CONTINUOUS FREEZE CASTING

MECHENG 450: Design and Manufacturing III

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EXECUTIVE SUMMARY

The team's project was to design a proof of concept prototype for continuous freeze casting. Currently, battery electrodes are manufactured using a solvent which is sprayed onto the substrate then dried, before being calendered, dried a second time, and cut to size. This process is advantageous due to its ability to produce 25-50 meters of material per hour and requires little to no physical labor. However, the solvent used is highly toxic and when sprayed on to the substrate, large quantities remain in the environment rather than depositing on the substrate. Freeze casting offers improved battery conductivity (more efficient batteries), as well as potentially being less toxic. Currently, freeze casting is a discrete process, so the goal of this project is to prove that it can be done continuously and therefore is a potential option for electrode production.

Requirements for this project include: continuous material processing, being dimensionally accurate, low cost, environmentally friendly, and recyclable. To that end, the specifications for this project are to be able to produce between .5-1m of material per minute, be dimensionally accurate within a tolerance of 5 mm in all directions, cost less than $5000, use less than 10kWh/kg of material produced, and be at least 70% recyclable.

The team generated many concepts before landing on a build/final concept. This final concept focused on the continuous aspect of the task, because the freeze casting aspect was deemed to be out of scope for a semester-long project. To this end, thermal simulations were utilized to determine the optimal length of the design, in order to enable further iterations of the project to have enough room to add on the freeze casting portion.

The team validated the design by utilizing an eco audit, and running tests of the apparatus while under load. The team was not able to validate the dimensionally accurate requirement, because that would require a freeze casting set up to be added to the design, which was decided to be outside of what was feasible in a semester-long project. In future, testing for this requirement would require multiple parts to be made and measured to determine the accuracy of the device.

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INTRODUCTION

Professor Wenda Tan from the University of Michigan proposed this project to build a prototype of a roll-to-roll freeze casting setup. After the University was approached by Ford Motor Company to create a setup for their electric vehicles, Professor Tan saw an opportunity to develop a technology not yet proven. Ford decided to go elsewhere after learning the University did not already have a roll-to-roll setup in place, but Professor Tan still sees the potential for this project to be important to help the production of battery electrodes for several electric vehicle companies. [1]

Intellectual Property

This project is under the research of Professor Wenda Tan through the University of Michigan. Thus, intellectual property belongs to Tan's lab and the University. Should a new continuous freeze casting method be used as a result of this project, that property would belong to the University.

Information Sources

The sources used are listed in the References section of this report. Sources were gathered using tools such as Google Scholar and the Michigan Library system. The team consulted many textbooks, research reports, standards, and relevant articles to find out information for the background of our project and benchmarking. By refining our searches and using key words and filtering, we were able to find sufficient information for our project. We found it challenging to find more general information and had to determine what general words would lead to the information we were looking for. With some iteration and persistence, we were able to find what we were looking for.

Electrodes

Electrodes are a fundamental part of all electronics. An electrode is a conductor that makes contact with nonmetallic parts of a circuit; they are used in semiconductors, diodes, and batteries. The positive electrode is called the anode, while the negative electrode is called the cathode. Currently, elemental copper or graphite are the most common anode, [2] while the cathode can be characterized by many different materials, but is mostly made from oxides of metals [3]. Over the course of this report, when referring to electrodes and their manufacturing we are primarily focused on the cathode production.

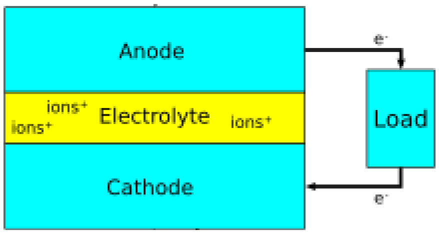


Figure 1: A simplified diagram showing the anode and cathode of a traditional electrical cell, the arrows represent the flow of electrons, conventional current flows in the opposite direction.

Of all the industries that are reliant on battery electrodes, the automotive industry is one of the largest. With the industry trending towards all electric cars in the near future, [4] the need for more energy dense batteries is one of the main challenges to growing electrification. One method of improving the energy density of electrodes is by altering the composition and microstructure of the electrode to decrease the resistance to flow of charges, thereby allowing more energy storage and more conductive cells. Current research shows that by generating more porous, parallel structures in electrode materials, higher conductivity, and by extension energy density, is achievable. In order to meet this goal, automotive manufacturers are looking towards new methods of manufacturing cell electrodes [1].

Roll to Roll

Currently, battery electrodes are manufactured using roll to roll methods, whereby a flexible substrate is rolled across a manufacturing line. This substrate is first coated in an electrically conductive liquid solvent through the use of sprayers. This coating must then be cured in a convection oven/dryer to fully form and bond to the substrate. Once cured, the roll undergoes a secondary drying process after which it is slit, in a process called calendaring, and rewound into long, continuous rolls of electrode material. [5]

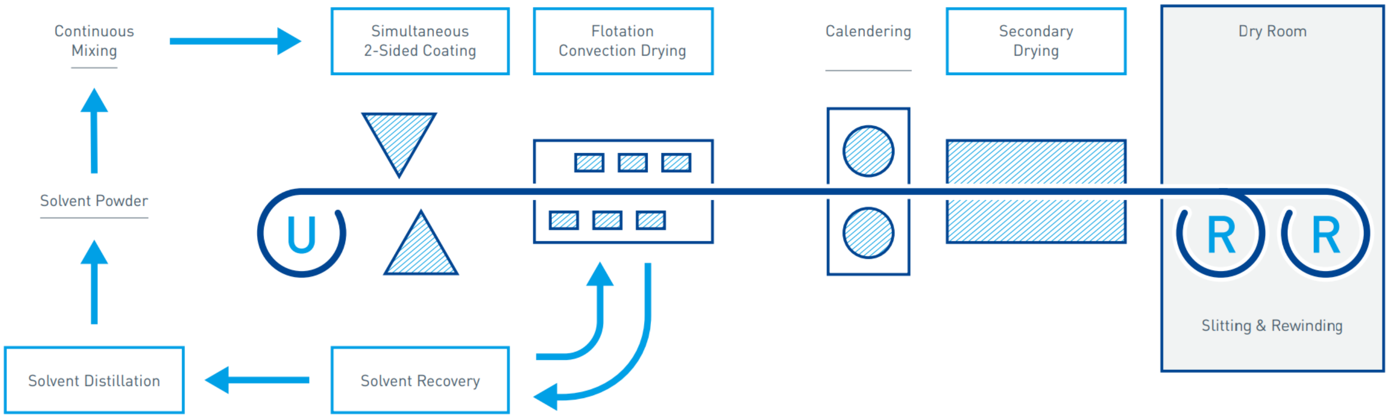


Figure 2: Current Roll to Roll manufacturing set-up for lithium-ion electrode manufacturing. [5]

The benefits of producing electrodes using roll to roll manufacturing is the high speed and yield per hour: the process is capable of producing between 25 and 50 m of electrode material per minute depending on the scale of production and mechanical limitations. It is currently the most widely utilized method of producing flexible electrodes, as it is a continuous process that requires no manual labor to perform. [6]

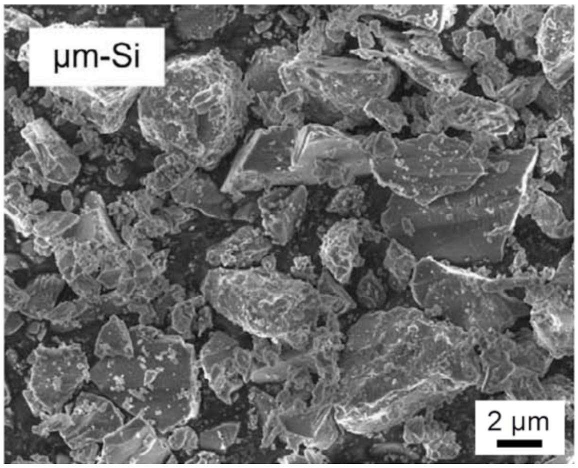
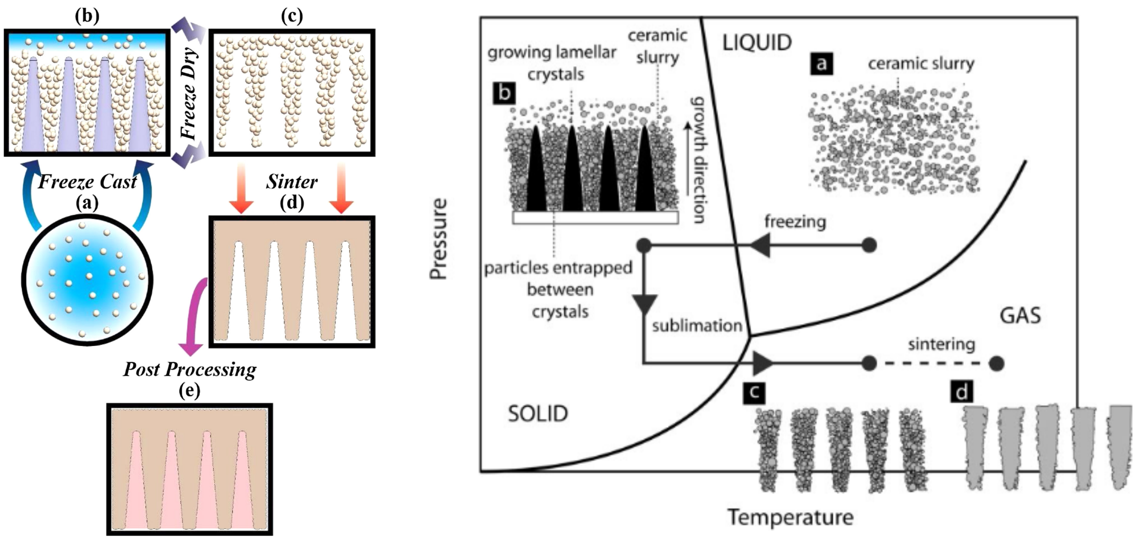


Figure 3: Microstructure of roll to roll silicon electrode, grain formation is uncontrolled. Smaller particle sizes resulted in a more viscous composition that was difficult to spray [7]

However, this roll to roll process creates many harmful byproducts. The liquid solvent solutions that are used to create electrodes tend to be highly toxic. More importantly, the method by which the solvent is deposited on the electrode limits the control over the microstructure geometry, which could be optimized to improve conductivity. Thus, improvements need to be made.

Freeze Casting

To that end, freeze casting comes in as a suitable solution. Freeze casting is an additive manufacturing process whereby a slurry containing a mixture of organic or inorganic minerals in a solvent is frozen in a mold with a cold finger. The cold finger is in contact with a very cold substance, such as liquid nitrogen, which produces ice fingers that align the grain structures in such a way to promote electrical conductivity. Once frozen, the solvent is sublimated out, and the mineral suspension holds the shape that it was frozen in. The resulting structure is then sintered to fix the microstructures, resulting in a finished product.



Figures 4 and 5: Process flow chart [8] and corresponding phase diagram for the freeze casting process [9]

The versatility of freeze casting comes from the ability to utilize many different materials in a mineral slurry, as well as the control it offers over the final microstructure [8]. By controlling the temperature gradient and environmental conditions through which the slurry is frozen, the alignment and size of the resulting grains can be controlled to generate a highly porous electrode that possesses high conductivity[10] [8]. Equation 1 governs how porosity affects conductivity.

$$\sigma_R = \left(1 - \Theta^s\right)^t \qquad (1)$$

In this equation, σ_R represents the resistivity, Θ represents the porosity of the structure and s and t represent constants that are dependent on the material. [11]

Resistivity, σ_R is related to conductivity σ_C as seen in Equation 2.

$$\sigma_C = \frac{1}{\sigma_R} \qquad (2)$$

The overall goal in order to improve energy density is to maximize this σ_C value.

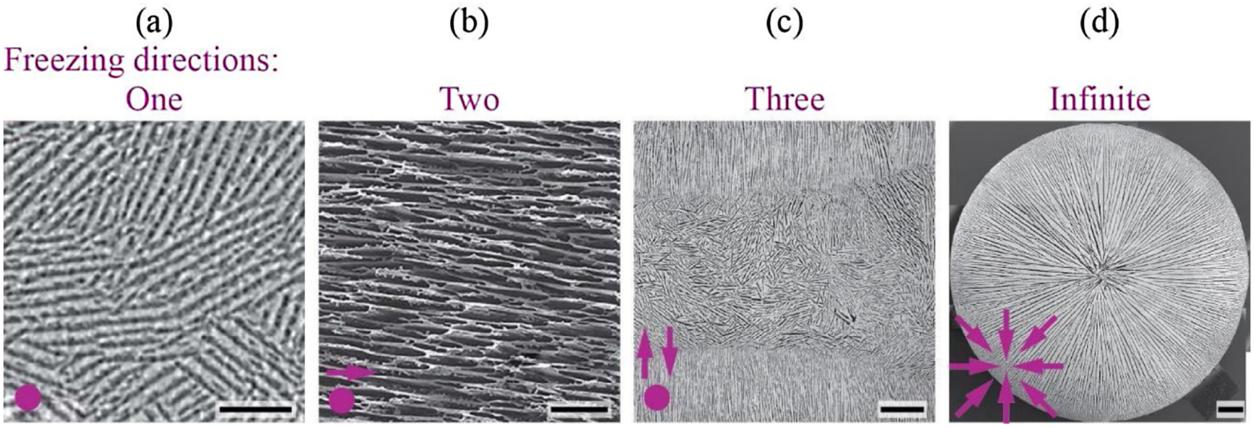


Figure 6: Effect of freezing direction on final grain formation [8].

That being said, currently, freeze casting is a discrete process and requires that the manufacturer control many environmental factors in order to create the desired product. The speed of the reaction is also slower than traditional methods of manufacture on account of the freezing process of the slurry and sintering at the end of the process. This is on account of pore size, *w*, being inversely proportional to the ice front velocity, *v*, the speed at which the slurry continues freezing, and *n* being a constant depending on the material and solvent, as seen in Equation 3 [8].

$$w \propto \frac{1}{v^n} \tag{3}$$

Combination

By combining the strengths of the two means of manufacturing, the project aims to create a new form of manufacturing that is capable of producing at a rate equivalent to that of current roll to roll methods. The combination will also be less wasteful, and, most importantly, able to create an electrode of higher conductivity than normal means of manufacturing. The team envisions that this will take the form of roller based substrates being chemically treated with a slurry mixture that will be frozen in place for further manufacture. This also highlights the design challenges that currently stop the merging of these two processes, namely the temperature and temperature gradient requirements for freeze casting alongside the time constraints that accompany the process. Since the slurry needs to be frozen completely and sufficiently slowly to form the desired microstructure, environmental factors also need to be considered in the processing environment.

In order to achieve this combination, the main goal of this project for the semester is to develop a proof of concept of one or more of the core functions of the desired manufacturing process: ideally, a functional prototype of the roll to roll mechanism and/or the freezing mechanism.

Benchmarking

As mentioned previously, the goal of this project is to create a prototype of one or more of the essential functions of our vision of a R2R-freeze casting setup. In order to meet this, the team looked at the two processes independently and based the goals on the current standards of both commercial roll to roll processes and tested freeze casting research. These benchmarks are evaluated largely separately from one another given that the field of freeze casting and roll to roll have not been combined on any commercially available scale.

