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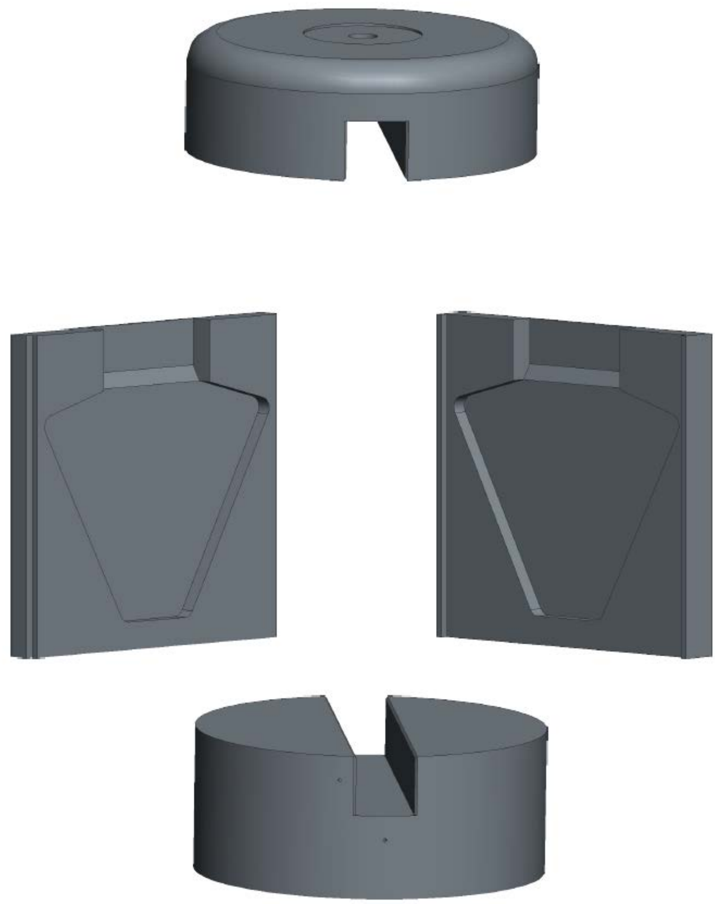

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Scope and Summary

LANL was approached to provide material and design guidance for a fan-shaped fuel element. A total of at least three castings were planned. The first casting is a simple billet mold to be made from high carbon DU-10Mo charge material. The second and third castings are for optimization of the actual fuel plate mold. The experimental scope for optimization is only broad enough for a second iteration of the mold design. It is important to note that partway through FY17, this project was cancelled by the sponsor. This report is being written in order to capture the knowledge gained should this project resume at a later date.

1.0 Billet Casting Operations

Task	Start	Finish
Mold Preparation	9/20/2016	9/22/2016
Mold Coating	9/28/2016	10/12/2016
Ingot sectioning	9/21/2016	10/25/2016
Charge Weighing	10/26/2016	10/25/2016
Button Melting	11/8/2016	11/14/2016
MC&A	11/14/2016	11/17/2016
Mold Assembly	11/3/2016	11/3/2016
Inventory Shutdown	11/17/2016	12/1/2016
Casting	12/13/2016	12/14/2016
Breakout	12/15/2016	12/15/2016
MC&A	12/15/2016	12/23/2016
Hot Top Removal	12/15/2016	12/19/2016
MC&A	12/19/2016	12/20/2016
Homogenization	1/9/2017	1/10/2017
Packaging	1/12/2017	1/12/2017
Shipment	1/24/2017	1/24/2017

Planned
Completed
No Work
In Progress

Table 1: Current schedule for the high-carbon DU-10Mo billet casting.

2.1) Billet Casting Mold Details

The billet mold itself is a relatively simple, but tested design. The interior dimensions are 7.25”x5.125”x1” with rounded corners and a hot top. The gradient is controlled by the large mold clamps on the top and bottom of the casting and the position in the mold. The mold and crucible assembly can be seen in Figure 1.

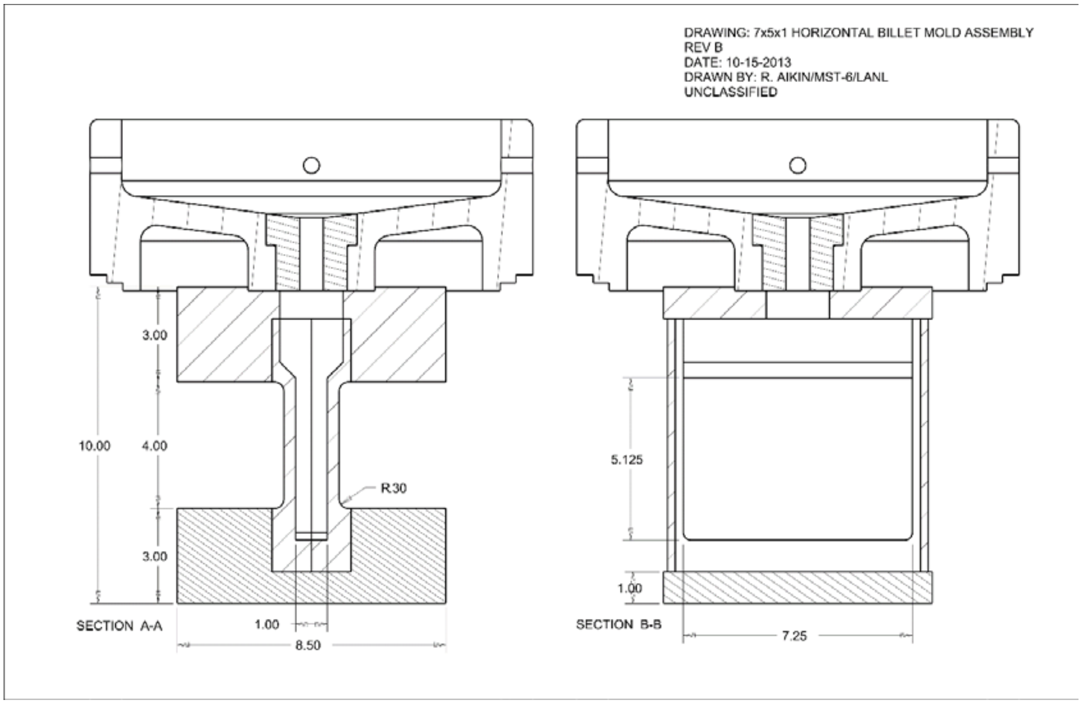

Figure 1: *Mold drawing with crucible. This drawing was also provided to PNNL to develop the sampling plan.*

