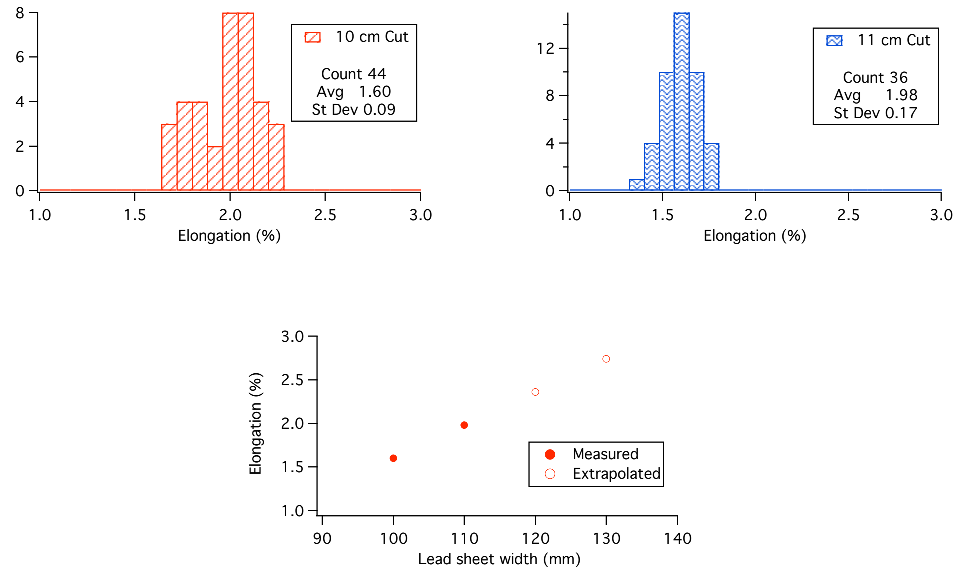

Fig. 5. Histogram of the percent elongation of the lead for the 10-cm (top left) and 11 cm (top right) cuts. The average elongation is plotted versus the lead sheet width/cut (bottom) assuming a linear behaviour. Details are provided in the text.

3.4 Material Analysis

A small sample of lead was sent from Regina to JLab for material analysis. To this end a X-ray fluorescence system model alpha-2000 (S/N 9326) was used [3]. The scan indicated 100% Pb with no significant alloys. The accuracy

[3] Innov-X Systems, Inc., Wo burn, MA 01801, USA (www.innovx.com)

of the test was 0.63%. The material analysis by Vulcan showed 99.94% purity, a number that is consistent with the JLab scan.

4 Conclusions

The first-article lead from Vulcan Resources Inc. meets the GlueX BCAL specifications as laid out in the JLab contract to Vulcan [1].

Specifically, the overall condition of the lead was satisfactory, since the lead was free of any deformations, was relatively clean, namely devoid of flakes or large particulate matter. Moreover, the thickness was uniform, (0.489 ± 0.030) mm and within the 10% RMS in the contractual specifications. In any case, minor non-uniformities are suppressed further after passing the lead sheets through the swaging machine. Likewise, the pre-cut widths of the rolls, (99.97 ± 0.17) mm and (110.02 ± 0.05) mm, meet specifications (are within ± 2.5 mm (± 0.100 inches) and slight deviations from the nominal values would disappear following the machining of the completed BCAL modules.

A chemical composition analysis showed that the lead is 100% pure with an error of ± 0.63%, a result within contract specifications.

The total length of the lead rolls delivered in the production stage needs to be calculated carefully as integer multiples of 400 cm, as stated in the contract, in order to minimize waste at the end of each roll. Finally, the package met specifications and all polyethylene bags should contain descicate pouches.

5 Acknowledgements

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