When it comes to roll to roll manufacturing, one of the more commonly produced cells for use in the automotive industry are 18650 cells [12]. To produce these cells, the substrate film is coated in a conductive solvent followed by a drying process. While the speeds vary based on machine, the average time for solvent evaporation and initial curing is around 50 m of material per minute [12]. These sheets are further calendared to pack the surface composition closely, for these cells, the thickness of the conductive electrode is 125 µm thick [13]. Further processing cuts the large sheets down to 65 mm wide sheets of electrodes that are sent out to secondary manufacturers [12]. This entire process is capable of continuously producing sheets of electrodes at a rate of 50 m per minute, with the drying process taking the most time and limiting the manufacturing process [6].

Figure 7: comparison of 18650 cell to traditional a AA cell

On the other hand, freeze casting is largely dependent on the desired final product. As such, the required cooling rate, desired temperature gradient and grain size are all dependent on the primary mineral contained in the slurry mixture.

Speaking broadly, the process of freeze casting takes place between -10 and -100 °C for most inorganic materials [8]. Similarly, freeze time of some general slurry mixtures are a few minutes for pieces of a few centimeters, with freezing time more or less linearly increasing with sample thickness [9]. If the mixture freezes too quickly the resulting microstructure is more or less randomly oriented while a slower, steady state freezing results in a high porosity structure that is aligned with the freezing direction [8]. There then exists a critical freezing velocity dependent on the thickness and desired grain alignment of a given solvent and mineral pair.

For this project, while the team is not aiming to develop a process to sublimate the ice nor a process to sinter the final product, generally these steps do represent a significant part of the overall process time. The freeze drying process to sublimate the water takes place at low temperatures and low pressures and can take place overnight for a thickness of a few centimeters[9]. While the sintering process takes place at constant pressure and a higher temperature at a heating rate of 1 to 3°C/min [14]. The whole process can be seen in Figure 4.

Current designs of freeze casting incorporate a copper cold finger in a liquid nitrogen bath as the freezing element and a wire wrapped around the cold finger as well as a heat flux from the top of the mold as the heating elements. The liquid nitrogen bath is contained in a styrofoam box, and the slurry is contained in a cylindrical PTFE mold. This design can be seen in Figure 8 [15].

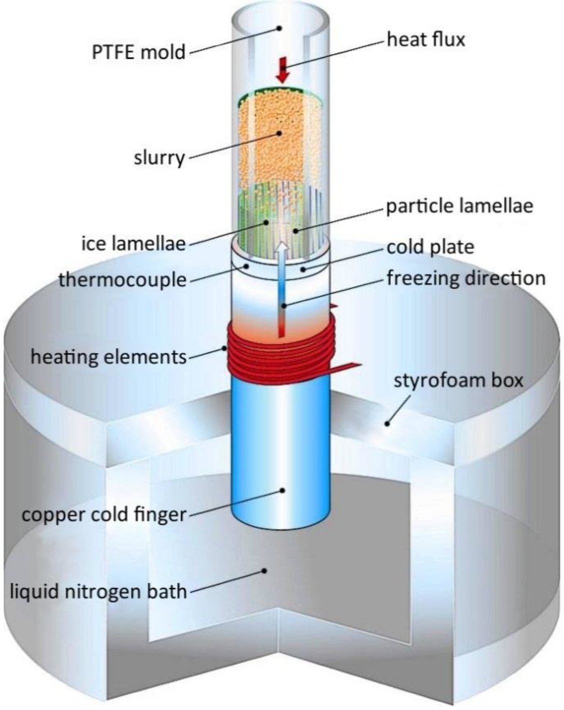


Figure 8: An example of a current design for freeze casting [15].

This design could use some improvement as well. The current process being discrete is not ideal for production of battery electrodes, which is a continuous process. Manipulating this process to form a continuous process is imperative. There is still much improvement to be made in the manipulation of the microstructures developed during freeze casting. Considering the microstructure, however, is out of the scope of this project, so the team will focus on transforming the current process into a continuous process.

DESIGN PROCESS

In selecting a design process for this project, the team considered several approaches. Initially, they leaned towards a solution-oriented, stage-based process. A solution-oriented process is one in which a designer begins with thinking of solutions when given a problem then adjusts the solution to fill the problem requirements. This method can be preferred because it is the natural place the brain goes to when given a problem. However, this method can tend to force convergent thinking on account of trying to fit a solution to their problem.

The team also considered a stage-based process in which the steps of the design process are separated into stages, which can include problem definition, concept generation and exploration, and solution development and verification. Dividing the process into steps that can be completed is appealing, as it breaks up a larger task into smaller, more achievable ones. The drawback with this approach is that once a step is completed, there is no iteration. If during concept generation, the team finds that the problem was misunderstood, there is no chance for correction. Solution-oriented and stage-based processes have their advantages, but overall would have led to limitations in the design process. [16]

After being introduced to the design process outlined for the whole ME 450 class, the team decided to shift their methods. Given the scope of this project and the open ended nature of the design problem, the team developed their own design process which is shown in Figure 9. As shown, the process has the scope to revisit any previous stage when needed. This allowed them to refine their problem definition and requirements based on research or further insights. It also allows scope for further development based on conclusions derived from engineering analysis and validation of the manufactured prototype. Thereby giving a good balance between stage based design and cyclical design. Thus, using a problem based approach with the scope to revisit stages due to new research and understanding can only expand the potential solution space while still providing some form of scaffolding for design timelines[17].

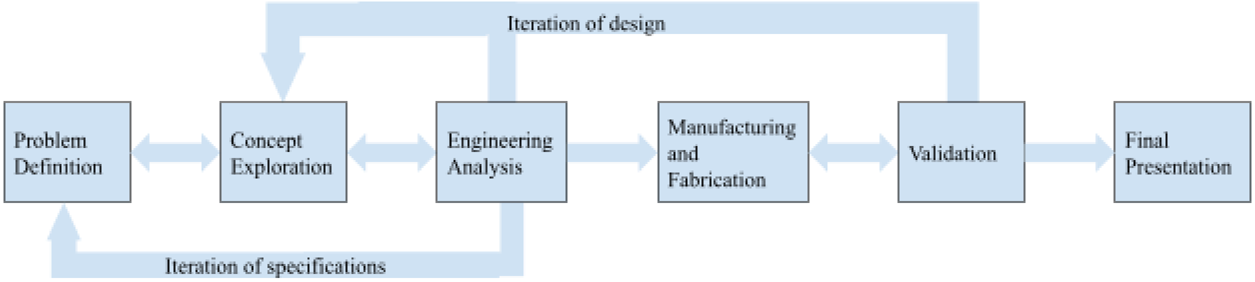


Figure 9: Representation of the design process [17]

In each step of the design process, the team has continued to iterate and improve based on new findings and discussions with the sponsor. The iterative process has been very beneficial, and allowed the team to improve the design in every step. This systematic design process greatly influenced our actions and designs throughout the semester.

DESIGN CONTEXT

Considering the broader context of this project, the team has put together a chart showing the primary, secondary and tertiary stakeholders that would be impacted by this project, shown in Figure 10.

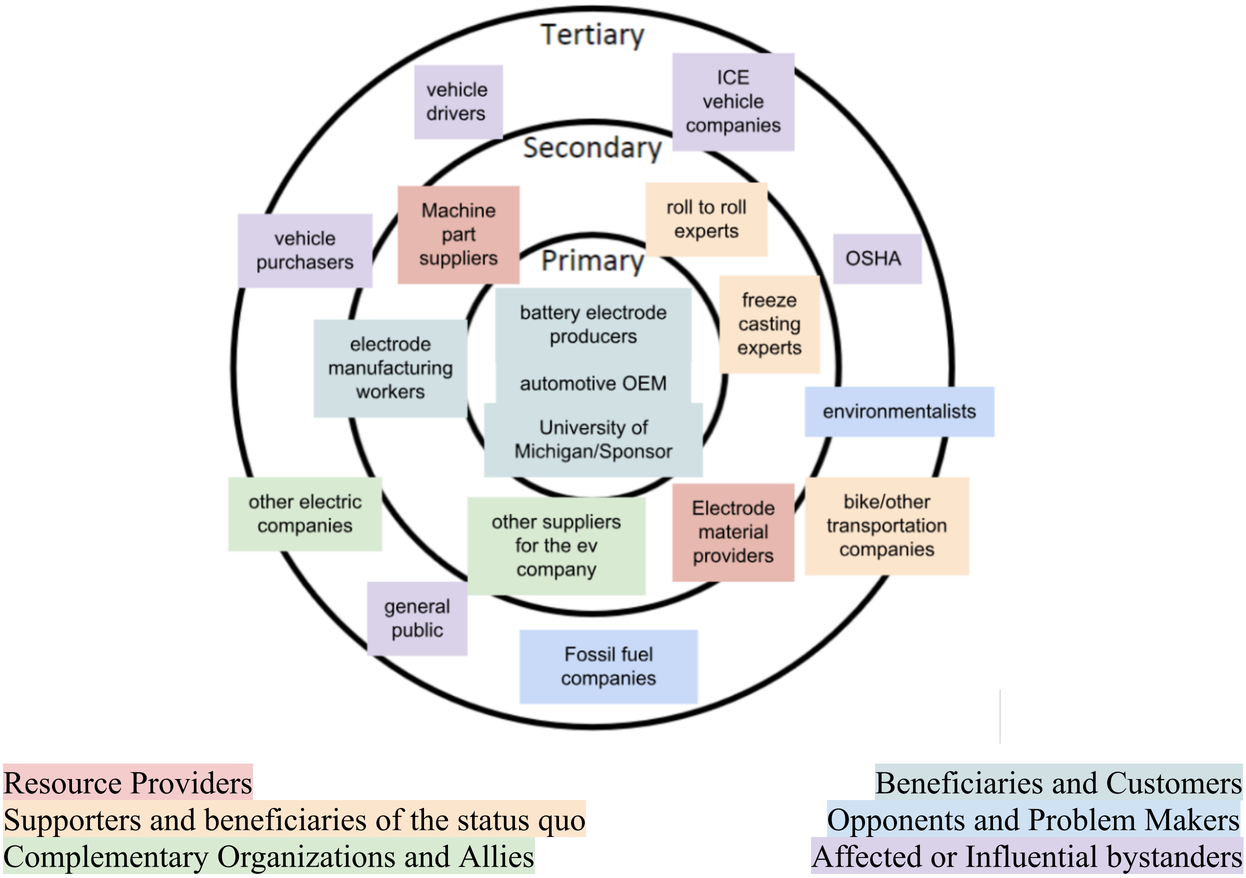


Figure 10: Stakeholder map of all affected parties by the introduction of roll to roll freeze casting

Roll to roll freeze casting process targets an increase in the efficiency of battery electrodes in lithium ion batteries that are currently used in electric vehicles. Thus, automotive OEMs stand to benefit from this process directly by gaining access to higher quality batteries for use in electric vehicles. Battery electrode manufacturers also stand to benefit from this process as it creates better quality battery electrodes while still maintaining their high rates of production. Given that the University of Michigan owns the intellectual property for this project, they stand to gain monetarily through the application of their IP in industry.

This improvement in production quality would create an increase in demand for electrode material providers, other electric companies, roll to roll experts, freeze casting experts, as well as other suppliers for the EV companies as it produces a direct application for their products and production methods. On the other hand, other battery electrode manufactures or other suppliers for the EV companies can also be negatively affected if they do not adopt the process, and their current electrode manufacturing technology may be outdated and no longer be profitable over the long term.

The sponsor will likely value process functionality and education over environmental impact and profit since the product we are developing is intended more as a proof of concept than a full scale machine. While small costs and profit margins could make a significant difference in a mass production context, for the small scale, profit is not an immediate concern in the design of this product. This order of priorities will affect the design by optimizing machine functionality, which means we may opt for a design that is not immediately profitable should it align more closely with the sponsor's desires.

As mentioned before, all intellectual property will belong to the University of Michigan. The personal ethics of the team align with the professional ethics of the University as we believe that the application of this technology can make a significant positive impact on industry.

The project sponsor will have decision making power over major design decisions of the roll to roll freeze casting machine. While lower level design decisions will be made by the engineering team members while also checking over one another's work to ensure that any decision is made with the most accurate and up-to-date engineering information. These decisions give the team power over the end users of the solution. However, the end users can also offer input on the features, requirements, and specs for further developments of the solution.

The roll to roll freeze casting process could have indirect environmental impacts. Certain materials might not be recyclable, and batteries are difficult to recycle. On the other hand, current electrode manufacturing processes rely on spraying toxic solvents onto material, leaving particles in the air to eventually pass into the environment. Freeze casting removes that step and can be more environmentally friendly in that regard. Freeze casting often uses PVA, which is "an organic binder used to strengthen the green body and also control the final pore size" as well as decreasing "pore size and favors the formation of dendritic structures with a higher degree of branching" [18]. If PVA is released in water form, it could impact the waterways and freshwater supplies, and if released in biosolid form, it could find its way into soil [19]

Over the lifetime of the product, the team expects that it will be sustainable if the power requirements of the machinery are considered in design and disposal of waste as well as the product itself is done responsibly. Additionally, for the manufacturing materials of the roll to roll freeze-casting, precious metals like copper need to be ethically sourced, the design of the machine needs to account for worker safety related to cryogenic gasses, as well as the manufacturing and disposal process having minimal environmental impacts.

This design could have larger effects on the economy, especially if it is successful and implemented into the electric vehicle industry. Creating a more efficient battery for electric vehicles would make them more affordable to the consumer, and save the company money as well. This could lead to economic growth for the country, and potentially the world if this technology is shared overseas. This would have positive social impacts, as a flourishing economy leads to a happier population and improved quality of life.

REQUIREMENTS AND SPECIFICATIONS

When approached with the idea for this project, the sponsor stressed the importance of continousness in the freeze casting process. Taking this information, we were able to determine requirements based on this goal, and considered different aspects of a design that would be important for our sponsor in his research work.

For the most part, the requirements and specifications for a functional prototype are based on current industry benchmarks that have been previously discussed. These specifications were written in order of importance for the functionality of the prototype. A brief justification for each is provided along with the corresponding requirement and specifications in Table 1. A more comprehensive justification is provided following the table.

Table 1: Requirements and specifications of the roll to roll freeze casting prototype.

Requirement	Specification	Justification
Continuous Material Processing	Able to produce between 0.5 and 1 m per minute of electrode material	Commercial roll to roll production is capable of producing at a rate of 25-50 m/min, as a proof of concept, being able to match this scaled-down rate would be ideal [5]
Dimensionally accurate	Produced material deviates no more than ±5mm in any dimension between runs	In order to be a viable manufacturing process, it must be consistent
Cost	Less than $5000 for a functional prototype	Budget provided by our sponsor as well as the university
Environmental impact	Requires less than 10kWh/kg of produced material	Targeting an energy requirement on par with current roll to roll methods
Recyclable	More than 70% of the parts of the machine can be recycled at the end of its lifecycle	Minimize environmental impact at end of product life
Slurry Containment	Able to prevent the slurry from spilling during processing	Important that the slurry does not move during freeze casting, as the viscosity is unknown [1].

The most important metric when grading the prototype's success is its manufacturing rate. This is the primary motivation for combining the two processes, thus being comparable or even matching the rate of traditional methods would be ideal. However, for a proof of concept, being able to achieve a fraction of the manufacturing rate would be sufficient to create a base for evaluating future development.

