Thermal Annealing Calorimeter Research and Prototyping

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1 Introduction

The Super Bigbite electromagnetic calorimeter for the GEp experiment is a lead-glass calorimeter with an active surface area of approximately 4 m^2 and serves as the primary electron trigger for that experiment. Due to the anticipated high radiation doses on the calorimeter and the resulting darkening of the crystals, continuous thermal annealing is proposed to allow for operation. Such a calorimeter has not been implemented at this scale before and represents a new experimental challenge.

To aid in the research and design of this calorimeter, two prototypes were developed. C16, a 16 block 4×4 small scale prototype, was constructed at

Jefferson Lab and used to produce a small-scale thermal gradient which was successfully used to demonstrate operation with an acceptable energy resolution in a high-radiation environment. These results are presented in other reports. C200, designed to support up to 400 blocks and the primary focus of this report, was constructed at Stony Brook University to aid in testing configurations for a full-scale design. Here we present the design concept of C200, the mechanical considerations, construction of scalable modules, and heating and cooling tests which are used to guide the ECal construction.

2 Executive Summary

A modular, scalable system for the full calorimeter has been implemented and tested. Individual support modules have been designed and allow for longitudinally non-uniform thermal expansion of the blocks. A heating and cooling system where heating is done predominantly from the front and back of the lead glass blocks has been tested and is in reasonable agreement with simulations and expectations from basic calculations. Heating from the back is done directly on the lightguides near the base of the blocks and a solid partition is inserted around the lightguides to reduce convective heating losses. Cooling by air jets from punctured tubing produces the desired thermal gradient along the lightguides and cools them from 185°C at the rear of the block to below 50°C at contact with the photomultiplier tube. Readily available materials which can be used for the full calorimeter show expected performance given the temperatures required.

3 Large Scale Design

The large scale design for a thermal annealing calorimeter has several major considerations in heating an maintaining structural integrity and stability.

Heating must be primarily done from the front and back to maintain a uniform gradient where the transverse lengths are much larger than the block length. Heating from the sides is required to compensate for heat loss into the structure and maintain a uniform gradient, in particular from the bottom where connections to support structures provide a thermal path. Insulation is required on five sides to minimize heat losses to the external environment. The frame must also be designed to reasonably minimize conduction to the external environment while providing support for the mechanical mass. Further, the thermal diffusivity of lead glass is 0.4 mm^2/s and for 34 cm blocks time-scales for equilibrium is on the order of a day.

Freedom for thermal expansion of the blocks on the order of millimeters is required for an calorimeter with dimensions on the order of meters. The positioning of lightguides and PMTs must not change relative to the blocks, but due to the large thermal difference from the blocks to the PMTs the thermal expansion is not uniform and relative shifts on the order of millimters can occur if the PMTs are held relative to the bottom support rather than the block. On small scales, small variations in block size (in transverse and longitudinal dimensions), aluminum foil covering thickness, and packing variations must be allowed.

Space for heating elements, air cooling, and access to PMTs must be a part of the design. In a tightly-packed row-column configuration, the minimum spacing between the lightguide edges is approximately 1/2 inch, which limits the size of elements and physical access to the back of the lead glass. In addition, this also restricts open airflow hindering cooling.

3.0.1 C200 Configuration

The C200 prototype is designed to support up to 400 blocks, or approximately 2000 lbs, with an internal open volume of about 1 m^3. The support frame is predominantly welded steel C-channel resting on hollow steel tubes. Four eye bolts can be attached to the top of the frame to allow lifting by crane. The unladen weight of the frame is approximately 500 lbs. Four sides have hollow aluminum panels which are filled with approximately 8 in thick FOAMGLAS insulation, Fig. 3. The front has an aluminum panel of 4 in FOAMGLAS. FOAMGLAS has a thermal conductivity of approximately 0.04 W/mK, or twice that of static air, non-reactive, capable of temperatures in excess of 900°C, is noncombustible, lightweight, and easy to cut. All five panels are supported by hollow steel tubes welded to the structure to minimize thermal conduction to the external environment. Access is provided by a door in the rear with a 10 in $\times$ 6 in port to allow for wiring and forced air ducts. Inside is a flat aluminum surface which provides a flat workspace and the front has a removable steel wire mesh to support heating elements. Several steel channels on the top and sides near the front where block are to be stacked are threaded to provide attachment of mechanical supports such as spring-loaded pistons.

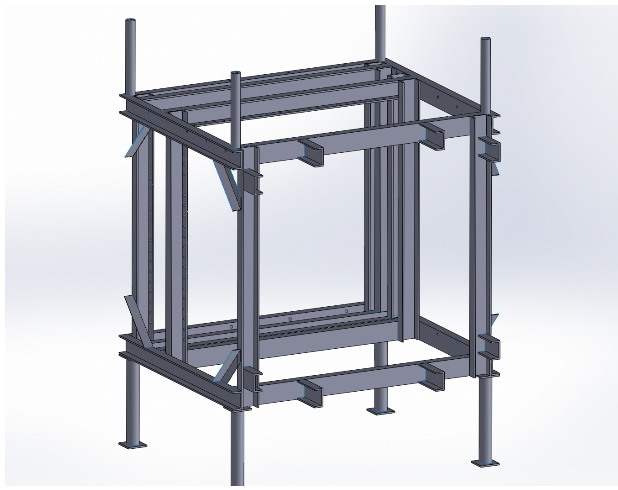


Figure 1: C200 bare skeleton

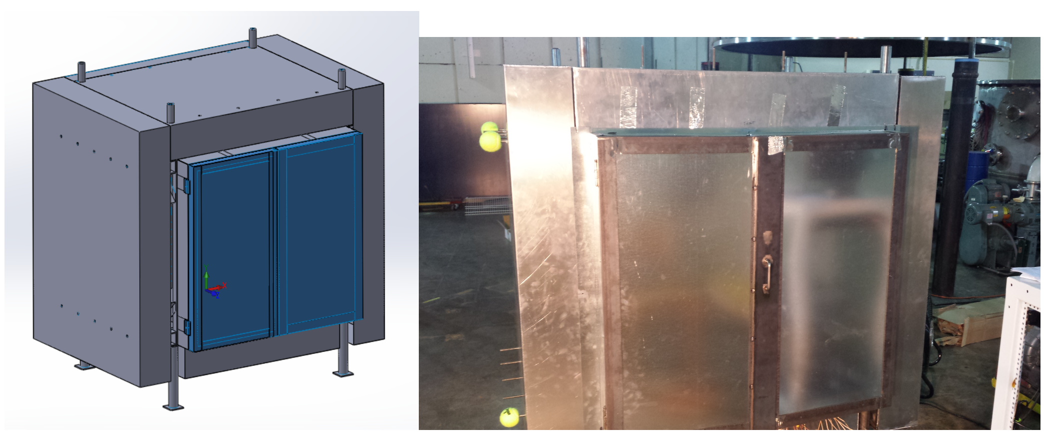


Figure 2: C200 from rear with insulation panels and doors.