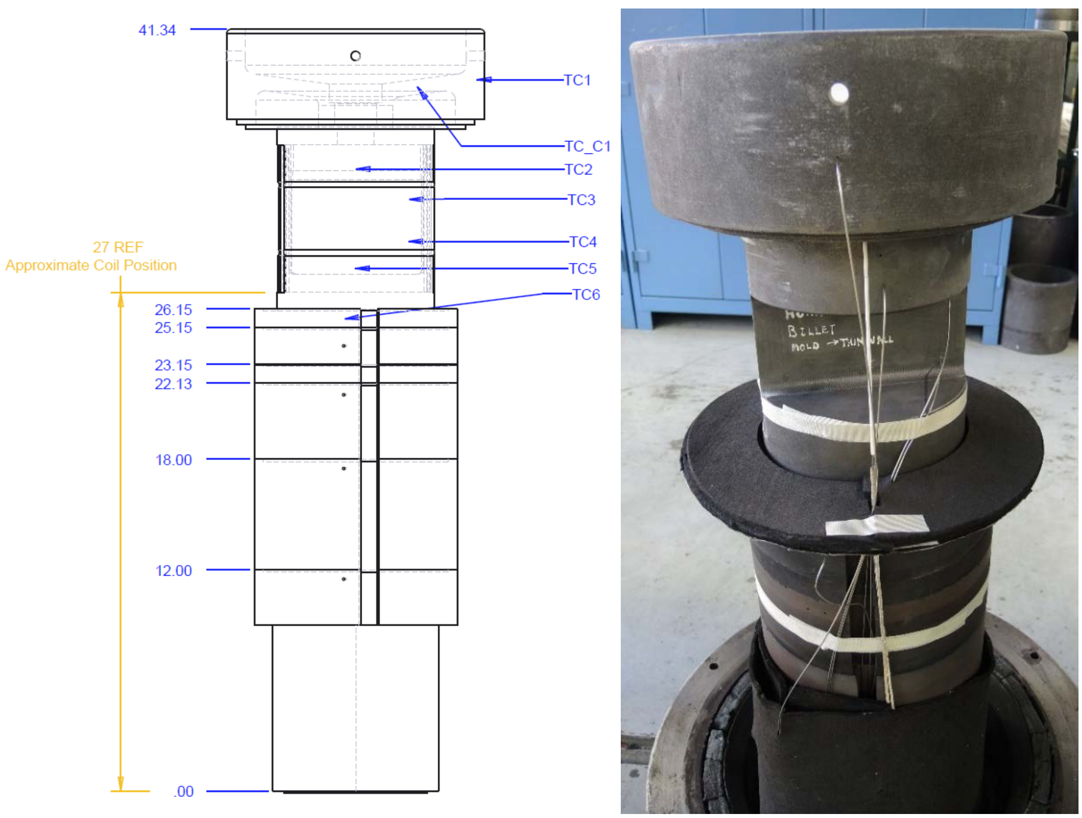

Figure 2: *Pictures of the mold stack assembly and charge material configuration. Note that TC1 and TC_C1 are rotated 90 degrees on the drawing for ease of viewing. Crucible covers are not shown in the drawing or picture. The drawing omits the 2 layers of felt and 1 layer of mica that are used to prevent radiative heating of the lower portion of the stack.*

Figure 3: *One half of the crucible cover configuration is depicted. The entire crucible is covered during casting. The interior hole is to allow the stopper rod to pass through and leave room for pyrometer measurements near the center of the crucible.*

2.2.) Charge material information

The charge material was made up of a prior high carbon DU casting, 00C-522. The pieces came from section A of this casting. A full carbon analysis was done on the facing section, from which this charge material was derived. Figure 4 shows the real layout of chemical analysis drill samples. Assuming no carbon contribution from the Mo, the final carbon content of the charge is nominally 540 wppm.

Sample ID	Trial 1	Trial 2	Averages
	C (ppmw)	C (ppmw)	C (ppmw)
OOC-522-11	619.66	644.31	
OOC-522-12	584.36	NA	
OOC-522-13	623.51	NA	618.0
OOC-522-21	618.49	584.39	
OOC-522-22	648.04	545.29	
OOC-522-23	596.32	NA	598.5
OOC-522-31	578.11	622.36	
OOC-522-32	587.34	NA	
OOC-522-33	601.19	622.08	602.2
OOC-522-41	617.39	584.4	
OOC-522-42	566.71	NA	
OOC-522-43	588.84	NA	589.3

Total:	602
+/-	26

Table 2 and Figure 4: *Carbon sampling from casting 00C-522 with drill samples throughout the cross section as shown in the accompanying picture.*

The charge material was then sectioned using electrical discharge machining in order to get consistent thicknesses and to minimize process losses. The ingot was sectioned into 11 slices. The slices were numbered 0-10 with zero being the top face of the casting and 10 being the bottom surface. Slices 1-10 were then used as charge material for non-consumable arc melting in order to make the alloy material.

The button charges were alloyed in two batches of 5 buttons each. 1-5 were processed under casting ID 16B-138 and 6-10 were processed under 16B-139. All of the buttons used here met the processing specification developed for the Convert program, which is part of the NQA-1 standard. All of the buttons would pass this quality standard if demanded (sans the chemistry specification due to program need for high carbon) and records are maintained within the Sigma Foundry. An image of the final buttons are shown in figure 5. The buttons used were 16B-138 (1-5) and 16B-139 (1,3,5) for a total mass of 15347.8 g.