Initially the team expected to incorporate freeze casting into the design by the end of the semester. Thus, a freezing and temperature requirement were present. The manufacturing rate also factors in the freezing of the slurry mixture, as such, the temperature requirement and cooling rate is based on current standards for most non-organic slurry mixtures. While heavily dependent on slurry composition, this range will encompass simple mixtures that will likely be available when testing functionality of the device, referring to table 1, we can see that being able to achieve sub zero temperatures for alumina and ferric based materials is all but required, especially given their current application in electrode manufacturing.

Given that the current targets are focussed on application in the automotive space, being able to achieve the dimensions for 18650 cell electrodes would be sufficient to prove our concept. The tolerances that are achievable using motorized rollers in the case of the electrode thickness and the precision of the cutting tools that are available to us [1]. While more expensive tooling would improve our manufacturing capabilities, the budget of this project, as set by the sponsor and the University, would likely be restrictive on sourcing industry-level cutting tools.

The remaining requirements are not essential towards project completion but would serve to guide the project should it go into full scale production beyond the scope of this semester. The environmental impact that we anticipate for our prototype is based on current roll to roll processes, however, since it is not a full scale prototype, this requirement is not essential towards project completion, instead serving as a target that we're able to scale our level of production towards. Similarly, the durability and recyclability of the product are based on anticipated industry requirements once the project goes into large scale manufacturing use. After some consideration to the scope of the project, durability was removed as a requirement since it will be unable to be tested this semester through the scope of the project.

The requirement to contain the slurry was added later in the semester due to a concern brought up by the sponsor that the viscosity of the slurry could be as low as the viscosity of water, so some sort of way to contain this and prevent spilling would be necessary. Additionally, requirements such as the cooling rate and temperature were removed once the scope of the project was narrowed to eliminate incorporation of freeze casting for this semester due to the safety risks and accessibility issues with liquid nitrogen.

CONCEPT GENERATION

To begin generating concepts for the design, the team individually came up with 40 concepts each, totalling 160 individual concepts, which can be found in Appendix E. These designs were developed via a combination of brainstorming, design heuristics, and functional decomposition.

Individual Designs

In using brainstorming, the team was able to think of many different, out of the box ideas. Without constraining ideas to what the team thought would be feasible, they were able to think of all the possible solutions to the problem. Through this process, ideas shown in Figure 11 were created, which show the eccentricity of ideas that were created through brainstorming.

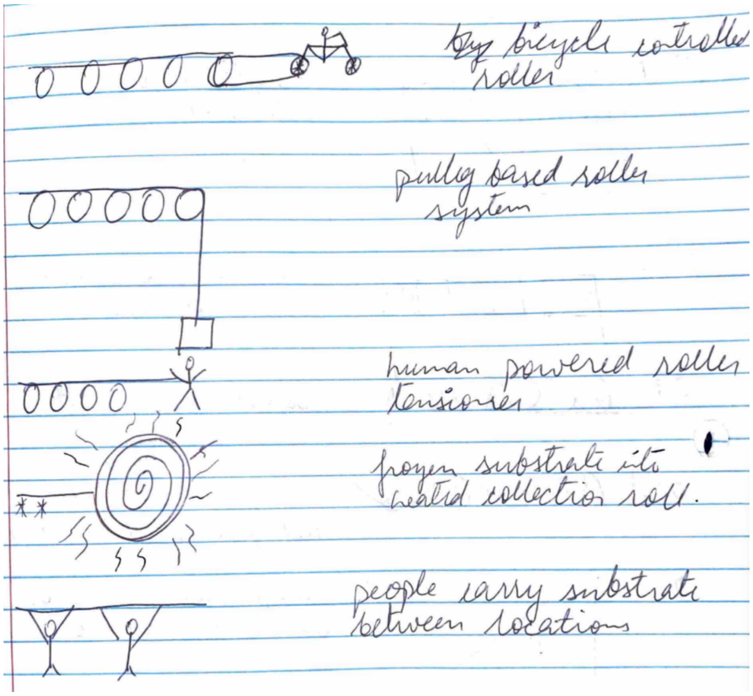


Figure 11: Brainstorming ideas such as the roller is controlled by a bicycle, a pulley, or a human, the substrate is heated and then collected into a roll, and people carry the substrate between locations.

Design heuristics allowed the team to think of different additions to designs, or ways to rework parts of the design. Specifically, thinking about user-customization led the team to consider if the thickness of the electrode should be adjustable. Considering how functions could be synthesized led to a combination of heating and cooling elements to create a temperature gradient. Thinking about different energy sources led to more consideration of where the energy for the roller would come from and how this would impact the workers and the environment as a whole. These all helped to think of what could be added or adjusted to created designs.

Lastly, the team utilized functional decomposition to consider each part of the design independently. There were three functions that were deemed essential to the design solution.

Firstly, the design needs to be able to freeze cast a slurry. This is part of the problem definition, and therefore is most critical to the design. Secondly, the design needs to allow for dimensional accuracy. This is critical for electrode manufacturing, as 18650 cells need to be a standard dimension so they can be used in electric vehicles. Thirdly, the design needs to incorporate roll to roll manufacturing, as this is also part of the problem definition. Roll to roll allows for continuous freeze casting to improve battery electrodes. The team generated ideas based off of each function independently in a morphological chart, as seen in Figure 12.

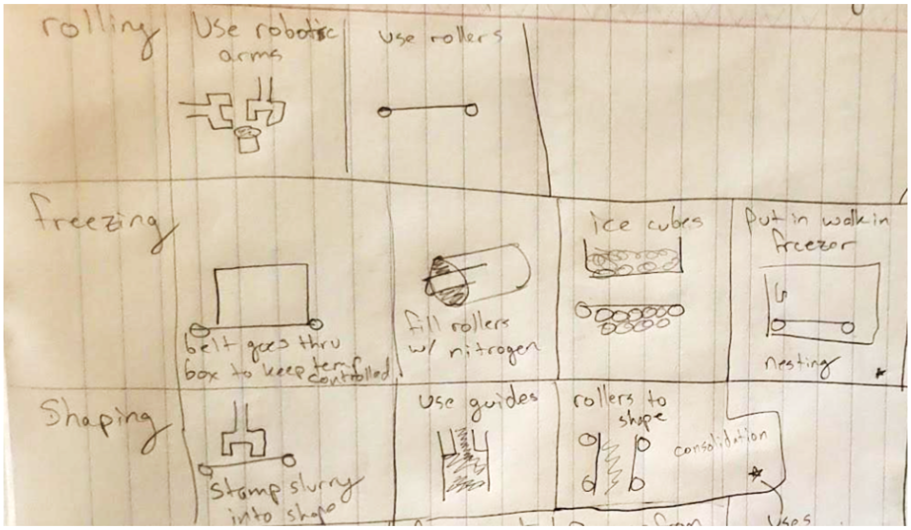


Figure 12: Morphological chart of the essential functions of the design, including rolling, freezing, and shaping of the slurry for electrode manufacturing.

Team Designs

From the 160 individual ideas, the team ruled out those ideas which were not feasible or within the scope of the project. The design needed to fit within the scope for the semester, since this project is for a class. Additionally, the design would ideally be able to run by itself, allowing the person running the machine to do other things and speed up the process. Next, the team tried to look at the ideas from an engineering perspective and decide whether or not it would be possible to make that idea. These criteria allowed the team to rule out many designs and narrow the ideas down to around 20 ideas. Taking these most feasible ideas, the team found the common ideas among the individual ideas and created four group designs in an iterative process, where each new design improved and built upon the previous design. These designs can be seen in Table 3. Designs were deemed feasible if they were capable of actually achieving freeze casting, as well as being a continuous process, which are two of the most important requirements for this project. Designs were also evaluated based on uniqueness. Since there are only a certain number of combinations that can be generated from existing industry freeze casting methods and current roll to roll processes, there were a lot of repeated ideas across the concept generation across all four group members. In addition, since design heuristics were used very frequently across the concepts generated by the members, there were a significant number of repeated concepts that share the same core functions, with small variations in its delivery and slurry deposition details. This was a common phenomenon within each member's generated ideas, as well as across the team. Thus, only the unique concepts were selected, and eventually narrowed down to the concepts shown in Table 2.

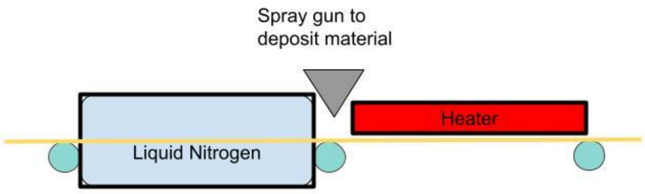
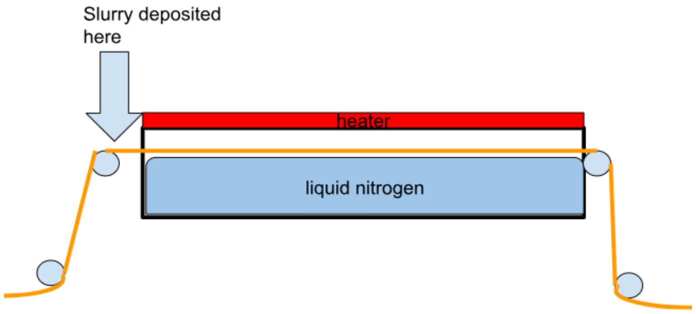
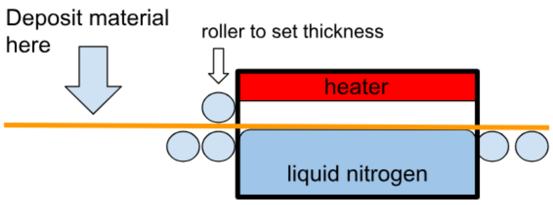
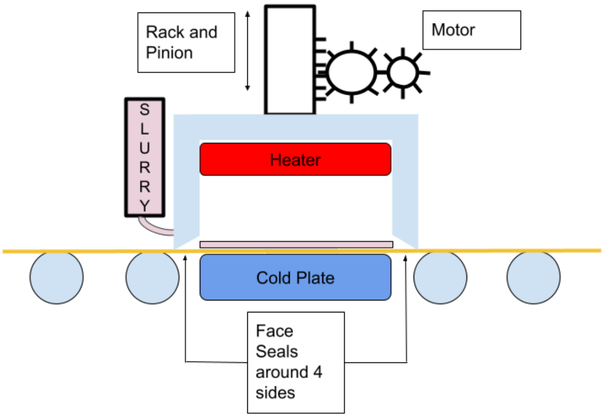
In Design 1, the substrate is run through liquid nitrogen, then the slurry is deposited onto the frozen substrate, and then run under a heater to control the temperature. This design was created through brainstorming and functional decomposition. It allows for freeze casting via the frozen substrate acting as the cold plate or cold finger, considers dimensional accuracy in the control of slurry deposition, and controls the temperature gradient through the heater. Some drawbacks that the team noticed with this design were the lack of control over the temperature gradient of the slurry, as well as the lack of fine control over the final microstructure.

In Design 2, the slurry is deposited before running through the freezing element, and the heating and cooling are combined to better control the temperature gradient. The team implemented design heuristics in thinking of how to combine functions, in this case the freeze casting and temperature gradient control functions. The dimensional accuracy comes from a slit in the side of the box containing the heating and cooling elements, determining the thickness of the slurry before freezing. That being said, this method lacked a way to change the thickness of the slurry beyond the width of the slit.

Design 3 includes an element of customization. The thickness of the substrate can be adjusted by setting a movable roller which sets the thickness before the slurry enters the box containing the heating and cooling elements. This design was made using design heuristics and considering user customization. It uses the combined functions for freeze casting and temperature control in addition to this customization of the dimensional accuracy.

Design 4 was created in response to feedback from our sponsor in which it was emphasized that the slurry might not be significantly viscous to prevent spillage from the sides of the substrate. The team considered implementing a box with four face seals, in which the slurry would be deposited and settled to a set outer dimension. The box with the face seals is able to be moved up and down via a rack and pinion so the process can be continued and the frozen slurry can go on to further processing. The freeze casting and temperature gradient control also occur simultaneously in Design 4.

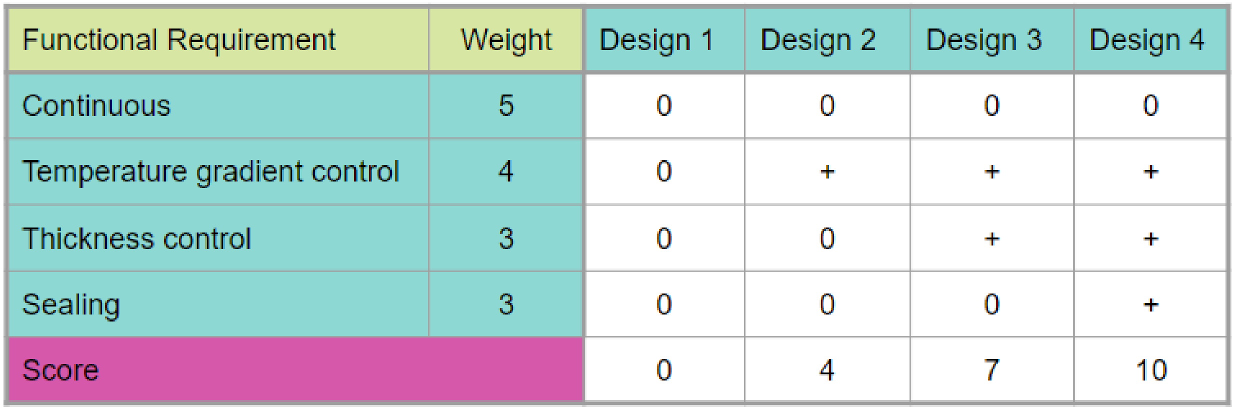
Table 2: Group designs generated from the combinations of individual designs.

Design 1	
Design 2	
Design 3	
Design 4	

CONCEPT SELECTION

From the four group designs outlined in Table 2, the team created a Pugh chart to weigh them against one another. The most critical functional requirement, weighted at a 5, is that the design allows for a continuous process as this is one of the primary motivations of choosing roll to roll manufacturing . This is part of the problem definition, and is most important in the manufacturing of battery electrodes on a large scale. Next, the temperature gradient was weighted at a 4, since controlling the temperature gradient is essential to controlling the microstructure of the slurry. By cooling too quickly, the microstructure can form large non-porous sections while the opposite would take too long to be viable. Thickness control of the slurry and sealing of the slurry to prevent spill were equally weighted at 3, since they would both improve the design. Sealing was added as a functional requirement after input from our sponsor that the viscosity of the slurry is unknown, and therefore, some sort of seal or containment is required to be usable in multiple scenarios while thickness controls are required to use the electrodes in batteries currently in production . The comparison of the four designs can be seen in Table 3.

Table 3: Pugh chart of the four group designs weighted based on the most important functional requirements.



Functional Requirement	Weight	Design 1	Design 2	Design 3	Design 4
Continuous	5	0	0	0	0
Temperature gradient control	4	0	+	+	+
Thickness control	3	0	0	+	+
Sealing	3	0	0	0	+
Score		0	4	7	10

Design 1 was used as the base design, and therefore was given all zeros for the Pugh chart. It allowed for a continuous process, implemented a temperature gradient control via a heater after freeze casting, allowed for thickness control from the amount of slurry deposited, and did not consider sealing. This design gets a score of 0 as the base design.