Figure 3: Inside view of C200 mounted insulation panels wrapped in aluminum foil.

The heating elements for all tests in this document were FGR-80 heating rope from Omega, which provides approximately up to 4 W/in at 120 V. These were powered by wall outlets switched by zero-crossing solid state relays. The relays were controlled through a PC serial port and proportional power was provided by duty cycles on the order of 5 seconds. K-type thermocouples were used with 16 channels into a scalable automated data acquisition system for constant monitoring and logging with dozens of additional thermocouples for hand-held readout. All controls and readout were integrated together into a single software suite for unified control, feedback, monitoring, and logging.

Forced air cooling was provided by as Gast R4110-2 blower, Appendix A, specified to be capable of up to 96 cfm to open atmosphere. A PVC ball valve allowed for control over the flow rate which was measured by an inline acryllic tapered bore flow meter. In practice the blower system had approximately 30 inH_2O pressure for nominal flow of 20 cfm.

3.0.2 Thermal and Mechanical Simulations

Thermal and mechanical simulations were produced by the finite element package COMSOL using the thermal, non-isothermal fluid dynamics, and solid mechanics modules. Detailed fluid-dynamics air cooling was typically done for small scale simulations and effective cooling parameters (either tuned to data where available or simulation) are used for larger scale thermal simulations to decrease computation time.

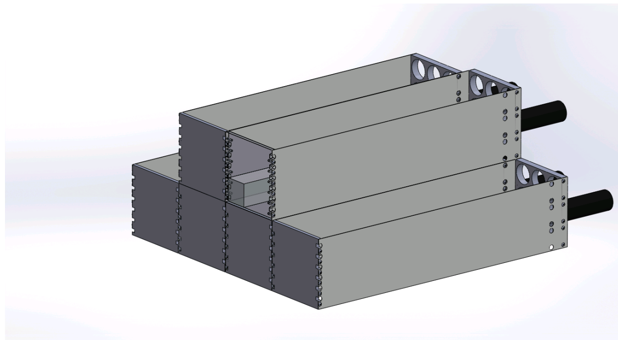


Figure 4: Supermodule stacking concept.

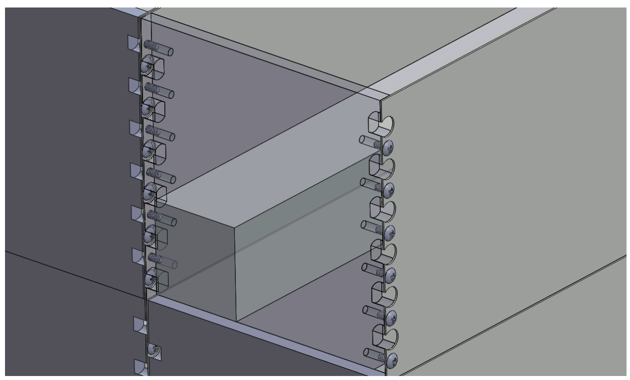


Figure 5: Supermodule front plates interlocking in tight-stack configuration.

3.1 Scalable Modular Design

The supermodule concept was implemented for these tests and is described in the ECal conceptual design report. These modules are designed for a scalable caloriemter and allow for independent non-uniform thermal expansion of the blocks, Figs. 4, 5 6.

20 of these modules were constructed between Stony Brook University and Jefferson Lab for testing in C200.

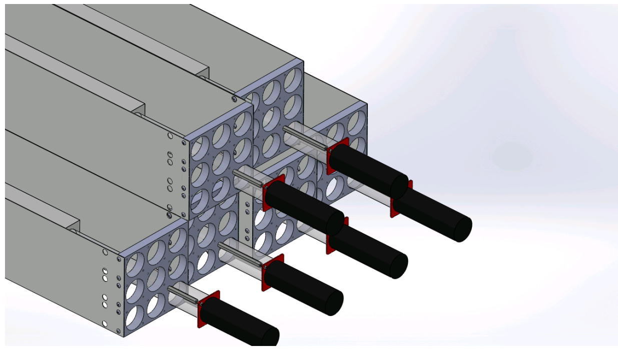


Figure 6: Supermodule rear stacking. Longer modules provide a small access gap to lightguide area and holes for short module screw heads.

3.2 Heating Considerations

Heating elements must be present on all sides to establish a uniform thermal gradient and compensate for small thermal losses in the system. For C200, we have the goal for establishing the necessary parameters to build a full calorimeter by implementing a similar heating design by heating predominantly the front and back and scaling the transverse size. Given a configuration that is well insulated, a large number of blocks is not required to constrain the requirements. The larger prototypes allow for more realistic testing conditions, in particular, where heating is predominantly done through the front and back, with heating on the sides to compensate for losses.

3.2.1 Requirements

We start with a simple one dimensional model to characterize the system, Fig. 7 which does not include convective losses or losses in the side. Heat is applied evenly per block to the front face and rear face and we assume ambient temperature externally. The total power required for the front and back is of the same magnitude and requires a total of approximately 1 W/block. With similar considerations, the steel walls add an additional average 1 W per block using general carbon steel.