Figure 5: *a.) Final buttons from casting IDs 16B-138 and 16B-139. Elemental masses are shown on the sample bags since they were still considered in-process by the time of this photo. b.) The arrangement of the charge material is also presented.*

2.3.) Furnace Conditions, Thermal Profile, and Casting Details

The casting conditions were chosen based upon experience from mold optimization runs conducted in 2013 and 2014. The following temperatures should be considered guidelines based on previous runs with some expected run-to-run deviation. The goal temperatures and the process temperatures are given in table 3 along with additional furnace processing parameters. A graph of the temperature data is given in figure 6 and the relevant gradients are shown in figure 7. For reference, the vacuum levels were poor in comparison to common specifications, are at the upper limits of acceptability for the Sigma Foundry C Furnace (Ultimate: 593, Maximum: 903 mTorr). It should be noted that shortly after this furnace run, it was discovered that the vacuum gauge was malfunctioning. Based upon the subsequent trials, the foundry staff are confident that the actual ultimate vacuum would have been closer to 40 mTorr.

Casting Plan and Summary: 16C-796				
			Date Cast:	12/14/2016
Material:	DU-10Mo (High Carbon) Billet			
Mold:	7.125"W x 5.125"H x 1"T (LANL Horiz.)			

Furnace Details		
Parameter	Goal	Actual
Initial Power	55 kW	55 kW
Time at 55kW	40 min	30 min
Hold Temp	1328 °C	1330 °C
Soak Time	10 min	10 min

Temperatures				
Position	Goal	Actual	Deviation	TC ID
Melt	1328 °C	1336 °C	8 °C	Pyro
Crucible	NA °C	1278 °C	NA °C	1
Melt (C1)	NA °C	1212 °C	NA °C	C1
Top Clamp	1177 °C	1156 °C	-21 °C	2
Mold Top	1101 °C	1106 °C	5 °C	3
Mold Bottom	1034 °C	1078 °C	44 °C	4
Bottom Clamp	924 °C	958 °C	34 °C	5
Pedestal	NA °C	733 °C	NA °C	6

Table 3: *A casting plan and summary of parameters used for the high carbon DU-10Mo billet mold casting (16C-796).*

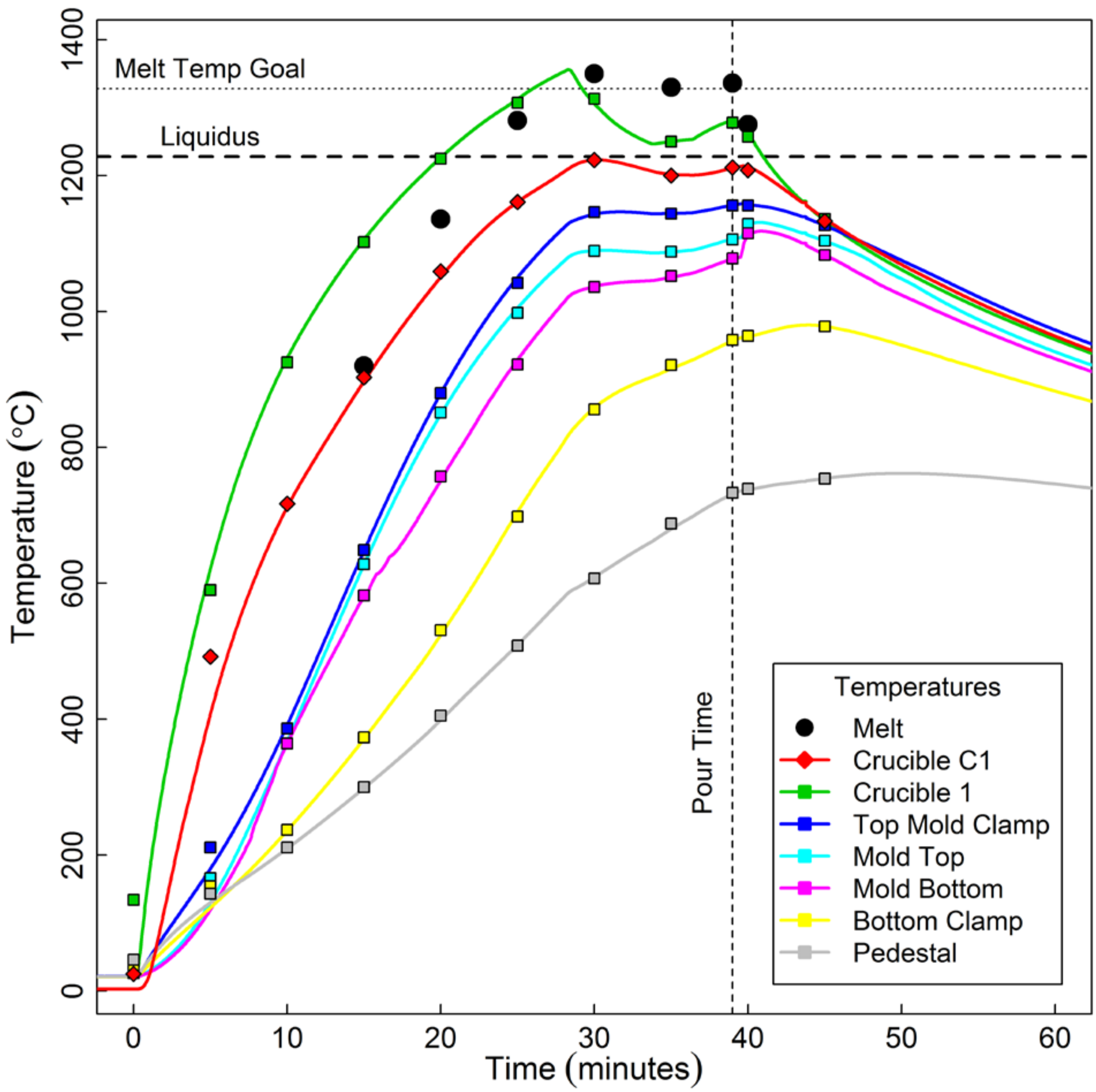

Figure 6: *A graphical output showing the temperatures during the casting run. Solid points refer to manually entered data and the smooth curves correspond to digitally acquired data. Horizontal and vertical lines are drawn to indicate important temperatures or times.*