Design 2 was similar to Design 1 in that it was also continuous, allowed for a similar amount of thickness control, and also did not consider sealing; however, Design 2 combined the heating and cooling elements into one step, which allows for better control of the temperature gradient. This leads to the score of 4 due to the improved temperature gradient control.

Design 3 was similar to Design 1 in that it was continuous and had no sealing element. It was similarly better in temperature gradient control as Design 2, as it also combined the heating and freezing elements. In addition, Design 3 implemented better thickness control, as it had a roller to set thickness, and allowed for adjustment by moving the roller up and down. This design gets a score of 7, as it improved in both temperature gradient control and thickness control.

Design 4 was similar to Design 1 only in that both were continuous. Similarly to Design 3, Design 4 allowed for better temperature gradient control and thickness control. It combined the heating and cooling elements, but had a set box dimension where the thickness can be controlled based on how much slurry is deposited. Design 4 also has a sealing element from the box, which prevents spillage of the slurry during freeze casting. This gives Design 4 a score of 12.

Design 4 received the best score from the Pugh chart, but the team decided to implement aspects of both Designs 3 and 4. After input from the sponsor, it was brought to the attention of the team that the slurry also might be too viscous to evenly spread out in the box of Design 4. This led to an additional functional requirement of slurry containment. In Design 4, the slurry would also start freeze casting before being totally spread out, which would negatively affect the grain structure. Therefore, the team decided to use a method similar to Design 3, but with individually set boxes to contain the slurry on the substrate based on the new functional requirement. This chosen design does not currently exist in the market, as roll to roll freeze casting has not been done before, and it better fits every functional requirement.

ALPHA DESIGN

Based on the results of the Pugh chart and with consultation from the sponsor, the team decided to adapt Design 3 to better fit the functional requirement. The Alpha Design takes Design 3, and adds incremental molds for the slurry to be deposited. This way, the slurry will not spill off of the substrate when deposited, and the freeze casting can adequately manipulate the grain structure for better conductivity. The Alpha Design can be seen in Figure 13.

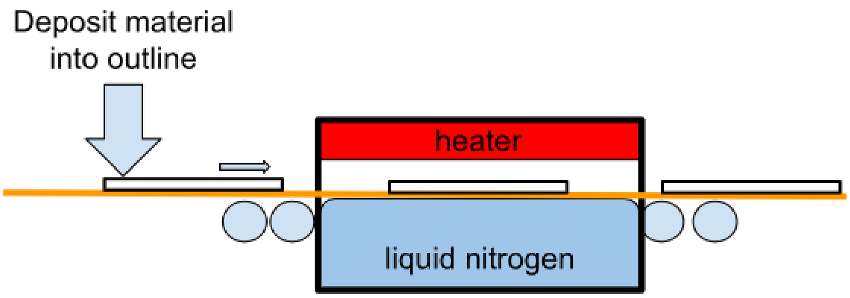


Figure 13: Drawing of the Alpha Design. The slurry material is deposited into the molds, where it then enters the heating and cooling zone for freeze casting.

Figure 14 shows a 3D CAD view of the alpha design, and Figure 15 shows a drawing with dimensions of the Alpha design. These dimensions are subject to change based on availability of materials and theoretical analysis, which has yet to be fully completed.

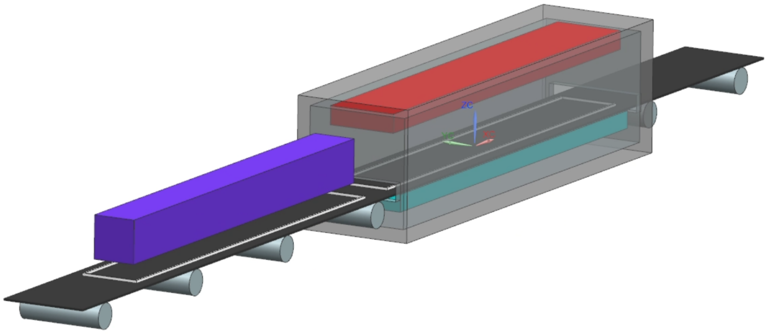


Figure 14: Isometric view of CAD model for Alpha Design.

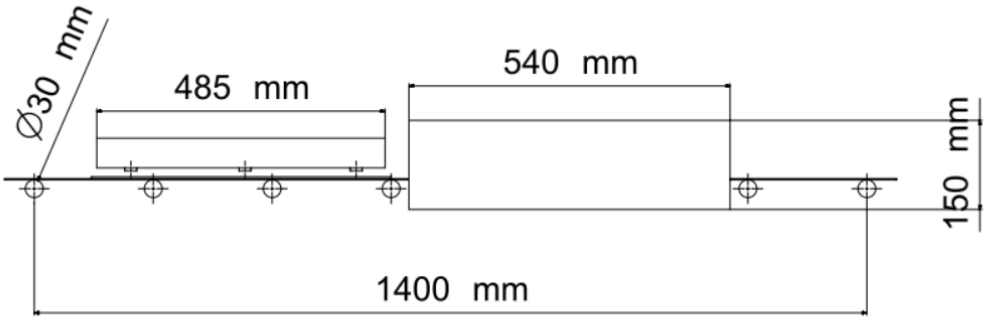


Figure 15: Drawing with dimensions of Alpha Design.

The Alpha Design best fits all of the functional requirements. First, considering those with the most weight from the Pugh chart, it is continuous, and allows for sufficient control of both the temperature and the thickness. The molds on the rollers that pass through the freeze casting box follow a continuous process. The molds containing slurry material can be continuously moved while freeze casting, or stopped on the rollers while in the freeze casting box, if necessary. The freeze casting box with both liquid nitrogen and a heater allows for control of the temperature gradient within the box. Here, the substrate can act as the cold finger for freeze casting. The molds on the substrate control the thickness as well as the length and width of the electrodes. The Alpha Design also incorporates sealing since the mold contains the slurry material. This incorporates all of the functional requirements from the Pugh chart.

In addition to the requirements from the Pugh chart, the Alpha Design also fits the functional requirements from Table 1. The design can fit the cooling rate required by adjusting the rate at which the substrate moves through the freeze casting box and how long it spends in that temperature controlled zone. The mold allows for dimensional accuracy, as well as thickness control. The setup for this design should be within budget, based on the team's initial bill of materials, found in Appendix G, since it can be operated with a couple simple motors and the rollers and freeze casting box can also be made from inexpensive materials. With this design, the environmental impact is minimized by reducing the amount of slurry material that would be airborne by deposition via a hose. The team has also considered how to contain the liquid nitrogen safely, and having the freeze casting contained in a box would minimize the risk of freeze burns.

While not complete yet, during motor selection, the team will also consider durability to ensure that this mechanism will be able to run for the duration of the project. During material selection, the team will also consider recyclability of the materials. By selecting materials that are more recyclable, the team can achieve the requirement of greater than 70% of materials recyclable. Thus the Alpha Design best fits every functional requirement.

The team believes that though the project is challenging, one not practiced in industry, the prototype is feasible for this course. Simplifying the process to exclude the sublimation and sintering aspect while still maintaining the roll-to-roll aspect means that the core functionality of the project is maintained while the overall scope of the project remains within the scope of ME450. That being said, for the scope of ME450, a complete model is likely not possible.

ENGINEERING ANALYSIS

In order to determine how the Alpha design fits our specifications, the team focused on using theoretical engineering analysis due to the nature of the project. Since the scope of our project is mainly a proof of concept, theoretical analysis is critical to our design development. In particular, it will be most important to run analysis on the temperature gradient of the system, since it is critical to freeze casting. Additionally, there is analysis to be done to determine the motor requirements based on our desired manufacturing rate and cooling rate.

Motor And Drive Line Requirements

The roller system's analysis determined the necessary motor and gearbox specifications in order to run. At constant speed, the only forces that would need to be overcome in order for the mechanism to run is the friction between the stainless steel roller mechanism and the aluminum tray that is being used to transport the slurry along the track. Thus, in order to maintain a constant rate, the motor's torque was estimated to overcome that frictional force based on the following formulae [27]

$$F_f = \eta M g \tag{4}$$

$$T_m = \frac{F_f r}{\zeta} \tag{5}$$

Here, F_f is the frictional force between the tray and the roller, M is the mass of the tray and slurry being frozen, g is acceleration due to gravity, T_m is the torque of the motor, r is the radius of the roller, and ζ is the efficiency of the overall system.

Based on this analysis, we get that in order for the system to maintain a constant speed of 1 m/min, the output of the motor and gearbox need to supply a torque of at least 0.92 Nm. This number includes a 2x safety factor. Based on this analysis, the required rotational speed of the motor/gearbox output was also calculated to be 5.13 RPM. The complete analysis can be found in Appendix C.

Heat Transfer Hand Calculations

Initial heat transfer hand calculations were performed to evaluate the temperature gradient that needs to be achieved for proper freeze casting to happen given the requirements and specifications. This calculation and its assumptions are in Appendix B and are validated via Ansys Fluent.

Fluent Simulation

In order to determine the length of the freeze casting chamber, Fluent Ansys was used. The simulation was provided to the team by the sponsor's graduate student. The team then validated the simulation prior to use. The simulation was set up as follows: the top boundary was set as the "hot" plate, the bottom boundary was set as the "cold" plate, and the sides were set to have a heat flux of 0.

First the simulation was validated in the x direction by altering the length in the x direction. After a tray was selected by the design team, this simulation was redone with the length in the x direction matching the tray width (254 mm) to ensure the simulation was valid through the necessary length in x. Because the boundary conditions at the walls are set so that the heat flux is 0, the simulation should respond the same regardless of length in x. This was proven to be true.

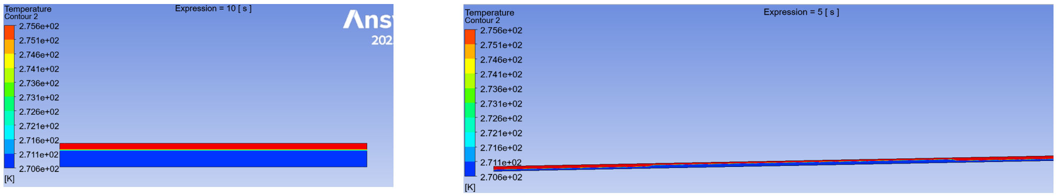


Figure 16: Comparison of simulation results for x length of 65mm (left) and 254 mm (right), both are uniform in x direction.

Next, the simulation geometry was changed to be 2mm x 2mm to speed up processing time, and multiple trials were run with a mesh size of 0.01mm at different temperatures of the cold and hot plates. The simulations were performed with a time step of 0.1 seconds. Between 0.1 and 10 seconds, the simulation acts as expected, with the cold front (green and yellow band seen in Figure 17 below) moving up as the slurry freezes (blue section). Results are shown below of the slurry at 0.1 and 5 seconds for the simulation at 30 ℃ & -30 ℃, as well as the results for 30 ℃ & -40 ℃. By running the simulation at varying temperatures for the cold and hot plates, the simulation was proven to be sensitive to temperature. For the 30 ℃ hot plate and -40 ℃ cold plate, the simulation shows that the slurry starts at a colder temperature and thus freezes faster than the 30℃ hot plate and -30℃ cold plate case. This aligns with expectations, and holds true across multiple trials, which can be found in Appendix G. The simulation is sensitive to temperature, which indicates that it is accurate.

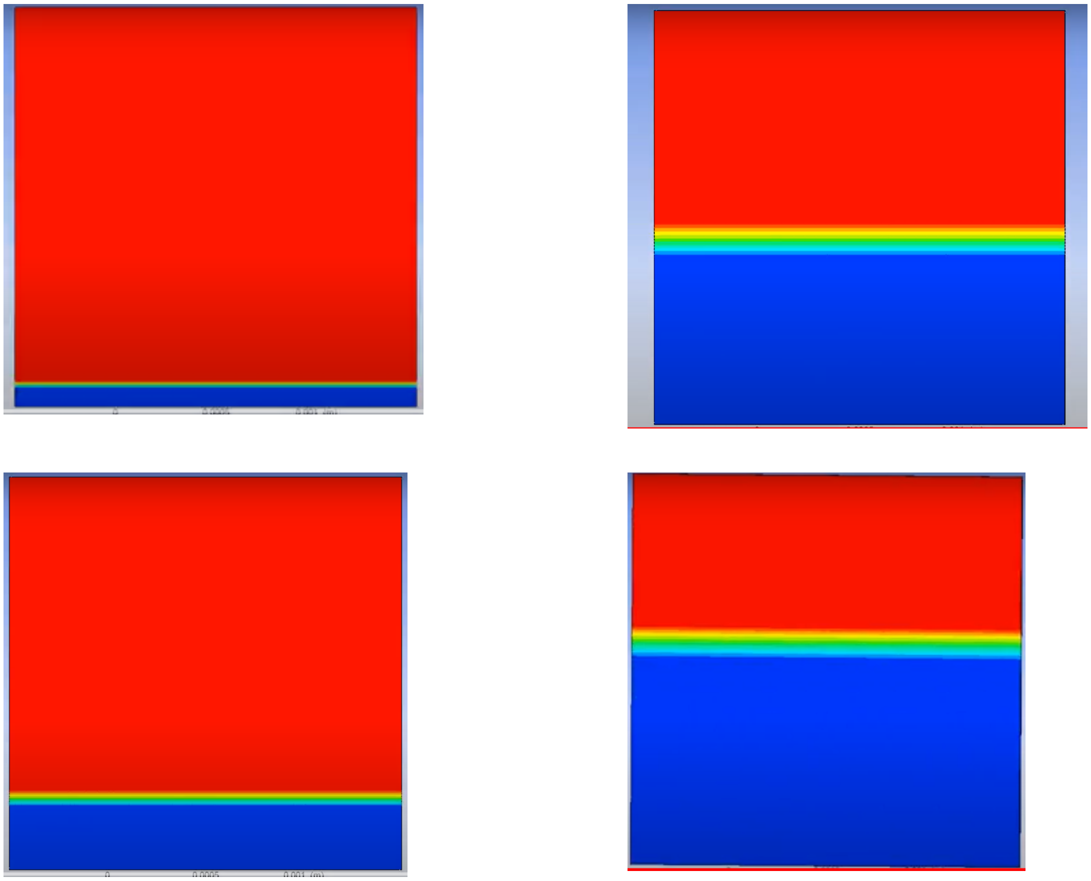


Figure 17: Top left and right are simulated at 30 ℃ and -30 ℃, at 0.1 and 5 seconds, respectively. Bottom left and right are simulated at 30 ℃ and -40 ℃, at 0.1 and 5 seconds, respectively. Note movement of the green band upwards between 0.1 and 5 seconds, as well as the higher placement of the band in the bottom figures compared to the top figures.

Once the simulation was validated, it was run at the 30 ℃ and -30 ℃ case again, this time to determine the time to freeze 1 mm of the slurry. It was found that it took 5 seconds for the slurry to freeze. This was found by setting the y dimension of the geometry to 2 mm and then going through the animation step by step (0.1 second time step) until the viewer could definitively say that half of the geometry (1 mm) was frozen. Once the time to freeze was found, the length of time the tray would travel in that time period was found using the maximum speed of 1 m/min from the design specification. This distance was found to be 8.3 cm. The tray the team picked out, which was chosen because it is copper and therefore minimizes deviation from the simulated conditions, is 0.1 m long. Which means that when combined with the travel distance, the chamber at absolute minimum must be 0.183 m long. When a safety factor of 2 is used, the chamber must be at least 0.4 m long. The team opted for a chamber length of 0.5 m to be more conservative and to allow for larger parts to be freeze casted in the future, should the sponsor desire.