Losses from the sides of the stack are dependent on the specific implementation of insulation and scales with stack perimeter rather than number

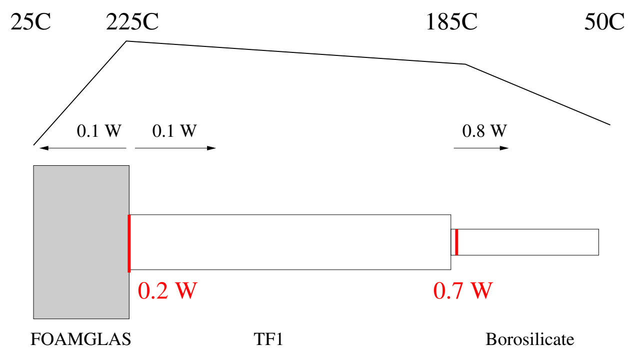


Figure 7: One dimensional schematic of heat flow based on temperature gradients.

of blocks. These losses are typically much smaller than the total heating power, about an order of magnitude less for a well insulated design.

The thermal diffusivity of lead glass and lightguides is 0.4 mm^2/s and 0.7 mm^2/s respectively. With the front and back blocks held at a constant temperature, this requires about one day for the to heat to diffuse and to reach equilibrium regardless of the scale of the configuration. When heating, temperatures cannot be raised significantly above equilibrium due to the temperature restriction on the PMTs. We take this limit to be 50°C for these tests, but have been shown to operate without signficiant degredation in quantum efficiency for periods on the order of an hour at 100°C (described further in the ECal CDR).

3.2.2 Element Placement

Heating for the front of the blocks is accomplished by stringing heating rope elements in a steel mesh which was pressed directly onto the front of the supermodule aluminum plates by the front panel.

Rear heating was done with elements placed directly on the lightguides to prevent extreme local gradients on the lead glass blocks themselves, but close to the block bases to minimize convective losses between the block and the element. Thermocouples were generally placed near the base of the lightguide and block. A 1/8 in polyimide board partition with 33 mm holes is fitted around the lightguides in the supermodule and held in place by high-temperature silicone O-rings (capable of sustained operation of ∼200°C) on

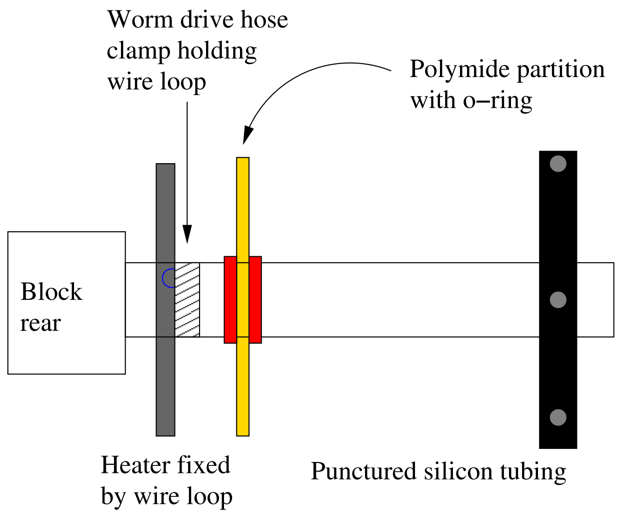


Figure 8: Rear heating/cooling organization

both sides of the partition. This creates a seal which blocks open airflow to the heating area, Figs. 8 and 9.

3.2.3 Heating Tests and Simulation

Several heating tests were done with the C200 modules to validate these requirements under realistic conditions which then can be scaled to the full design. The goal of these tests is to provide verification of calculations under different configurations, empirical values to be added to calculations, to test robustness of the system, and give experience in practical assembly and mechanical design.

The first test, which produced more extreme gradients and losses than for the full design, consisted of four supermodules placed on two single block layers on directly the aluminum surface without additional heating on the sides. FOAMGLAS insulation was placed in contact around the top and sides, with thinner additional pieces to fill the gap between the heating mesh and front panel of C200. The partitioned heating area was closed from above and below by additional polyimide board sealed with adhesive Kapton. This configuration established considerable variation in the blocks which tests the overall conductivity as heat moves to the bottom. A non-uniform placement of heating elements was also implemented to look at variations in tempera-

Figure 9: Rear heating of block stack with partition implementation.

tures on the rear of the blocks and test thermal conductivity and contact of the blocks. Front and back temperatures were brought up to approximately 150°C at the hottest points and were heated for about one day.

The configuration was simulated in COMSOL with effective convection losses for surfaces with some tuning to establish agreement with data, presented in Table 1, Figs. 10 and 11. Several conclusions were drawn from this configuration.

The higher conductivity of the steel introduces losses from the exposed “fins” as shown in Figs. 12,13, 14. An equivalent system with a full gradient would have variations on the order of 10s of degrees, Figs. 15.

The lightguides which were exposed to open air reached approximately air temperature when no lightguides were attached and is in rougher agreement with simulated predictions and is highly dependent on the placement of heating elements, Fig. 16. This is an important result as it shows that lightguides immersed in air will cool themselves over the exposed area. Forced air cooling is discussed in Sec. 3.3.

A second test configuration was implemented with heating from the bottom and the four modules were placed on a two plate aluminum shelf supported by four steel I-beams, Fig. 17. The two plates are heated to compensate for heat losses from the bottom and establish the full gradient. Heating elements were placed in contact with the lightguide bases uniformly for even heating. FOAMGLAS insulation again surrounded the top and sides and additional cut pieces were inserted to fill the gap between the shelf plates

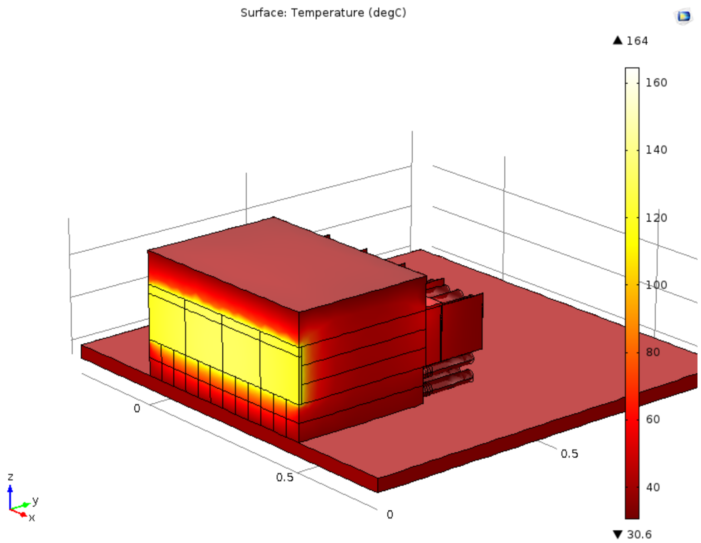


Figure 10: First test configuration. Insulation was also present on the sides (not shown).