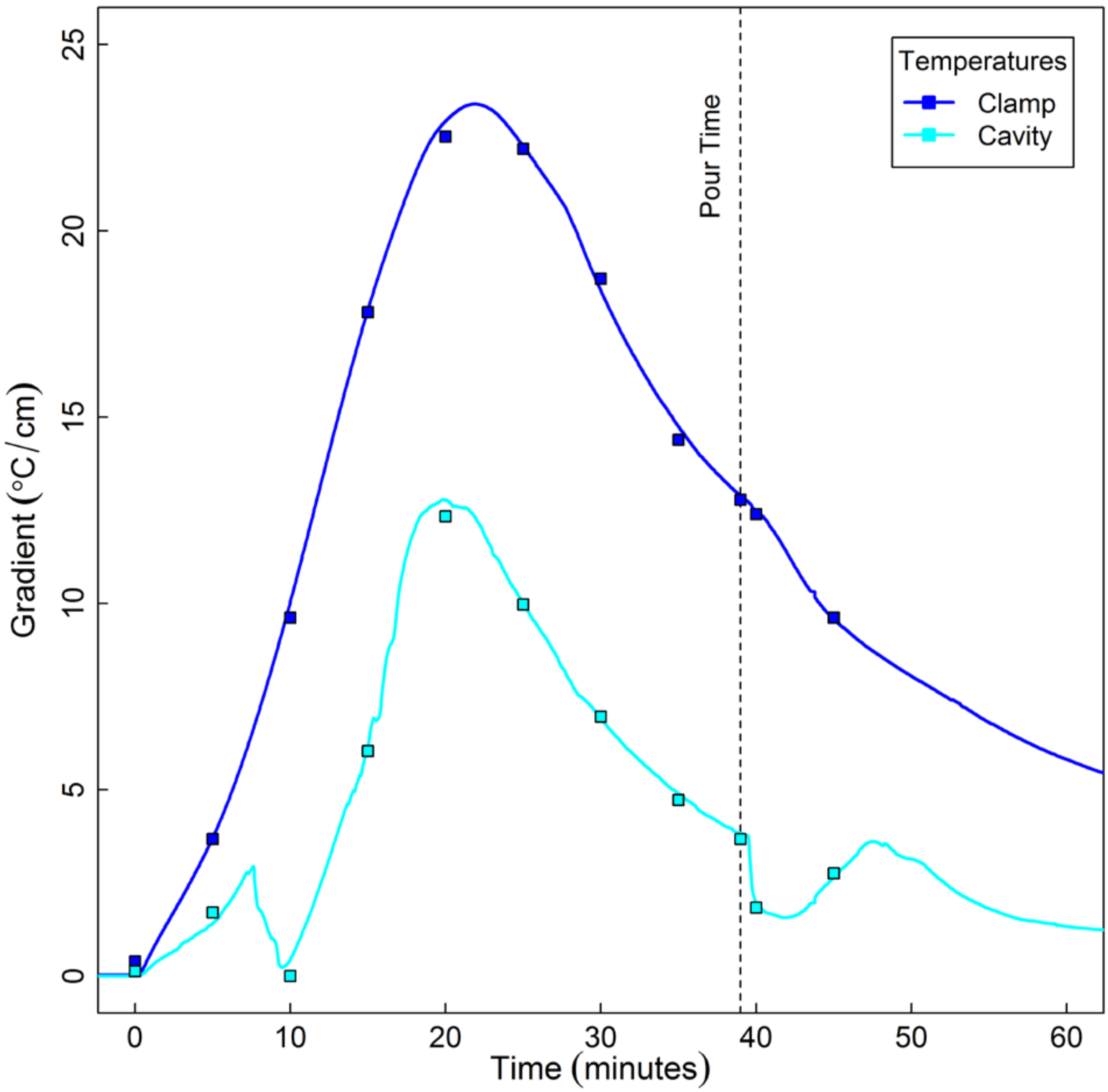

Figure 7: *A graphical output showing the important temperature gradients during casting. Solid points refer to manually entered data and the smooth curves correspond to digitally acquired data.*

Breakout of this casting was performed within the Sigma foundry on 12/15/2016 using standard operating procedure. The casting is removed from the mold above a downdraft hood. The metal product, crucible, and all mold pieces are washed using water and acetone with light abrasion. Images of the cast product are shown in figure 8. The total yield of this casting was 95.6%