Empirical Testing

Empirical testing should be done on the motor drive and gear assembly to ensure the mechanism can move on its own power effectively. This test will require a motor, final gear ratio, as well as a working roller system to measure the input and output speeds.

Additionally, the spillage from the tray needs to be tested empirically, since that will be based on the specific geometry and sealing of the tray. The team can fill the tray with water to determine if there is spilling, and add some water-tight sealant to prevent any leaking or spilling.

BUILD DESIGN/FINAL DESIGN

Figure 18 shows our final design model in CAD.

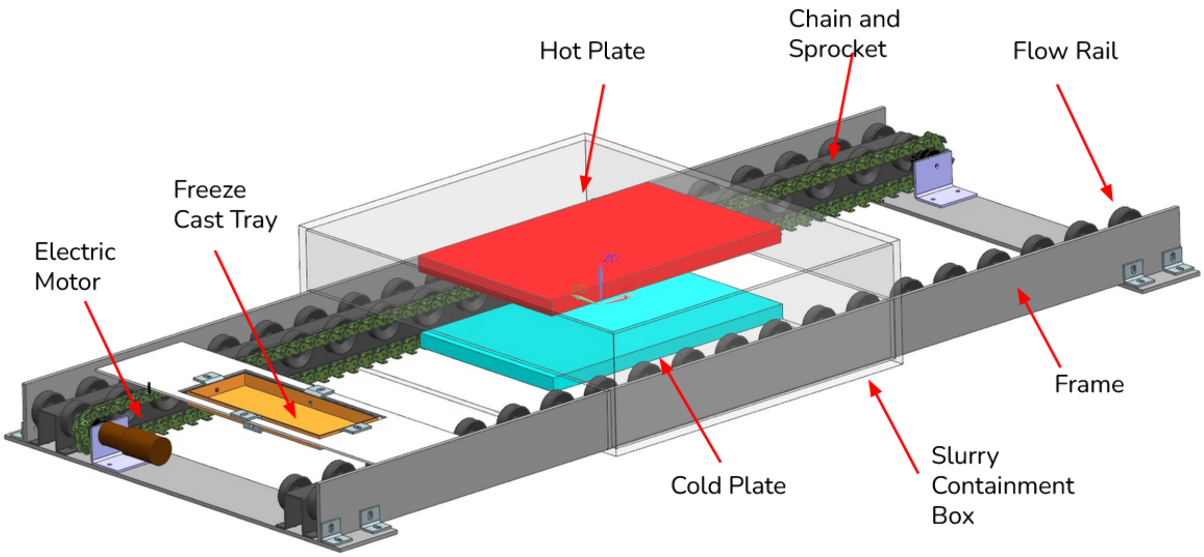


Figure 18: Isometric view of final build design with labeled components

Figure 19 shows the dimensions of the final build design, along with different perspectives of the design. Dimensions are measured in millimeters.

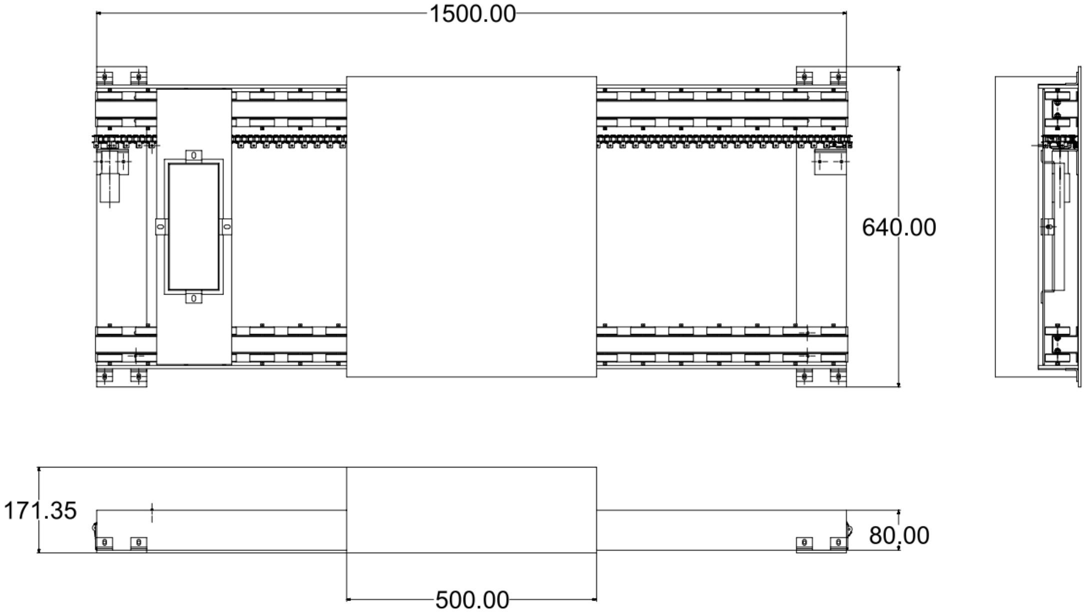


Figure 19: Top, front, and left view drawings with dimensions of the final build design with labeled components. Dimensions are in millimeters.

Roller mechanism

The initial idea for moving the slurry in a continuous manner throughout the roll to roll freeze-casting process was a simple conveyor belt process which is widely used in the roll to roll industry, hence why the initial project was named roll to roll freeze casting. However, in the design iteration process throughout the course, the team and sponsor realized that controlling the slurry and slurry containment component height in the Z direction has large implications on the heat transfer of the freeze casting process. The problem with the conveyor belt process was that it utilized a rubber or some other hyper-elastic material for the conveyor belt, which is flexible enough to withstand the roll to roll process with its rollers and bend radii. The rubber conveyor belt does not have a consistent thickness throughout the process, since a hyperelastic material will expand and compress rapidly in extremely low temperature seen in the freeze casting process, the negative thermal expansion was a huge concern, since the heat transfer, according to the Fluent simulation, was very sensitive to the distance between the slurry tray to the cold plate itself. A conveyor belt has insufficient dimensional control and will lead to inconsistent slurry tray height, which will lead to improper freeze casting, and thus fail to meet project requirements.

Thus it was decided that instead of having the conveyor belt drive the continuous process while carrying the slurry, the design would have a slurry tray that sits directly on a roller system with good dimensional control, and the slurry tray be powered via other means. Upon searching for off the shelf products, McMaster offered a flow rail system, which is basically a large number of roller wheels fastened on a steel extrusion. These wheels have high strength and modulus, and most importantly, good dimensional stability, and will see minimal thermal expansion effects. This allows for the slurry container to rest on the plate of 6061 aluminum, and the plate will contact the flow rail directly, achieving height control for freeze casting. The driving mechanism will be via a simple chain and sprocket system, with the motor direct driving the chain and sprocket system. The chains will have attachments once every couple of chain links that will have a fastener to hook to the 6061 tray and move the slurry in a continuous manner. The tray will also have guide pieces of aluminum such that the tray is constrained in the y direction, so that the chain and sprocket can drive the tray only in the x direction.

In this case the build design is the same as the final design, meaning the final prototype will be a “one off” item being created as a laboratory instrument, as suggested by our sponsor. The design illustrates the important aspects that are needed such that the design can meet the functional requirements. For example, the flow rail system and the powered chain and sprocket system that supports the continuous movement of the slurry tray will be present in the design, and will be built and tested to make sure the tray can move at the desired speed such that cooling requirements can be met. The design will have a functional continuous process that carries the slurry tray in the speed that allows for freeze casting. However, the design nor the prototype will contain any freeze-casting components, since that is outside the scope of the project. This verification is talked about more in depth later. The main idea is that the final design will be built to validate functional requirements (scope of ME450), as well as being used in a research setting for freeze casting after actual freeze casting components have been added (outside ME450).

Tray and Slurry container

In order to contain the slurry, the team in collaboration with the sponsor decided a tray was necessary. Since the viscosity of the slurry is unknown at this point, it is best to assume a low viscosity slurry to design for the worst case scenario. A tray would be able to hold the slurry even if it was made of water, and taller sides would prevent spilling. For the material of the tray, the team decided to go with a copper tray. Copper has a very high conductivity of 398 W/mK, meaning the thermal resistance is very low, allowing for better control over the freezing process. Copper is also the material currently used for the cold finger in freeze casting, and is very successful when used in freezing applications. Copper is also recyclable, which will help meet the sustainability requirement.

To move this tray along the rollers without interfering with the freeze casting abilities, the tray will be placed into an aluminum plate with a cutout and an attachment to the chain and sprocket. This will allow the copper tray to be in full contact with the cold plate for freeze casting, while still allowing it to move linearly along the rollers. Aluminum is also recyclable, and fairly easy to machine. Aluminum can withstand cold temperatures, so the frame will be able to go through the freeze casting chamber without breaking.

Motor Selection

Based on the previously completed motor and gearbox calculations, the goal for a viable motor was its ability to support a range of operating voltages while still being able to meet the torque and speed requirements. For this project, a planetary gearbox DC motor was selected. The chosen motor (part number 638263 from servo city) was selected on account of its torque speed curve shown below [28].

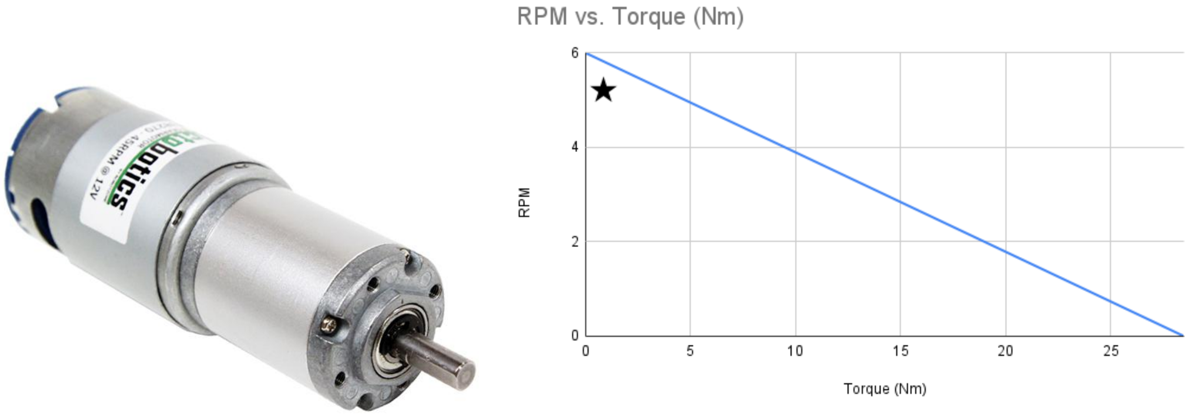


Figure 20: The chosen motor and torque-speed curve for the selected motor at 10 V, with the required maximum operating condition (0.92 Nm at 5.13 RPM) being shown as the star [28].

With the selected motor, the speed can be varied as a function of the applied voltage with the maximum required torque and speed being shown in the graph above at 10V, while the motor is rated to operate between 6 and 12 V. The benefit of choosing the given motor is the simplicity associated with using a direct drive system with no gearbox between the motor and the output.

Alternative options included stepper motors however, in order to properly run a stepper motor, a motor controller as well as an Arduino control unit which would have increased the cost of the project as well as added additional points of failure for the system. Since the operating condition for the conveyor system is at a constant speed, the chosen motor's ability to maintain a constant speed for a fixed voltage for an extended period of time made it the ideal choice.

Manufacturing Plan

Once the materials for the build design arrive, it will be critical to move quickly and efficiently to ensure the design can be built by the design expo. First, it will be important to waterjet all the aluminum parts for the design. The tray holder and frame for the rollers will both need to be waterjetted, which is a relatively simple manufacturing process that shouldn't take much time or cause many issues. Next, we can laser cut the acrylic pieces to use in our model for the freeze casting process. This process is also fairly simple and will likely not result in many issues. After the larger pieces are cut out, the brackets to support the motor and the copper tray will need to be drilled using the drill press to allow for fasteners. The drilling will be more challenging since the holes will need to be aligned to ensure proper alignment of parts. The acrylic for the freeze casting chamber can be assembled using hot glue, since this is just a placeholder for the actual freezing chamber. Next, the frame and tray can be assembled using fasteners. It will be important to ensure the parts are aligned properly in this step. Finally, the drive system and motor can be assembled and connected to the frame. This step will be the most critical in ensuring the success of our design. The detailed manufacturing plan can be found in Appendix I.

Final Design

In this project, our final design and our build design were the same thing. Thus, this design was able to meet the sponsor requirements and functions independently to aid in future research of freeze casting. This will add great value to future manufacturing applications after the research is conducted and distributed. The team was able to manufacture and assemble the final design and deliver it to our sponsor. The final product can be seen in Figure 21.

Figure 21: Final build design mechanism, including an acrylic box to model the freeze casting chamber.

The team bought the flow rail, copper tray, as well as the chain and sprocket off the shelf, and cut out and made the frame assembly from aluminum sheet. Holes were drilled into the frame and rails for fasteners to hold everything together. By assembling the motor with the chain and sprocket, the team was able to make an assembly that functioned on its own, providing the necessary functions for the design required by the sponsor.

VERIFICATION AND VALIDATION

In order to determine if the build design fits the requirements and specifications, verification and tests are required. In addition, it is necessary to validate that the design addresses the overall design problem.

Manufacturing Rate

According to the design requirements, the final design needs to be able to run at a manufacturing rate of 0.5-1 m/min. The completed assembly would be set up with a variable voltage supply. The verification test involves operating the drive mechanism under normal load conditions, that is, with the tray and a water solution to represent the slurry mixture. The linear speed of the mechanism will correspond to the manufacturing rate required. This linear speed can be measured and tuned by adjusting the voltage to verify that this rate is met. Comparing the measured speed to the required rate can verify this specification as well as validate previously discussed hand calculations for the operating condition of the roller/motor. The team was able to verify that the output manufacturing rate of the mechanism indeed met the specification, allowing for continuous freeze casting in future research.

Sealing and Dimensional Accuracy

For the slurry containment tray, verification will be fairly simple. To test for sealing of the slurry containment, the tray can be filled with water and run on the mechanism. Visual inspection will be able to determine if the tray is properly sealed if there are no leaks or water outside the tray. The team was able to verify that no water leaked from the tray, thus meeting this specification as well. In terms of dimensional accuracy, the freeze casting process could be repeated multiple times and the resulting electrode measured to determine the accuracy and precision of the slurry tray. Since the team will not be incorporating freeze casting into the build design, this would need to be verified in the future once freeze casting is implemented.

Sustainability, Durability, and Cost

To verify the sustainability requirement, the team created an eco-audit of materials in the final build design. Using this tool, the team determined the energy consumption of the design to be 3347 kWh over its entire lifetime. The results of this eco audit can be seen in Appendix F. To further verify this requirement, the freeze casting aspect must be added so that the material produced can be measured. Most materials, which can be seen in our Bill of Materials in Appendix G, are indeed recyclable, which would increase the sustainability of our product. In terms of the life cycle, the team will need to make best assumptions on how long the product will last. This goes into durability, which is a specification we are not able to determine this semester. In order to determine the durability, the mechanism would need to be run several times and examined for fatigue and wear over time. Lastly, in order to verify we are under budget, the team calculated the total cost of the build design in the Bill of Materials, and it can be seen that the design is indeed within the budget specified.