TC	240 W	COMSOL	320 W	COMSOL
1	134	132	157	158
2	90	94	118	109
3	100	114	128	135
4	73	92	97	106
5	36	38	40	38
6	69	77	88	88
7	60	65	75	72
10	128	134	160	166
11	99	93	123	111
12	123	127	153	156
13	99	92	122	111
14	111	113	138	139
15	88	85	110	100
16	81	92	100	109

Table 1: Data comparison with COMSOL for first test. Thermocouple placements are shown in Fig. 11.

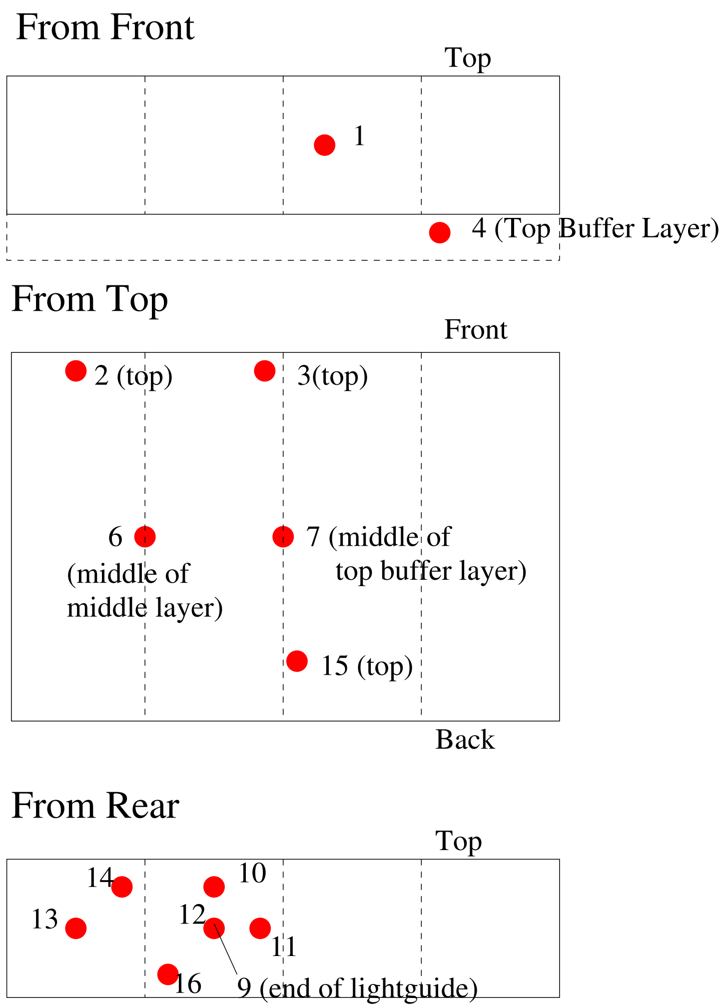


Figure 11: Thermocouple placement for first test.

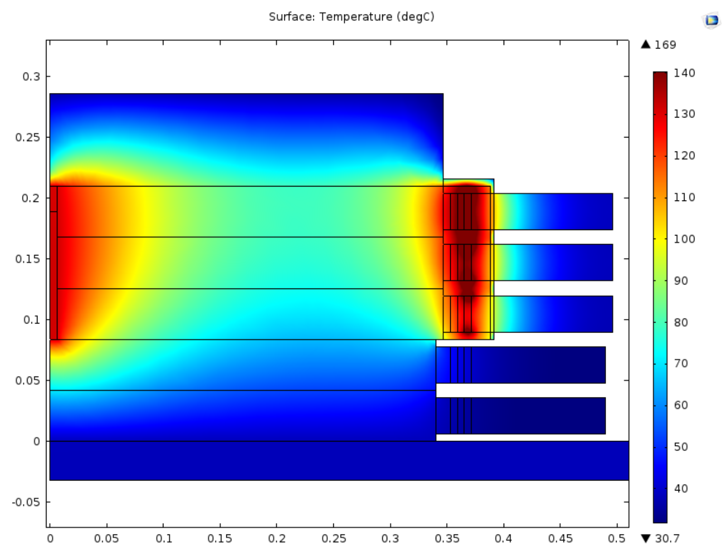


Figure 12: Longitudinal temperature profile for block for the first heating test.

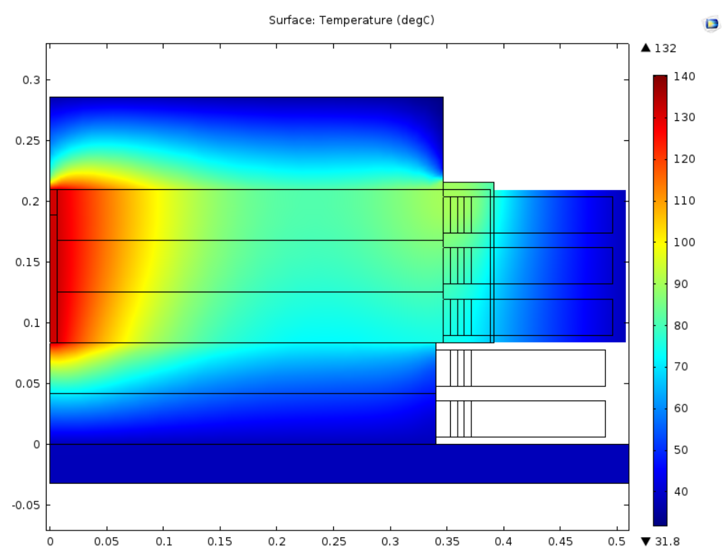


Figure 13: Longitudinal temperature profile for steel wall for the first heating test.