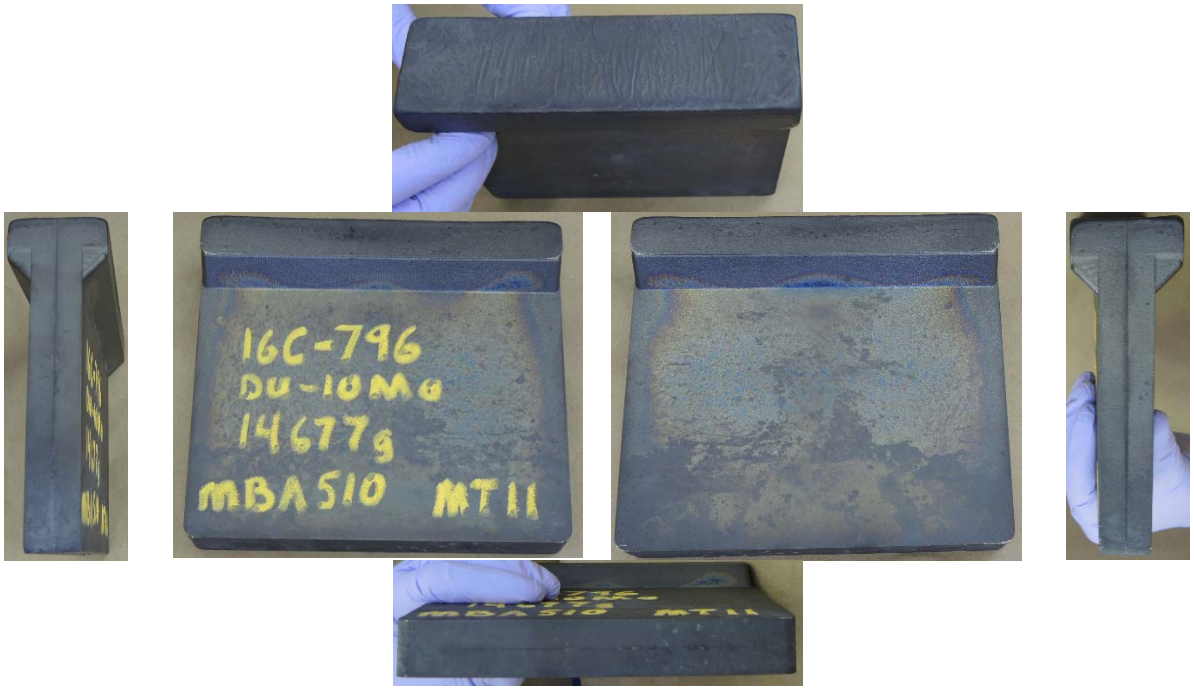

Figure 8: *Pictures of all 6 faces of the cast billet.*

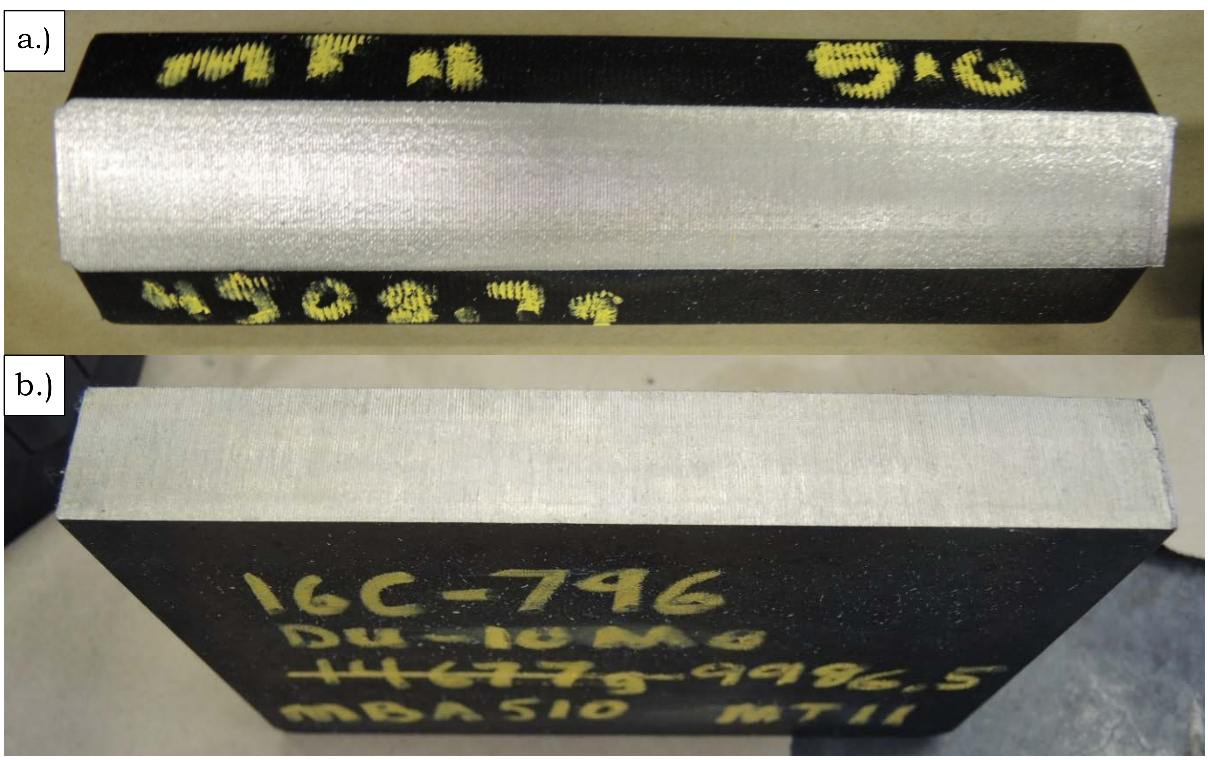

Figure 9: *Cut surfaces after hot top removal. No voids were observed on the cut faces.*

3.0) Mold Optimization

The fuel design for this work is significantly different than other mold designs that have been assessed in the past. The unique shape of the casting and relatively large size have required features in the mold that are not generally preferred when casting this type of product. The first iteration of the mold design has utilized two guiding principles: 1.) The generic machining blank as provided at the start of this project, and 2.) general plate design when utilizing VIM casting. These are broad guidelines, however, are more than enough to build a mold and assess potential problems which would reduce robustness of design.

The generic machining blank as provided is roughly arrowhead shaped with the narrow end at the bottom of the mold. A small hot top which does not extend the length of the casting is available for feeding, however the presence of graphite-metal contact surfaces near the top of the casting are an immediate concern. Therefore, the thermal gradient will be of the utmost importance. Large mold clamps are used on the top and bottom of the mold.

An exploded view of the mold can be assessed in figure 9

Task	Start	Finish
Mold Design	10/13/2016	11/9/2016
Mold Fabrication	11/9/2016	12/13/2016
Mold Assembly	12/14/2016	12/19/2016
Test Heat-up	12/19/2016	12/22/2016
Charge Weighing	12/14/2016	12/14/2016
Button Melting	12/14/2016	1/4/2017
MC&A	1/2/2017	1/6/2017
Mold Coating	1/3/2016	1/4/2016
Mold Assembly	1/5/2017	1/5/2017
Casting	1/9/2017	1/9/2017
Breakout	1/10/2017	1/10/2017
MC&A	1/11/2017	1/18/2017
Hot top removal	1/12/2017	1/17/2017
MC&A	1/17/2017	1/20/2017
Homogenization	1/23/2017	1/25/2017
Packaging	Cancelled	Cancelled
Shipping	Cancelled	Cancelled

Legend
Planned
Completed
No Work
In Progress

Table 4: Schedule for the fan-type fuel optimization casting #1.