Future Verification

If this project were to continue past the timeline of this course, there would be several other validation tests carried out. Most importantly would be to determine if this mechanism can indeed allow for continuous freeze casting. With this, it would also be important to verify the freeze casting simulation with experimentation. Specifically, it would be critical to determine the time it takes the slurry to freeze, the necessary temperature gradient for freezing, and the cooling rate of the process. If the simulation was fairly accurate, the manufacturing rate should be sufficient to meet the specification.

Additionally, in order to determine the dimensional accuracy of the design, freeze casting parts is necessary. The electrode part could be freezecast multiple times to determine accuracy of the dimensions.

Validation

The problem to be addressed was the need for improvement of battery electrode manufacturing. Implementation of a continuous freeze casting setup was one method proposed by our sponsor to solve this problem. Validating this need would mean creating a workable continuous mechanism for a freeze casting setup. This design does indeed address this need. In order to determine if the need satisfies the overall problem, it would be important to continue research into this method and examine the effects when this process is used for battery electrode manufacturing. If continuous freeze casting does indeed improve the safety and conductivity of battery electrodes, that would validate this design.

DISCUSSION

Revisiting the project definition, the team quantified the problem well given our limited understanding of freeze casting before this project. However, the scope of the project was adjusted multiple times through the design process. A narrower, better defined initial scope may have helped in converging on a final design sooner. Initially, the team was tasked with designing a roll to roll mechanism that was also able to freeze a mineral slurry. After discussion with the project sponsor, the roll to roll aspect was changed to be any form of continuous manufacturing and the freezing mechanism was deemed to be out of the scope of the project. Thus, the final product uses a chain driven mechanism that moves a tray along a roller array.

This is the version of the project that was manufactured and turned over to the project sponsor. First, the mechanism is able to meet its required manufacturing rate and operate continuously. Having a direct motor drive system meant that the system had fewer moving parts and thus fewer points of failure. The motor speed is also variable based on the supplied voltage which adds adjustability to the end user’s needs. Additionally, the aluminum frame provided sufficient structural support while still being light enough to be transported easily by two people.

However, the current build requires the user to manually change the polarity of the motor in order to change the direction of the system. While out of the scope of the project, implementing a control system that streamlines changing direction and voltage would be ideal. The drive system could also be optimized to minimize slack in the chain at the halfway point which is a problem that if not properly controlled could pull the chain off one or both sprockets under certain loading conditions. This slack is currently controlled using a support that adds tension to the chain. If there was sufficient time, having a slot along which the driven sprocket could be adjusted would give a simple but effective means of controlling the tension.

As alluded to above, the main challenges through this project were the changing scope. The lack of constant vision made engineering analyses difficult as they had to be conducted repeatedly as the project moved forward. This had the consequence of delaying the manufacturing of the final build on account of consistent delays in design. The slack in the chain being the most notable problem but was still mitigated in the final build. The team was able to overcome this by clearly distributing the workload and frequently working together to evaluate one another's work to ensure that nothing was overlooked. That being said, a clear initial scope for the project would have streamlined the engineering analysis resulting in more time to manufacture and conduct validation testing on the prototype.

REFLECTION

Relevant Factors

Public health, safety, and welfare is somewhat relevant to the project. Since the team made a small scale prototype, the prototype itself doesn't affect public health and safety. However, the technology that this prototype will be used to develop will potentially reduce pollution from particles being sprayed in the air during battery electrode manufacturing. It will also potentially increase worker safety, as workers will not be breathing in as many particles.

If our prototype is able to be scaled up, it could potentially revolutionize how electrodes are manufactured. This could lead to less material being used to manufacture electrodes, as the control over grain alignment would allow for more efficient electrodes. This would also potentially enable battery electrodes to become cheaper, lowering the cost to manufacture electric vehicles, which would in turn smooth the way for an all electric vehicle future. Currently the high price of electric vehicles is a large barrier in mass adoption, removing this barrier would speed up the switch away from fossil fuels in transportation.

Because of how simple the design is, companies may opt for robots to manufacture it, but some of the fastener locations are tight enough together that humans may still need to be utilized. The design is made of aluminum and copper, which are both easy and desirable to recycle for industry. This incentivizes care at the end of life for this product, reducing waste and environmental harm.

The team utilized a stakeholder map and life cycle analysis to ensure that all stakeholders were considered in the design. The life cycle analysis was to ensure that the design met relevant environmental requirements that the team came up with (requires less than 10kWh/kg of produced material, at least 70% recyclable at end of lifecycle).

DEI

Although the team is made up of people with different backgrounds, this mostly had little effect on how the team approached the project. Certainly, the difference in experiences had an effect, with the more experienced members of the team gravitating towards doing CAD and generating more technical ideas. But privilege, identity, and cultural similarities/differences did not have much bearing on this design, due to the nature of the project being much more technically oriented than people oriented. On the other hand, given that the team's sponsor was also the team's professor, the sponsor/professor may have had more influence than intended. This dual role made it difficult for the team to truly get the interaction with a sponsor that this course seems designed to provide. Because the sponsor was grading the team, the team's creative expression was somewhat limited and instead of being able to bounce ideas off of a professor, every review was also a presentation to the sponsor. Potentially, this means the final design is more closely aligned to the sponsor's needs and desires, but it also means that some of the learning process for the team was stunted. Instead of having to struggle through a problem, the team could get weekly feedback on where to go next, something that while helpful, also meant that the team didn't have as much control over the final design.

The more experienced members of the team definitely had more sway when it came to idea development, which highlights the importance of every member of a team feeling comfortable with multiple aspects of the project, so that more diverse ideas can be generated. One thing the team could have done better on, was not allowing one viewpoint to take over. Oftentimes, the sponsor's viewpoint prevailed, with little to no consideration of various team members' viewpoints or consideration of other stakeholders. Because the main stakeholder was the sponsor and his graduate student, very little effort was made to contact other stakeholders related to this project, which is not ideal.

In terms of ethics, this project didn't touch on very many during the design process. If this project were to go into commercial use, there may be some concern about worker safety or ergonomics, mostly relating to assembly and the eventual use of liquid nitrogen. The professional ethics that the University of Michigan expects the team to uphold are aligned with the team's as a whole. Our future employer's ethics will align with the team's, because each team member will not work with a company that violates the professional ethics taught at the University of Michigan.

PROBLEM ANALYSIS

The main deliverable for this project will be a proof of concept of roll to roll freeze casting. Ideally, this would take the form of in-depth analysis, and a prototype of one or more of the critical functions of the design. Given the current project timeline, this prototype can be developed during the second half of the semester.

This project touches on many aspects of engineering. While roll to roll manufacturing is a developed and well understood field, the ability of a team of engineers to apply it to a functional prototype is dependent on their understanding of mechatronics and their applications. The continuous processing and cooling rate can both depend on this knowledge, since they will influence the speed and torque of the motors needed for the roll to roll system. This will incorporate the team’s knowledge from ME350: Design and Manufacturing II. This understanding of mechanical systems must also be combined with an active understanding of thermodynamics to control the temperature gradients that facilitate the microstructure formation during freeze casting, which will incorporate knowledge from ME 335: Heat Transfer.

System Decomposition

In order to fully understand the design and to simplify engineering analysis, a system decomposition is required. The design chosen can be divided into three major subsystems which are discussed below.

The motor and drive unit comprise of any motors, rollers, gearing, and drive mechanisms in the design. The motor and drive system needs to be able to reach the specified manufacturing rate in order to meet current industry standards for roll to roll.The temperature control system includes any heaters, fluids, and freezing mechanisms for the freeze casting process. This system controls the temperature and gradient at which the slurry is frozen, which is critical for the freeze casting process. An electrical control system is not required since the DC motor speed can be adjusted by changing the voltage manually. For the scope of this project, the team will focus on the motor and drive system since it will not be implementing freeze casting.

Anticipated Challenges

Since the scope of this project excludes the freeze casting process, the challenges of dealing with a cryogenic gas and controlling the temperature gradient will not be as significant. These challenges will be passed onto the research team that will use our design for future freeze casting work. In order to design around the freeze casting process, it was necessary to understand how this process works and to run a simulation to determine the temperature gradient required for this application. Both knowledge from ME 335: Heat Transfer and ME 382: Mechanical Behavior of Materials will be needed.

Additionally, creating an accurate scaled down prototype will also be a challenge. Replicating this complicated manufacturing process will require a lot of assumptions and simplification. While 18650 electrodes are 125 µm thick [13], the prototype will create parts around 1 mm thick. The team aims to create a prototype that takes into consideration the potential differences in size, time, cost, and energy when freeze-casting a prototype several magnitudes thicker than what will be made in industry.

RECOMMENDATIONS

For future use of the project, the team has a few recommendations. The first recommendation is to create a simple circuit to reverse the polarity of the motor so that the user does not have to physically switch the wires. A nut should be attached to the bolt being used to push the freeze casting plate, as well as a shorter bolt should be used. When considering the freeze casting process, the sponsor may want to look into having the cold plate not in contact with the freeze casting tray in order to freeze the slurry slower. This would require a different, more robust simulation than the one used during this project.

Second, the copper tray used in the current prototype is attached to four L brackets using fasteners, all four have the bolt length too long due to limited hardware availability. The use of fasteners could prove to be a problem with sealing, thus requiring additional sealing strategies used to seal the holes the fasteners go through. Also, the protrusion of the fasteners into the tray could interfere with the freeze casting process depending on the desired slurry height. Therefore, it is recommended that the brackets be adhesively bonded to the copper tray in the future, in order to save weight as well as add simplicity. An adhesive bond with properly calculated bond area and bond strength would be beneficial, assuming the adhesive used can withstand the freeze-casting temperature range. An adhesive bond would also be less sensitive to thermal expansion under the temperature fluctuations. Repeated thermal cycling on the bolted joints connecting the L-bracket to the copper tray will cause the clamping force to decrease over time as the joint experiences less torque, thus loosening and causing the assembly to lose structural integrity, compromising Z-height and changing the freeze cast boundary conditions. Adhesive bonds will be affected less by thermal expansion, since the L brackets are not constrained to the copper other than the adhesive, so as long as there is sufficient clearance between the moving tray and L-brackets, there won't be an issue. Lastly, adhesive bonds will save a drastic amount of weight compared to bolted joints, which requires 4 bolts and 4 nuts as well as washers. Reduction of weight can also help reduce the friction force between the moving plate and the flow rail, thus reducing the possibility of failure scenarios where the moving tray gets stuck. This brings us to the next recommendation.

Third, there are some proposed changes to the moving plate. It is recommended to change the tolerance between the moving plate and the vertical frame guiding rails. As of right now, the prototype moving plate is pushed along the continuous direction via a fastener attached to the sprocket chain, since the bolt is not centered to the moving plate, a moment is applied to the plate as it moves. Due to manufacturing defects, the moving plate is smaller than the desired tolerances, and due to the large gap between the moving plate and the vertical guide rails, there is a risk of the moving plate getting stuck as it moves. Additionally, since the flow rail uses large diameter wheels, there is a significant gap between the wheels. Since the moving plate is narrow in width, as the plate transitions from one wheel to the other, there might be minor pitch deviations, which cause the z-height to be poorly controlled. This might impact the freeze casting process since the simulation was very sensitive to the z-height. However, adding width to the moving plate adds unwanted mass that increases friction force. To combat this, the moving plate should have more lightweighting features, which could be waterjet. Ideally, the profile of the lightweighting can be structurally optimized in softwares like Ansys Mechanical; the profile of the moving plate should minimize the amount of unneeded material to save as much weight as possible.

CONCLUSION

The goal for this project is to convert freeze casting into a continuous process by analyzing current industry methods like roll to roll manufacturing. This would produce battery electrodes with higher conductivity and ability to store a higher amount of energy.

This report highlights the current state of both roll to roll manufacturing and the current state of research into freeze casting. As such, it highlights the high production rate of roll to roll but also the lack of control over the final electrode's microstructure, which directly affects the ability of the battery to store energy. It also covers the benefits of freeze casting, namely the control it offers over the grain of the material, thereby giving a much more conductive final product, but also its time consuming nature.

Through this report, the team has highlighted the current industry and research standards and used those to derive requirements for an engineering prototype, the most important of which is the designed machine must be able to process materials at a rate comparable to roll to roll machines, though at a much smaller scale, while incorporating the ability to freeze a mineral slurry so as to facilitate freeze casting. This research was also used to highlight those who would be most impacted by the deployment of this process on a large scale in a mass manufacturing setting as well as the positive impact it would have on the primary stakeholders in the project, Automotive OEMs, The University of Michigan, and Battery electrode manufacturers.

This report also serves to highlight the engineering design that the team has put forward. After much deliberation, 160 different designs have been narrowed down to 5 and finally a single design after consultation with the project sponsor. This design was narrowed down using functional decomposition and analysis resulting in a Pugh chart. This design focused on combining both freezing and heating to maintain a favorable temperature gradient while using containers to contain the slurry during the casting process all along a continuous conveyor line, the goal being to combine roll to roll and freeze casting in a manufacturable prototype model.

However, after further discussions with the project sponsor, the scope of the project was re-considered to only incorporate a drive mechanism with the freezing mechanism falling out of the scope for this project. The drive system was also re-designed to minimize the number of thermal boundaries as well as potential points of failure in the mechanism. The new design involved guided rails on either side of a tray that would hold the slurry.

Moving forward, engineering analyses were conducted to determine the solution space fully. To that end, heat transfer analysis was conducted by hand. This analysis was then validated using a CFD simulation to determine how long the chamber must be in order to facilitate complete freezing of the slurry based on the manufacturing rate. Additionally, motor requirements were also calculated for the drive system at a constant manufacturing rate. Moving forward, these analyses were used to determine which materials and motors to procure before manufacturing as well as establish a manufacturing guideline for the final assembly.

To that end, a preliminary bill of materials was drafted which included all materials required to build the final assembly as well as drive it. Following sponsor approval, the team set out to acquire all the necessary components and materials to assemble the final assembly. In addition to finalizing the the bill of materials, the team also established a set of testing procedures to be conducted to validate the completed build and verify that it does meet all the specifications established by the project sponsor, chief among which being that the drive unit is able to reach and maintain the final continuous manufacturing rate.

This build design is a small step in the larger goal of improving the manufacturing of battery electrodes. Past this semester, the set-up can be used in freeze casting research, which can contribute to future research in battery electrode manufacturing. Should this design be successful, lithium-ion batteries could be more efficient and safe, resulting in less expensive electric vehicles that are safer for the manufacturing workers, electric vehicle drivers, and the environment as a whole.

ACKNOWLEDGEMENTS

Firstly, the team would like to thank the MECHENG 450 course instructors and the University of Michigan as a whole for the opportunity to work on this project. This project has helped us to hone our skills as engineers and work in an environment to improve our collaboration and communication skills. Having this experience to work on a real-world project will set us up for success in our future careers as engineers.