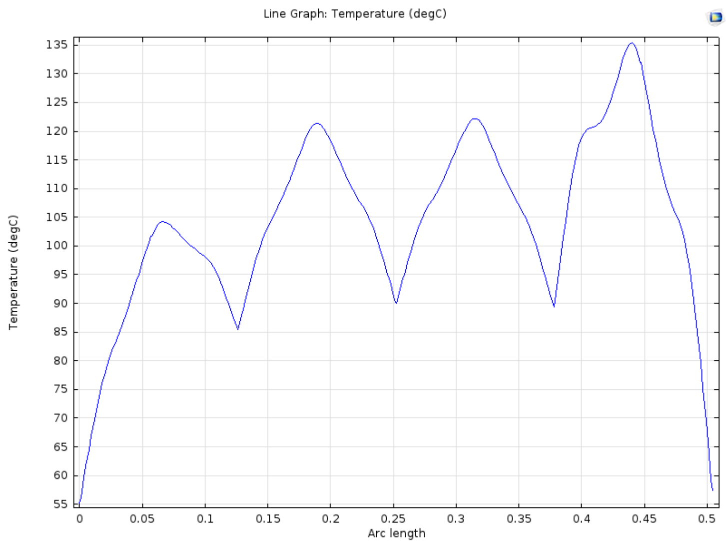


Figure 14: Transverse temperature profile along rear of blocks for the first heating test.

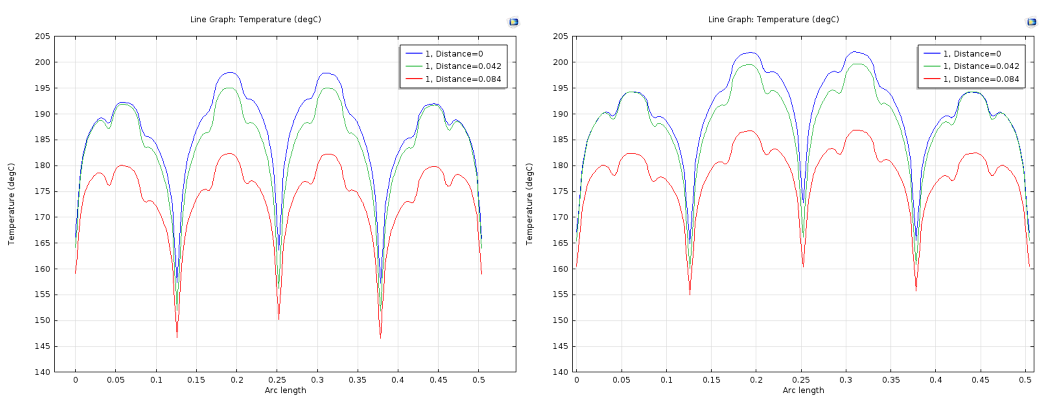


Figure 15: Extrapolated transverse profile approximating a full gradient for bare steel (left) and steel with 1/8 in polyimide insulation given identical heating power. This simulation includes uniform heating from the back and heating from the bottom to support the full gradient. The variation for uncompensated steel walls is on the order of 10s of degrees. The red, green, and blue lines are for the top, middle, and bottom rows respectively.

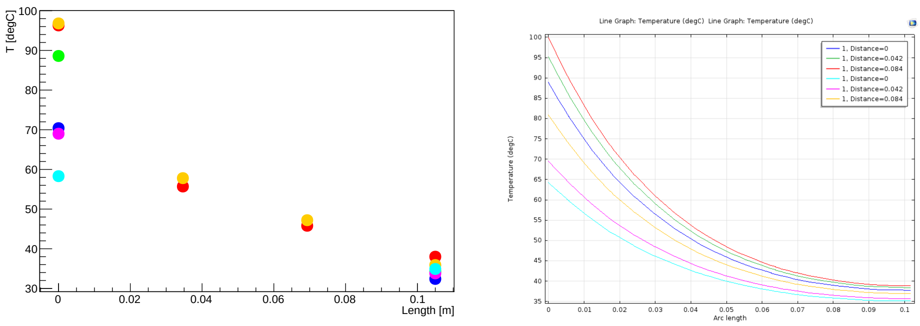


Figure 16: Lightguide temperature profiles from the partition base (arc length of 0) to the end of the lightguide as measured (left) and simulated (right) with identical color coding. Red, blue, and green represent the top row. Cyan, magenta, and orange represent the middle row. Some points just have the partition point and end measurements.

and the support base plate. Thermocouples were placed on the base of the blocks and near the steel to measure uniformity of the rear under a realistic condition. Sets of thermocouples were also placed near the partition and base of the lightguide for cooling to test uniformity.

Comparison to COMSOL under two power conditions is shown in Table 2 for thermocouples placements shown in Fig. 18 and reasonable agreement is obtained. The inferred longitudinal profile of the middle row of blocks is shown in Fig. 19 and demonstrates sagging when the temperature of the support is not held sufficiently high. The support was then warmed to the block temperature to support a linear gradient, PMTs were attached to the two middle modules and 5 cfm of air was supplied to each of the two middle modules, right in the same figure. A linear gradient is established and the temperature at the PMT is below 50°C. The inferred rear temperature profile is shown in Fig. 20. No heating from the side or top is supplied and there is a temperature gradient from top to bottom. Significant cooling is caused by the exposed steel.

A final iteration was made by moving to a larger 1/2 in ID cooling manifold, described in Sec. 3.3 and 15 cfm was flowed to all four modules with the middle two modules fitted with PMTs. The full gradient of 225-185-50°C was established with the exception of the areas near the metal module sides as

Front	60 W		80 W	
Back	120 W		300 W	
Plate	450 W		700 W	
TC		COMSOL		COMSOL
1	185	188	225	216
2	167	187	206	215
3	174	187	217	215
4	137	128	157	158
5	146	151	162	190
6	164	149	177	152
7	165	153	173	156
9	152	148	157	171
10	143	149	184	184
11	139	149	189	184
12	145	149	203	184
13	163	172	170	179
14	142	132	151	137
15	137	143	142	150
16	144	145	145	146

Table 2: Data comparison with COMSOL for second configuration. Thermocouple placements are shown in Fig. 18. The higher power data was after one hour from the low power configuration.