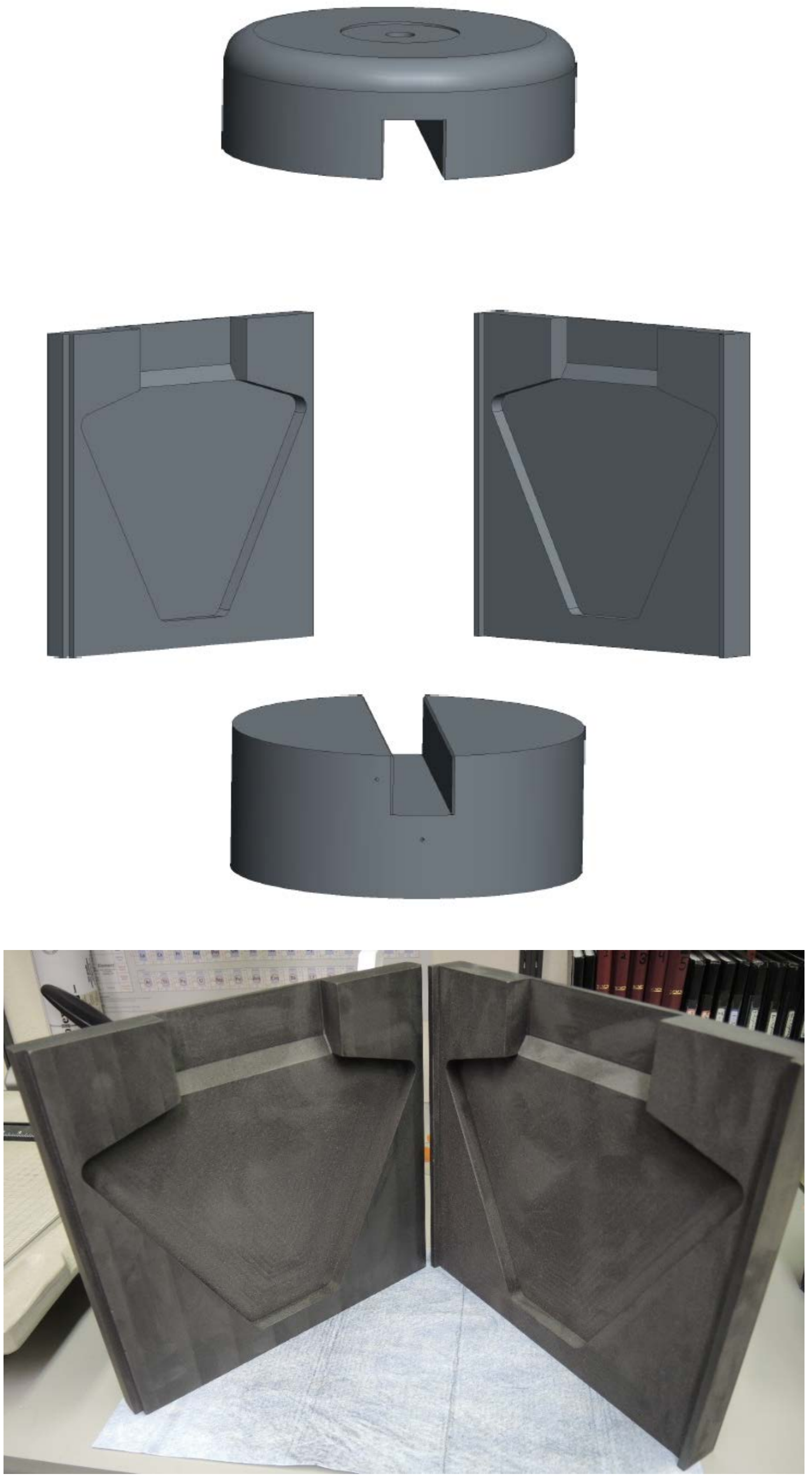

Figure 9: *a.) An exploded view of the first iteration of the mold design. The bottom clamp, two mold halves, and top clamp are visible. b.) The finished mold halves are shown for comparison.*

3.1 Parameter adjustment and simulations

3.1.1 Test Heating

The simulation was setup prior to the test heating, but certain variables and initial conditions benefit strongly from a test heating when a mold is available. For instance, the power supply adjusts the frequency depending upon the inductive load in the coils. Since the mold was ready before the charge material was fully prepared, this provided an excellent opportunity to dial in the parameters more fully. The advantage in doing this is that there is additional confidence in the simulations which are most useful for adjusting the mold stack height and initial power settings. In order to provide consistent boundary conditions for the heat-up simulation.

An initial mold stack assembly was constructed according to figure 10 showing all of the thermocouple locations. A pyrometer is also used to monitor the crucible floor near the pour hole. The test heating is recorded with casting ID 16C-797 and was performed on 12/22/2018. (4.83", 12.27 cm between TC3 and TC6; 8.83", 22.43 cm between TC2 and TC7). In order to contain the mushy zone to less than 2 cm, a gradient from mold cavity bottom to hot top of ~25 K/cm should be maintained. Therefore, from mold cavity bottom to hot top difference in temperature should be 560 K. However, to prevent cold-laps in the casting, the bottom of the mold cavity should be a minimum of 950°C, requiring a mold temperature at the top of 1510°C, which is higher than we would want to cast this object. Pushing the melt temperature up to 1358 would provide 150K of superheat, reducing the tendency for cold laps. A maximum expected temperature for the top mold clamp should be put at ~1175. Therefore, the gradient would fall to ~10 K/cm. (mushy zone length of ~5cm).

Our initial mold heat-up experiment concluded that a gradient of +23 K/cm was possible in the mold at the time of projected pour under the initial design. This would indicate a mushy zone length of 2.17 cm. One serious point of possible failure is the top of the casting due to the contact with graphite and hot top that does not extend the length of the casting. A gradient of 65 K/cm should give some indication that this is doable.

3.1.2 Simulation of mold heat-up

Given the already noted importance of the thermal gradient, the decision was made to perform at least some mold heat-up simulations and/or experimentation before casting material. An initial assembly layout has been constructed. A member of the Truchas development team, Neil Carlson, has provided important input concerning the EM solution and mold simplification necessary for accurate, but reasonably fast modeling.

The project was cancelled prior to completion of the simulations.