Next, the team would like to thank our instructor and sponsor, Professor Wenda Tan. Without him, this project would not exist or have had the success that it did. He guided us throughout the semester in a way to help us learn and also understand how to meet expectations of a sponsor in industry. Juggling both sides of his role was not easy, and he took on the challenge anyways to help us succeed this semester.

Additionally, the team would like to thank the staff from the Undergraduate Machine Shop for their help on the build design. The team would not have had anything built if not for their help, including flexibility and support in thinking of creative ways to best manufacture our design.

The team would also like to thank other students and staff in the MECHENG 450 class for their critiques and suggestions throughout the semester. This helped the team improve on their design and ensure that every aspect was considered in the best way possible. Being able to take criticism in a constructive way was a large contribution to the success of the project.

Lastly, the team would like to thank their family and friends for their support, especially this semester. Taking on a semester-long project like this was not easy, but having people to help during challenging times was integral to the success of the project. We would not be where we are today without the support and help from our loved ones.

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BIOS

Michael Beltramo

Michael was born and raised in West Bloomfield, Michigan. Michael decided to major in mechanical engineering because it is applicable to many different fields and he has a wide array of interests. I was in robotics in highschool and developed a passion for hands-on work and learning how things function. He is interested in working for any company near Washington DC, where his siblings have moved to. He is treasurer for the Human Powered Submarine team at the University of Michigan. In his free time, he enjoys reading, running, and playing video games.

Emma Laible

Emma was born and raised in Traverse City, MI. They knew they wanted to study Engineering since middle school when they found out that it is possible to use math and science to create new inventions and solve real world problems. Emma has always loved math and science, but wanted to use their passions for the good of others. They chose Mechanical Engineering after learning about the different types of engineering in high school, and realizing that it was most aligned with their interests. They love hands-on work, and prefer to get their hands dirty. They also love machines and learning how things work, especially how things are made, so they chose to add on the Manufacturing Concentration to their engineering degree. Emma hopes to work in manufacturing next year anywhere they can get a job. Ideally, they would love to move to the east coast, and are a city girl at heart. When not doing engineering, Emma is always busy with theatre, music, and the arts. Emma is president of their theatre club, Not Even Really Drama Students, and has a minor in music. They love to sing and play the flute, piano, and ukulele. The most recent show they have been in was *The Music Man*, and they are currently acting in a student-written show called *A Murder Mystery Musical*. Emma loves to spend time with friends, watch the football games, and snuggle with their cat.

Zuoheng(Henry) He

Henry was born in Beijing, China and lived there for 13 years. Henry decided to study abroad in the US starting in 8th grade in southern california. While attending highschool in orange county, Henry joined a VEX robotics team and discovered his passion for cars. These two factors caused him to pursue mechanical engineering at the University of Michigan. While in the UofM, Henry was very involved in its Formula SAE team, MRacing. Starting out as a new member in the chassis division, Henry worked hard and eventually landed leadership roles such as ergonomics lead, monocoque lead, and eventually chassis director in the third year of involvement. During this time Henry enjoyed designing and manufacturing carbon fiber composite components on the car, as well as bonding, and competing with his teammates. Henry is a big car guy and enjoys working on, and driving his personal vehicle: a 2008 Mitsubishi Lancer Evolution X GSR that he has incorporated into his personality ever since obtaining the car. Henry also has *aspirations* of building an aesthetic physique, and dabbles in powerlifting and bodybuilding.

Rohit Kamath
Rohit was born and raised in Bangalore, India, a large city located in the center of the southern peninsula of the country. Growing up, he was fascinated by the world of motorsports and from a young age has wanted to work in the industry. Over time, this fascination developed into a deep appreciation for aerodynamics and its application in race cars, ultimately culminating in his desire to pursue mechanical engineering. Once admitted to The University of Michigan, Rohit worked heavily with MRacing, the university's Formula SAE team where he was elected to lead the team's aerodynamic division in his second year on the team. When he is not working on school work or on aerodynamic development for MRacing, he can be found playing video games or engaging with anything related to the cyberpunk genre.

APPENDIX

Appendix A

$$\alpha = \frac{h_E \xi}{RT_E} \tag{A}$$

Where *h*E is the latent heat, *R* is the gas constant, *T*E is the equilibrium temperature between the two phases and *ξ* is a factor that depends on the crystallography of the interface. Materials that have a value of *α*<1 grow in a dendritic fashion. [10]

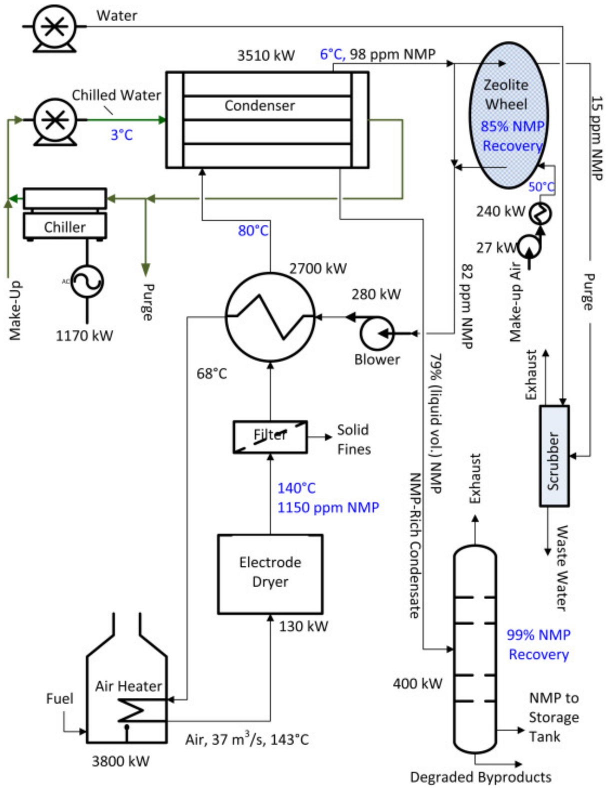
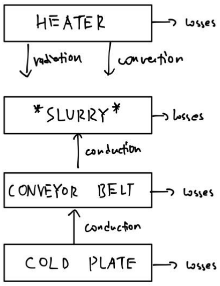


Figure A: Solvent recovery system in a battery manufacturing plant. NMP is the solvent n-methyl pyrrolidone, which is a common cathode solvent. [21]

Appendix B



Conditions;

SLURRY temp ≤ -30°C

Cooling rate ≤ 10°C/min
or
0.167°C/s

Electrode dimensions:

500±5mm × 65±5mm
× 1±1mm

Governing Equations;

conduction

$$q = -kA\frac{dT}{dx}$$

convection

$$q = hA(T_{solid} - T_{fluid})$$

radiation

$$q = \varepsilon_{SB}\sigma A[(T_{solid})^4 - (T_{\infty})^4]$$

$$Q = mc\Delta T$$

Assume LFP slurry true density of 3,6g/cm³

$V = 325mm^3 = 32,5cm^3$ $m = 3,6 \times 32,5 = 117g = 0,117kg$

$c_{LFP} = 1130\ J/kg/k$ Assume 25°C room temp

298k ⟶ 243k

$$Q = (0,117kg)(1130\ J/kg/k)(298k - 243k)$$

$$= 7271.55\ J$$

$$t = \frac{25°C - -30°C}{0,167°C/s} = 329,3 \text{ seconds}$$

$$q = \frac{7271.55}{329,3} = 22,08\ J/s$$

Assumptions!

LFP thru-plane conductivity $0,52\ \frac{W}{mK}$

no heat loss to environment

turbulent isothermal flow over an isothermal plate

Reynolds number at fully turbulent limit, aka 4000

LFP slurry is grey body w/ surface emissivity ε of 0,5

Tsurrounding is room temp at 25°C or 298k, heater is off

Tsolid is -30°C or 243k

$$q = kA\frac{\Delta T}{\Delta x} + hA(T_{solid} - T_{fluid}) + \varepsilon_{SB}\sigma A[(T_{solid})^4 - (T_{\infty})^4]$$

conduction convection radiation

$$Nu_x = \frac{h_x x}{k_f} = 0,0296\,Re_x^{4/5}\,Pr^{1/3}$$

$Pr_{air} = 0.7$ $Re = 4000$ $q = 22,08\ J/s$

$$h_x = \frac{0,52 \times 0,0296(4000)^{4/5}(0,7)^{1/3}}{0.5} = 20.813$$

$h = 20,813$

$k = 0,52$ $A = 500 \times 65 = 32500\ mm^2 = 0,0325m^2$ $\varepsilon = 0.5$ $\sigma = 5.67 \times 10^{-8}\ \frac{W}{m^2k^4}$

$$-kA\frac{\Delta T}{\Delta x} = -q + hA(T_{solid} - T_{fluid}) + \varepsilon_{SB}\sigma A[(T_{solid})^4 - (T_{\infty})^4]$$

$$\frac{\Delta T}{\Delta x} = \frac{-q + hA(T_{solid} - T_{fluid}) + \varepsilon_{SB}\sigma A[(T_{solid})^4 - (T_{\infty})^4]}{-kA}$$

$$\frac{\Delta T}{\Delta x} = \frac{q}{kA} - \frac{h(T_s - T_f)}{k} - \frac{\varepsilon\sigma(T_s^4 - T_{\infty}^4)}{k}$$

$$\frac{\Delta T}{\Delta x} = \frac{22,08}{0,52(0,0325)} - \frac{20,813(243-298)}{0.52} - \frac{0,5(5,67\times10^{-8})(243^4 - 298^4)}{0.52}$$

$$\boxed{\frac{\Delta T}{\Delta x} = 3747.73\ K/m \text{ or } 3,75\ K/mm}$$

Table B: Assumptions made in heat transfer analysis

Electrode dimensions at (500+- 5 mm) x (65+-5 mm) x (1+-1 mm)
Cooling rate is at least 10 C per min
Surrounding ambient temperature (also Tsurrounding) is 25 C
Slurry temperature (also Tsolid) is at least -3 0C
Slurry used is Lithium Iron Phosphate based compound
LFP true density at 3.6g/cm^3 [22]
LFP viscosity at 6000 CPS
LFP specific heat capacity at 1130 J/kg/K [23]
LFP thru-plane conductivity is 0.52 W/mK [23]
LFP is gray body with surface emissivity of 0.5
Electrode in freeze chamber behaves like turbulent isothermal flow over isothermal plate
Reynolds number of freeze chamber airflow is 4000 (limit of fully turbulent flow)
Prandtl's number of air is 0.7
Electrode/slurry surface exposed to convection & radiation is only the top flat face
Heater is initially off
No heat loss to environment
Slurry/electrode in the freeze chamber experiences conductive heat transfer from conveyor belt, as well as radiative and convective heat transfer from heater and surrounding air.

Initial calculations first found the total heat required for the electrode to reach the cooling rate and slurry temperature requirements, using the governing equation [25]

$$Q = m \cdot c \cdot \Delta T \tag{6}$$

Given the assumed volume of the electrode/slurry, an estimated mass can be determined from the assumed density, and the assumed specific heat allows the calculation of the total heat required for freeze casting to happen to be at 7.271 kJ. Using this number and the cooling rate, the required rate of heat transfer in the slurry is determined to be 22.08 J/s.

Next, the governing equations for conductive, convective, and radiative heat transfer was used to formulate an equation accounting for all modes of heat transfer of the electrode/slurry. [25]

Conduction
$$q = k \cdot A \cdot \frac{\Delta T}{\Delta x} \tag{7}$$

Convection
$$q = h \cdot A \cdot (T_{solid} - T_{fluid}) \tag{8}$$

Radiation
$$q = \varepsilon \cdot \sigma \cdot A \cdot (T^{4}_{solid} - T^{4}_{fluid}) \tag{9}$$

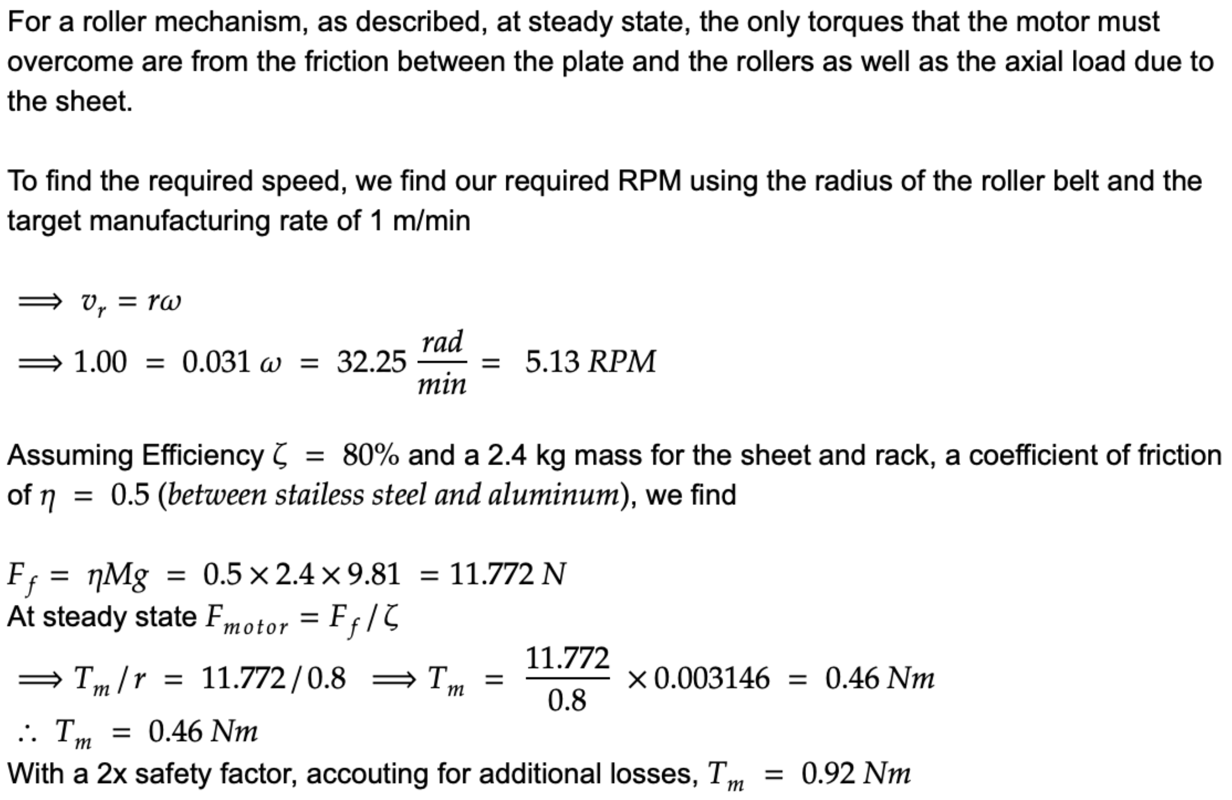
Final
$$q = k \cdot A \cdot \frac{\Delta T}{\Delta x} + h \cdot A \cdot (T_{solid} - T_{fluid}) + \varepsilon \cdot \sigma \cdot A \cdot (T^{4}_{solid} - T^{4}_{fluid}) \tag{10}$$

Using the boundary conditions, the only variable needed to solve for the temperature gradient is the h value for convective heat transfer. Thus, using the Nusselt's number equation for a turbulent isothermal flow over an isothermal plate, and given the Prandtl's number, Reynolds number, thermal conductivity, area, surface emissivity, and constants, the h value was determined to be 20.813.