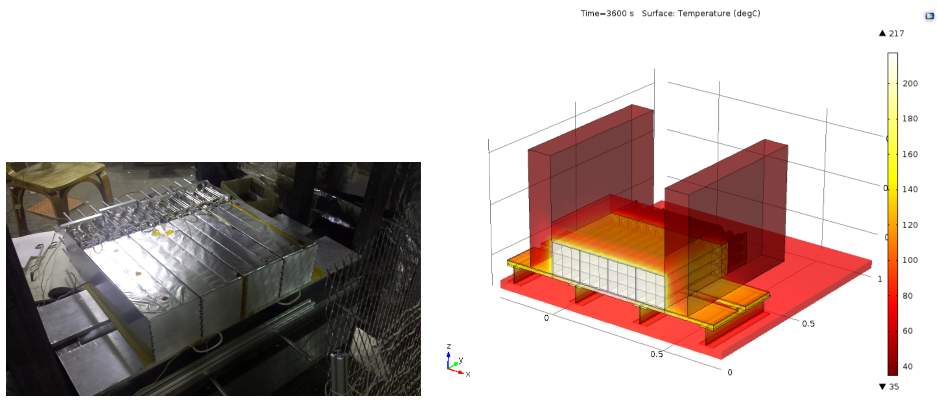


Figure 17: Second test configuration without covering (left) and in COMSOL (right).

anticipated. The power required for the rear is significantly higher due to the some likely leaking of cool air behind the partition and no heating from the top and sides. The thermocouple placement is identical to the previous test, Fig. 18, and comparisons to a COMSOL simulation are shown in Table 3.

The inferred rear and longitudinal profiles are shown in Figs. 21 and 22. While there are still areas below 185°C along the steel walls, this is understood in the simulation and can be mitigated with external heating or less conductive materials (such as thinner stainless steel). The longitudinal profile along the block centers remains above 185°C.

3.3 Cooling

Forced air cooling is required due to the restrictive volume once blocks are tightly stacked and PMTs are in place. Small gaps due to the length differences in the super modules allowing for air to be flowed in.

3.3.1 Requirements

Approximately 0.6 W of power will be lost from the lightguides per block and an additional 1 W on average per block from power lost to the steel supermodule wall. However, because the fins are coupled to the PMT holder plate which has a high surface area, it partly acts as a natural radiator. Under the condition of flushing air and with an 10-15 K rise from room

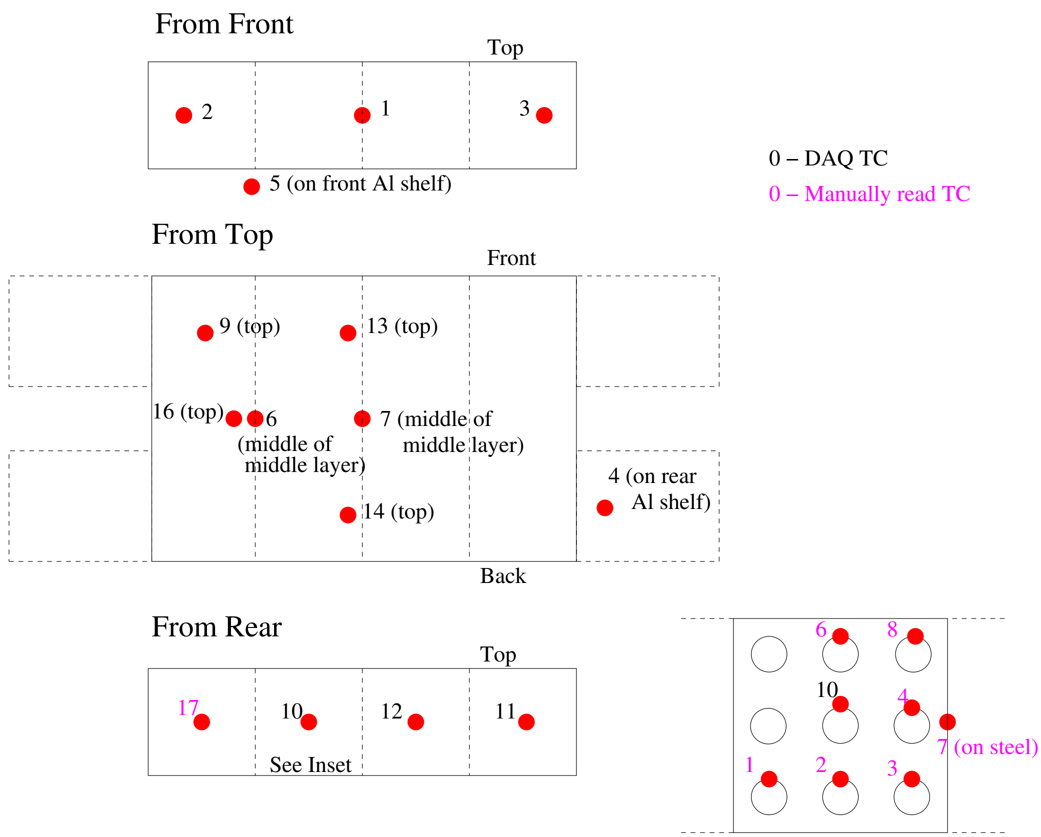


Figure 18: Thermocouple placement for second configuration. Numbers in magenta are read manually.