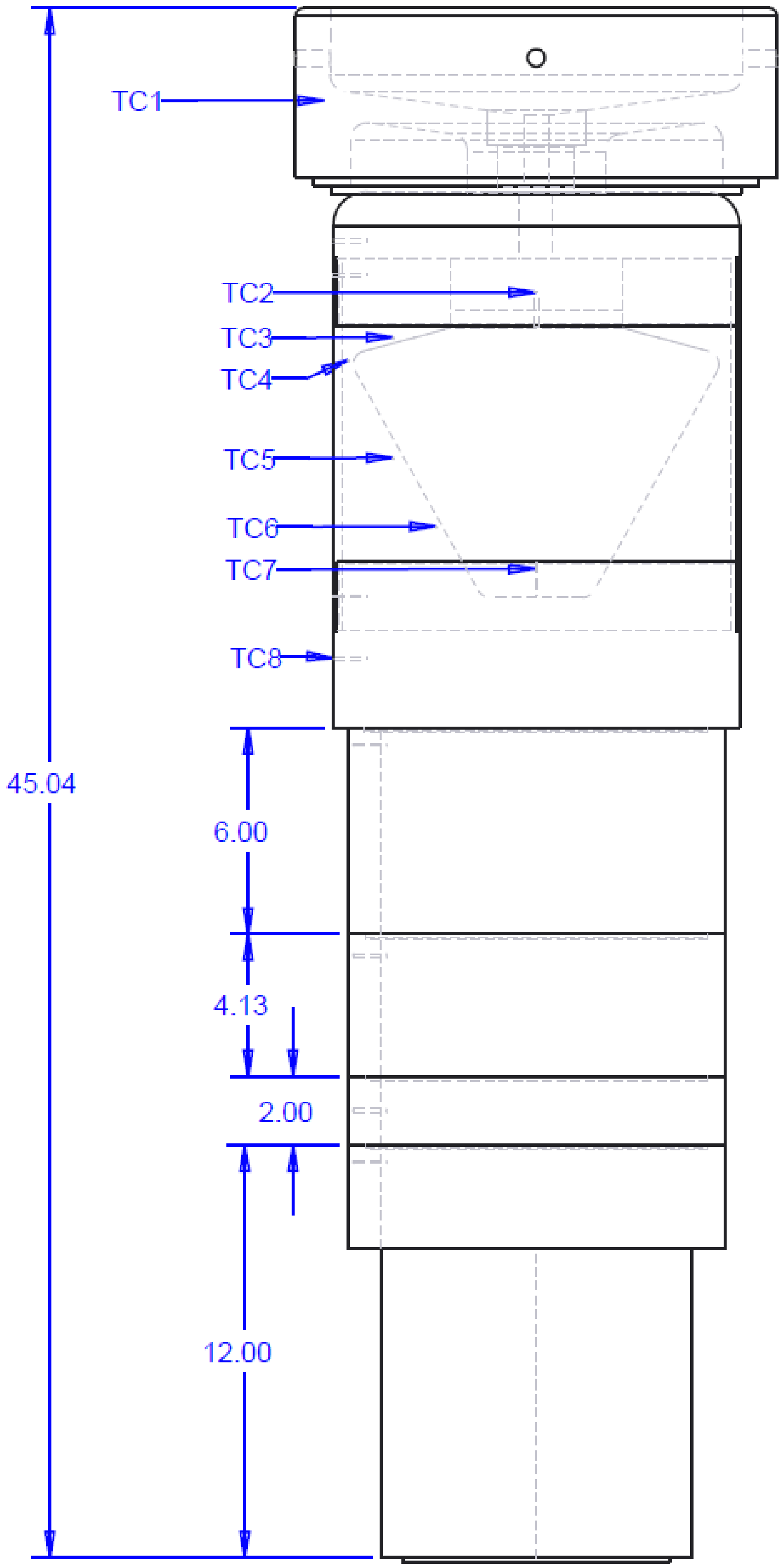

Figure 10*: Assembly drawing for the test heat-up experiment. The bottom of the coil is 27" from the bottom of the major ordinate dimension (approximately at the bottom of the mold cavity).*

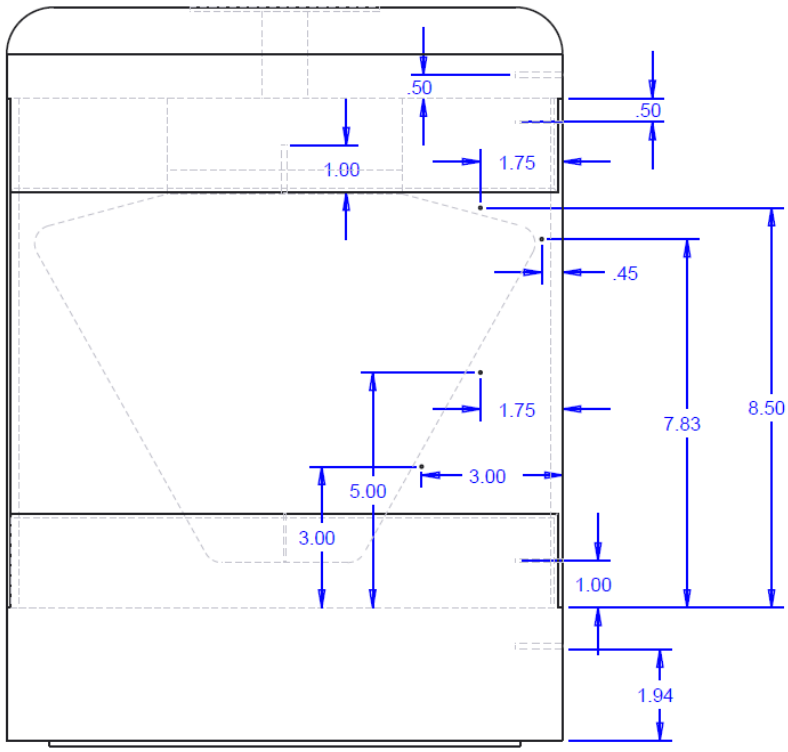

***Figure 11**: Thermocouple locations in the heat-up test run.*

3.) Optimization Charge and Casting

The charge for this casting was taken from a single lot of DU plate (two LANMASS IDs). The goal weight was 15250 g. The goal is approximate and the buttons were skewed to the high side in general since it is generally preferable to have slightly more material than needed rather than too little. There were two lots of buttons necessary to have the necessary charge mass (16B-140 and 16B-141). The final charge mass was 15348 g.