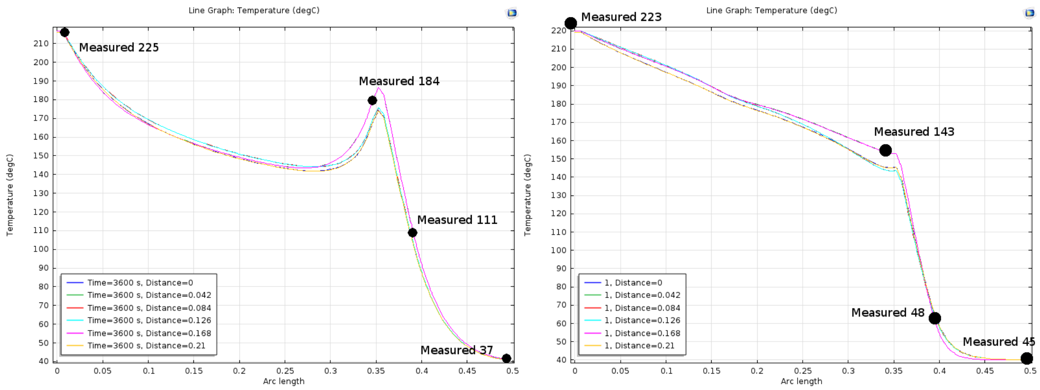


Figure 19: Inferred longitudinal temperature profile for the second test configuration along the center of a block for low support plate temperature (left) and matched temperature (right). The support plate temperature on the left is ∼160°C and does not support a linear gradient. Curve are for the middle row of the two center modules for the sequential columns (three curves are visible due to the symmetry).

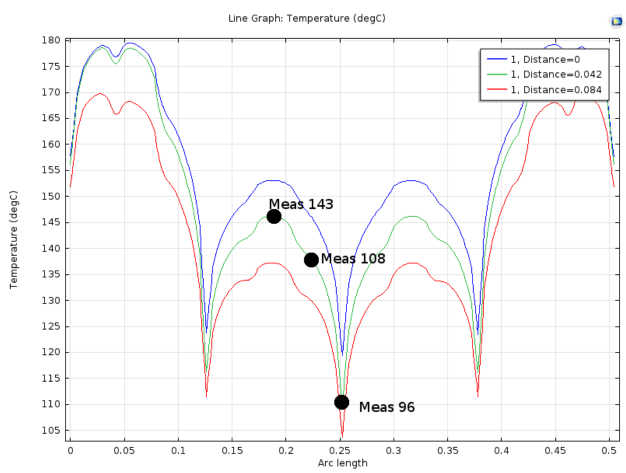


Figure 20: Inferred rear temperature profile for the second test configuration along a block for linear gradient test. Cooling was only supplied to the two middle blocks and warmer blocks are lower in the physical stack due to no additional heating on top. Red, green, and blue lines are for the top, middle, and bottom rows respectively.

Front	40 W	
Back	300 W	
Plate	720 W	
TC		COMSOL
1	229	228
2	208	226
3	221	226
4	179	179
5	207	213
6	212	195
7	213	201
9	187	206
10	184	199
11	178	193
12	202	198
13	206	213
14	172	176
15	173	184
16	174	188

Table 3: Data comparison with COMSOL for second configuration with the full gradient. Thermocouple placements are shown in Fig. 18.

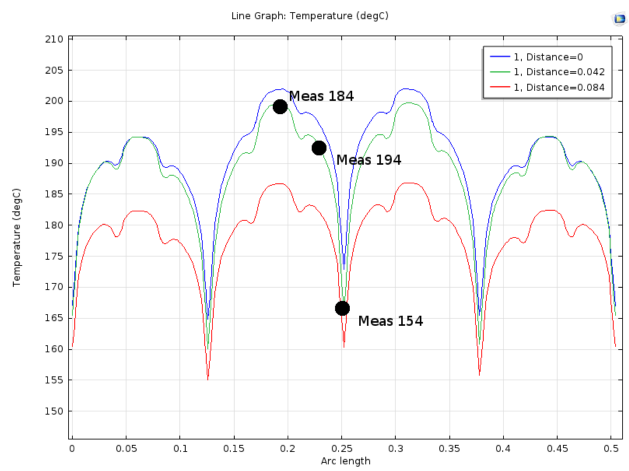


Figure 21: Inferred rear temperature profile along a block for full gradient test.

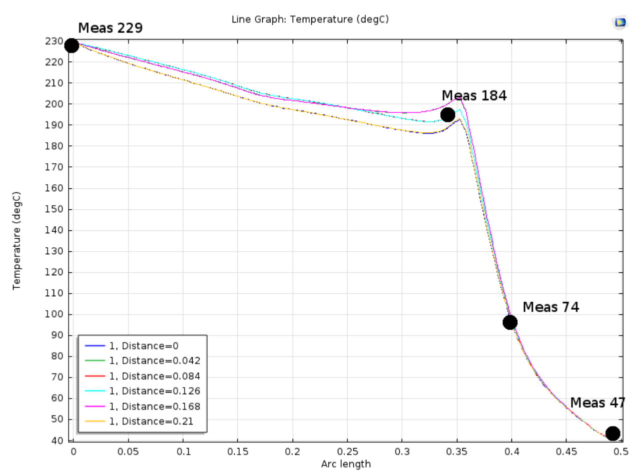


Figure 22: Inferred rear temperature profile along a block for full gradient test.

temperature, this requires approximately 2-3 cfm of air per supermodule. Constricting this air to channels on the order of 1/2 inch diameter to fit the lightguide spacing is in the turbulent flow regime, $Re \sim 10^5$, which demands as wide of tubes as possible to reduce frictional pressure losses.

3.3.2 Tests

A configuration where air from the Gast R4110-2 blower, App. A, is pushed into a flexible high-temperature silicon tubing manifold was tested. A ball valve was installed on the blower to control the airflow which was then measured with a flow meter. Two manifolds were tested: One eight-way manifold with 1/4 in ID tubes of about 2 ft length which is highly resistive, but can restrict the airflow to about 10 cfm and is useful for cooling one row. The tubes were punctured with a spacing equivalent of the block width in symmetric pairs of 3/64 in diameter holes (three holes on one side and three rows on the opposite side). Two four-way manifolds with 1/2 in ID tubing is also tested.

The first manifold was placed with polyimide board blocking flow from the top and bottom except for the supermodule gap, Fig. 23. The rear power supplied in this configuration was 40 W per supermodule with a total estimated power flux to the rear of 18 W per module or 2 W per block, similar to the anticipated required power flux. When the lightguides were covered and PMTs attached, the quickly rose to approximately 50°C before the cooling was started. Once cooling was established, the base of the lightguides fell to room temperature.

The second manifold consisted of 1/2 in ID tubing with eight 1/8 in diameter holes per tube. Each tube was placed near the end of the lightguides and blew air between the lightguides transverse to the lightguide cylinder axis, Figs. 24 and 25. This provided most cooling near the end of the lightguide allowing for a more gentle gradient from the heating elements to be established reducing the heat flow. Results for measurements along several lightguides is shown in Fig. 26 and show temperatures at least 185°C at the block base cooled to about or less than 50°C at the PMT as required.

Figure 23: Rear heating of block stack with 1/4" tube 8-way manifold cooling near the partition.

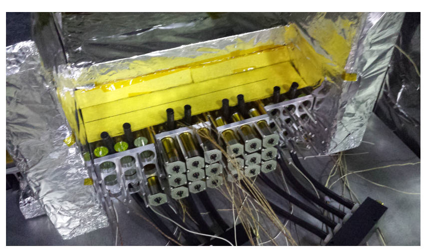


Figure 24: Larger 1/2 in ID manifold for full gradient test.

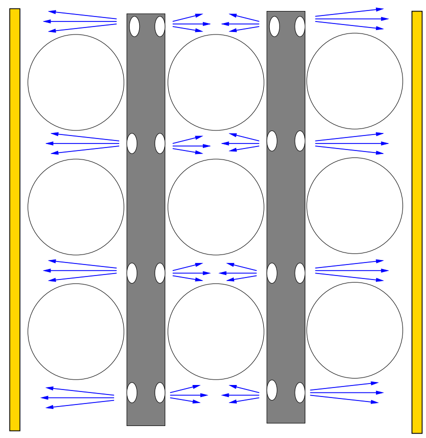


Figure 25: Cooling blowing air transverse to the lightguides near the end where it meets the PMT to establish a gradual thermal gradient down the cylinder.

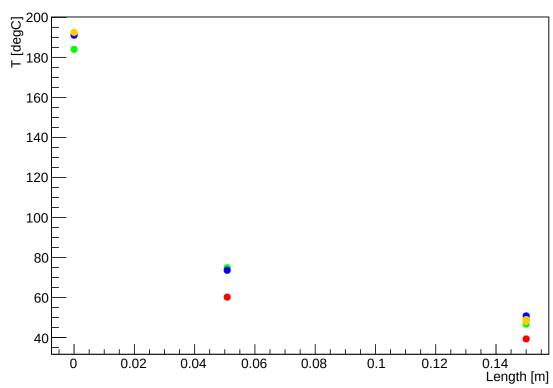


Figure 26: Measurements for several lightguides from the block to PMT with the transverse cooling configuration, Fig. 25.

4 Continuing Tests

Further testing is planned to continue for C200. Testing other supermodule wall materials, such as thinner stainless steel, is planned. Also planned is the heating elements near the wall-block seam to compensate for losses and force the rear gradient to be more uniform. Additional materials that could be used as support or filler, such as commercially available brick, will be useful for operational experience and test compact stacking and shimming. A full 4×4 stack is anticipated and long-term heating on the order of weeks will be tested.

Appendix A Gast Blower used for C200

GAST

Product Specifications

GAST MANUFACTURING, INC.
A Unit of IDEX Corporation
Post Office Box 97
Benton Harbor, Michigan
Ph: 269/926-6171
Fax: 269/925-8288

PART NUMBER: LTD142

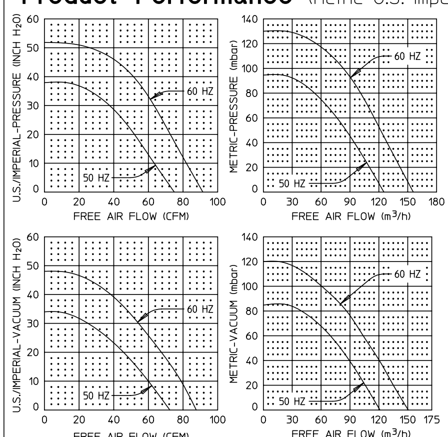
REV. D

MODEL NUMBER	MOTOR SPECIFICATIONS	RPM	MAX VAC		MAX PRESS		HP	kW	NET WT.	
			"H_2O	mbar	"H_2O	mbar			lbs.	kg
R4110-2	110/220-240-50-1	2850	34	85	38	95	0.6	0.45	41	18.6
R4110-3	115/208-230-60-1	3450	48	120	52	130	1.0	0.75		

SOUND LEVEL: 68/64 dB(A) MAX. @ 60/50 Hz
NORMAL AMBIENT: -29°C TO 40°C
RELATIVE HUMIDITY: 0% - 100% NON CONDENSING
ENVIRONMENT: CLEAN DUST FREE

TECHNICAL DATA SUBJECT TO CHANGE WITHOUT NOTICE.

Product Performance (Metric U.S. Imperial)



PERFORMANCE DATA
THE PERFORMANCE DATA SHOWN WAS DETERMINED UNDER THE FOLLOWING CONDITIONS:

LINE VOLTAGE @ 60 Hz. 230V OR 460V FOR 3 PHASE UNITS. 115V OR 230V FOR 1 PHASE UNITS.

LINE VOLTAGE @ 50 Hz. 220V FOR 3 PHASE OR 1 PHASE UNITS.

UNITS IN A TEMPERATURE STABLE CONDITION.

DELIVERY MEASUREMENTS MADE WITH OUTPUT PORT THROTTLED.

SUCTION MEASUREMENTS MADE WITH INPUT PORT THROTTLED.

TEST CONDITIONS: INLET AIR DENSITY @ 0.075 lbs. per cu. ft. [20°C (68°F), 29.92" Hg (14.7 PSIA)].

NORMAL PERFORMANCE VARIATIONS ON THE RISISTANCE CURVE WITHIN ±10% OF SUPPLIED DATA CAN BE EXPECTED.

Product Dimensions Metric (mm) / U.S. Imperial (inches)

Low Voltage, Single Phase
Blue P1 Line
Brown P2, Black 5 — Tie Together, Insulate
Orange 3
White 2, Yellow 4 — Tie Together, Line

High Voltage, Single Phase
Blue P1 Line
Brown P2 Insulate
Black 5, Orange 3, White 2 — Tie Together, Insulate
Yellow 4 Line

Wiring Diagram