The final assembly of the mold and charge follow the preceding diagrams. Images of setup are shown in Figures 12-14.

Figure 12*: A view of one half of the mold. The interior is coated with a yttria-based suspension with the commercial name of YK.*

Figure 13*: Charge arrangement inside of the crucible (left). Two insulating lids (right) are used as heat shields. The lids are placed on both halves of the crucible, but one half has been removed for clarity.*

Figure 14*: The entire mold stack shown without the insulating lids. Thermocouple placement is evident. Graphite felt was used as a radiative heat shield below the mold to protect the thermocouple feedthroughs and the safety crucible.*

The casting (16C-796) was performed on 12-13-2016. The temperatures were all within the desired range and full filling is indicated by the spikes in temperature shown at casting time in Figure 15. The resulting casting, Figure 16, showed no signs of porosity. There was some metal flash on the outer edge of the casting which was probably due to high melt fluidity (high casting temperature) or a less-than-tight mold fit-up.

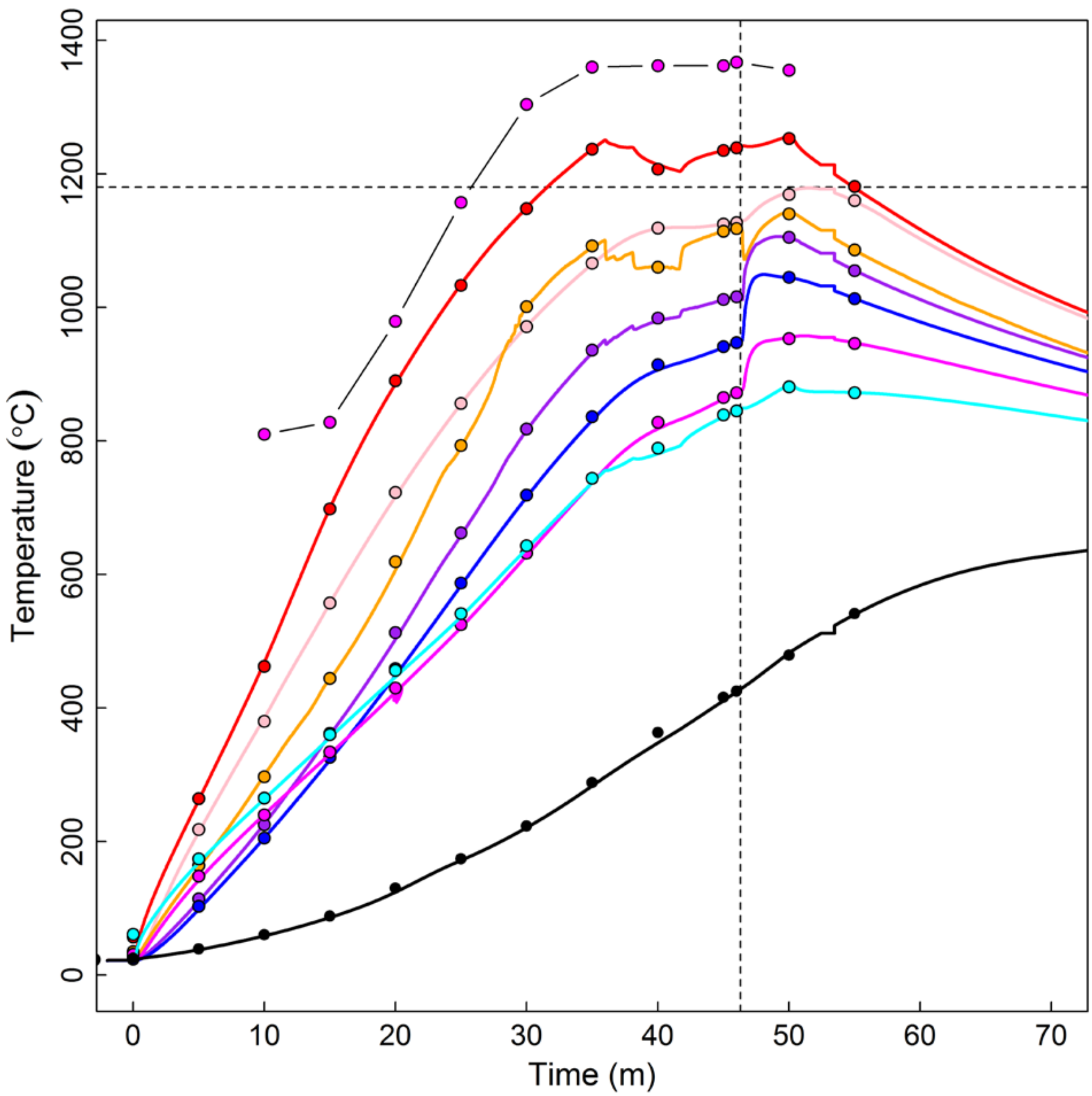

Figure 15: *Thermocouple traces of mold heat-up during casting. Solid lines correspond to digital data acquisition and the points correspond to manual acquisition. The vertical dashed line indicates pour time and the horizontal line indicates the approximate solidus temperature.*

Figure 16: *Pictures of all 6 faces of the cast billet.*

4.) Conclusions

This project covered two main aspects of fuel development. The first was a billet casting which was to be used for mechanical and chemical testing. The requirement was that it be doped with carbon. The second aspect of the project was to design a mold which would achieve the given geometry.

The billet casting was shipped on-time and within the processing guidance given at the start of the project as well as through regular teleconference calls with the broader program. The optimization portion of the project proceeded very quickly and a high quality product was achieved on the first run. That said, it is unknown how robust this design is since only a single casting run was able to be performed prior to cancellation of the project. This report is being written in order to capture the knowledge gained should this project resume at a later date.