Lastly, plugging in the values calculated from before into the final heat transfer equation, the expected temperature gradient required for freeze casting an electrode of the assumed dimensions is 3747.73 K/m or 3.75K/mm.

Further analysis to be done include the calculation of the expected voltage, the current requirements of the system, as well as the dependent on motor choice. COMSOL or Ansys fluent simulation of the assembly should be performed to validate hand calculations, and to determine the potential safety concerns due to temperature.

Appendix C : Motor specification calculations



For a roller mechanism, as described, at steady state, the only torques that the motor must overcome are from the friction between the plate and the rollers as well as the axial load due to the sheet.

To find the required speed, we find our required RPM using the radius of the roller belt and the target manufacturing rate of 1 m/min

$$\Longrightarrow\ v_r = r\omega$$

$$\Longrightarrow 1.00 \ = \ 0.031\,\omega \ = \ 32.25\,\frac{rad}{min} \ = \ 5.13\ RPM$$

Assuming Efficiency $\zeta \ = \ 80\%$ and a 2.4 kg mass for the sheet and rack, a coefficient of friction of $\eta \ = \ 0.5$ (*between stailess steel and aluminum*), we find

$F_f \ = \ \eta Mg \ = \ 0.5 \times 2.4 \times 9.81 \ = 11.772\ N$

At steady state $F_{motor} = F_f\,/\,\zeta$

$$\Longrightarrow T_m\,/\,r \ = \ 11.772\,/\,0.8 \ \ \Longrightarrow T_m \ = \ \frac{11.772}{0.8} \times 0.003146 \ = \ 0.46\ Nm$$

$\therefore\ T_m \ = \ 0.46\ Nm$

With a 2x safety factor, accouting for additional losses, $T_m \ = \ 0.92\ Nm$

Figure F: motor calculations based on maximum required manufacturing speed and the torque that would be required to move the mechanism at this constant speed.

Appendix D

Table D: Comparison of materials and properties of different slurry mixtures[11]

Material	Particle size	Slurry composition	Solvent	Freezing Conditions
Al2O3	400 nm - 1 µm	20 - 62.5 % vol	Water	Up to −35 °C
Ferritic stainless steels	15–45 µm	36–56 wt%	Water	Between −40 °C and −80 °C
TiO2	100–200 nm	10–50 wt%	Water	−18 °C
YSZ	1.26 µm	15 vol%	tert-butyl alcohol	Copper rod
YSZ	0.55 µm	10–50 vol%	tert-butyl alcohol	Solidification at room temperature over Al foil
NiO-YSZ	<100 nm	20 vol%	Camphene	Solidification at room temperature

While these specifications are heavily dependent on electrode material and the mechanical capabilities of the machine, they are representative of the general industry in the case of roll to roll and research findings in the case of freeze casting and thus serve as a general benchmark.

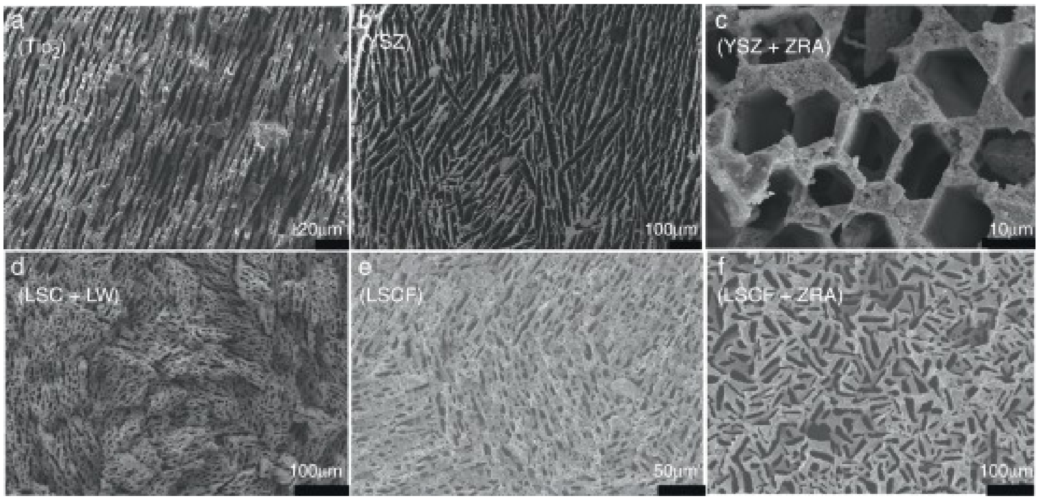


Figure D: Microstructure formation of different materials demonstrating a porous final product [26].

Appendix E: Concept Generation

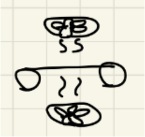
Emma’s Designs

Temperature Gradient

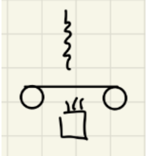
liquid nitrogen and heater

current through a wire and ice

heater and air conditioning



laser and dry ice

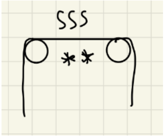


lava and cold water

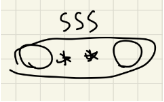
Continuously Freeze Cast

wheel

two rollers



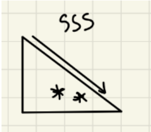
conveyer belt



four rollers

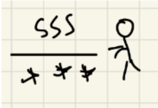
four bar linkage

sheet slides down ramp

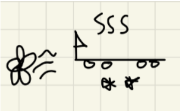


robot moves

person pulls sheet

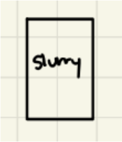


fan blows sheet with sail

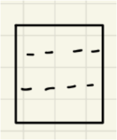


Dimensional Accuracy

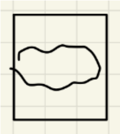
boxed-in area



person puts slurry in mold

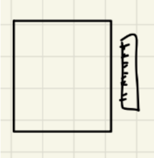


person eyeballs where to put slurry



camera sees slurry and measures x y location

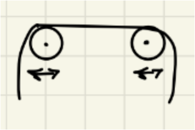
person measures dimensions of slurry



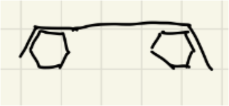
sheet is exact size of electrode

The two roller and liquid nitrogen and heater concepts were built upon or modified

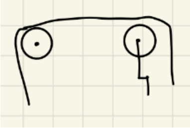
adjustable rollers



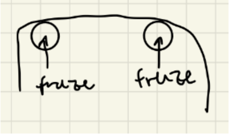
hexagonal rollers



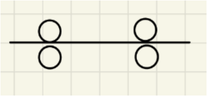
hand crank rollers



freeze cast from rollers

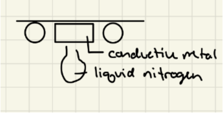


squeeze rollers

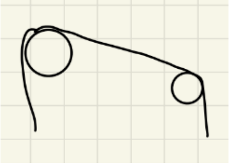


vertical rollers

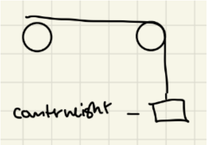
conductive metal to freeze cast



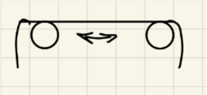
asymmetric rollers



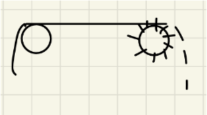
counterweight pulls sheet



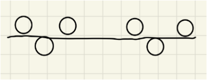
rollers vibrate



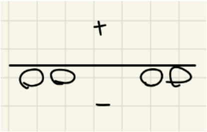
roller calendars electrodes as they roll



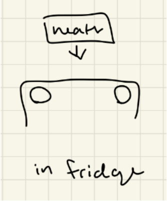
alternate rollers



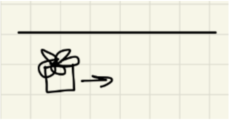
sheet moved by alternating electric field



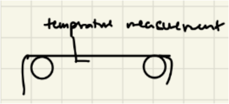
manufacture in a fridge



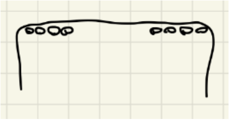
cooling part moves



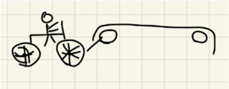
temperature feedback



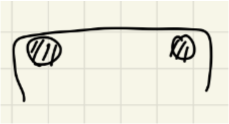
several smaller rollers



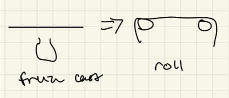
bicycle-powered rollers



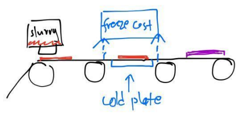
wooden rollers



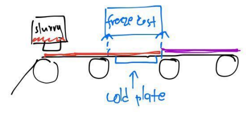
freeze cast then roll separately



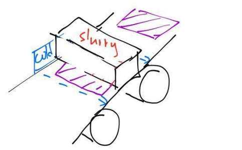
Henry's Designs



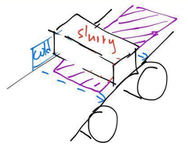
Standard R2R setup
discrete slurry deposits



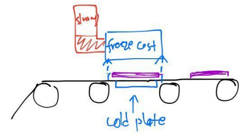
Standard R2R setup
continuous slurry deposits



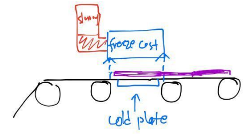
Standard R2R combined setup w/ lateral casting
direction & discrete slurry deposits



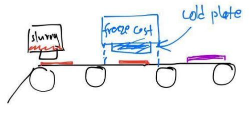
Standard R2R combined setup w/ lateral casting
direction & continuous slurry deposits



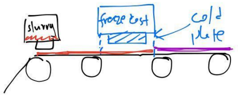
Standard R2R combined setup
discrete slurry deposits



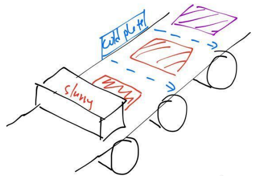
Standard R2R combined setup
continuous slurry deposits



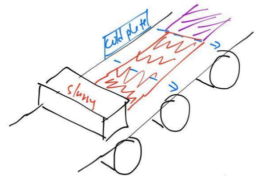
Standard R2R setup (inverted cold plate)
discrete slurry deposits



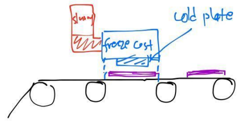
Standard R2R setup (inverted cold plate)
continuous slurry deposits



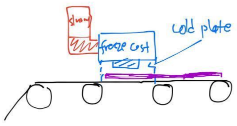
Standard R2R setup w/ lateral casting
direction & discrete slurry deposits



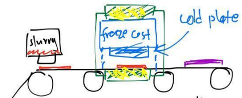
Standard R2R setup w/ lateral casting
direction & continuous slurry deposits



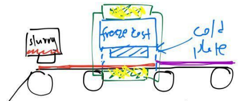
Standard R2R combined setup
discrete slurry deposits (inverted cold plate)



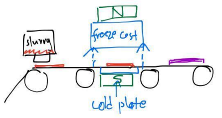
Standard R2R combined setup
continuous slurry deposits (inverted cold plate)



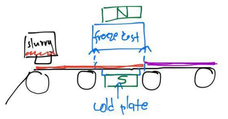
Standard R2R setup (ultra-sonic grain alignment) (inverted cold plate)
discrete slurry deposits



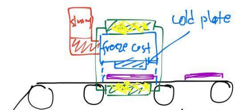
Standard R2R setup (ultra-sonic grain alignment) (inverted cold plate)
continuous slurry deposits



Standard R2R setup (magnetic grain alignment)
discrete slurry deposits

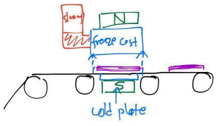


Standard R2R setup (magnetic grain alignment)
continuous slurry deposits

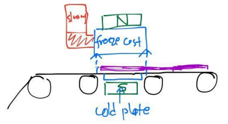


Standard R2R combined setup (ultra-sonic grain alignment)
discrete slurry deposits (inverted cold plate)

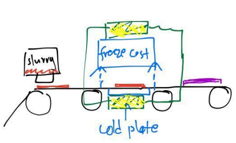
Standard R2R combined setup (ultra-sonic grain alignment)
continuous slurry deposits (inverted cold plate)



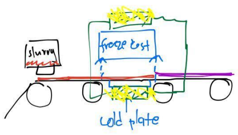
Standard R2R combined setup
discrete slurry deposits (magnetic grain alignment)



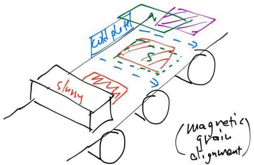
Standard R2R combined setup
continuous slurry deposits (magnetic grain alignment)



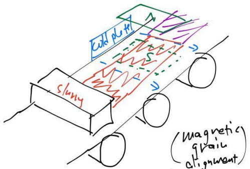
Standard R2R setup (ultra-sonic grain alignment)
discrete slurry deposits



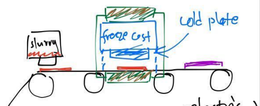
Standard R2R setup (ultra-sonic grain alignment)
continuous slurry deposits



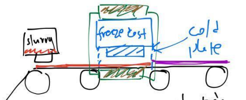
Standard R2R setup w/ lateral casting (magnetic grain alignment)
direction & discrete slurry deposits



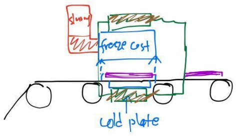
Standard R2R setup w/ lateral casting (magnetic grain alignment)
direction & continuous slurry deposits



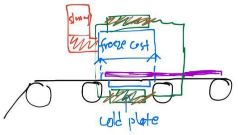
Standard R2R setup discrete slurry deposits (electric grain alignment) (inverted cold plate)



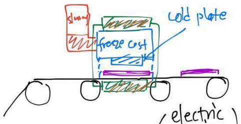
Standard R2R setup continuous slurry deposits (electric grain alignment) (inverted cold plate)



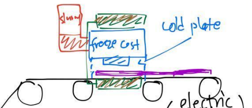
Standard R2R combined setup discrete slurry deposits (electric grain alignment)



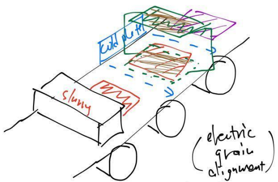
Standard R2R combined setup continuous slurry deposits (electric grain alignment)



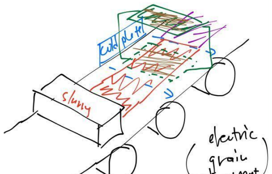
Standard R2R combined setup discrete slurry deposits (electric grain alignment) (inverted cold plate)



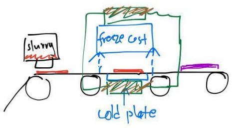
Standard R2R combined setup continuous slurry deposits (electric grain alignment) (inverted cold plate)



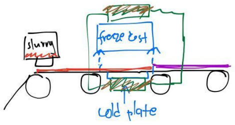
Standard R2R setup w/ lateral casting direction & discrete slurry deposits (electric grain alignment)



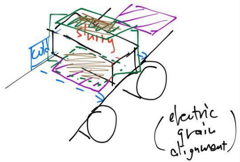
Standard R2R setup w/ lateral casting direction & continuous slurry deposits (electric grain alignment)



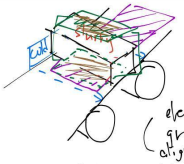
Standard R2R setup discrete slurry deposits (electric grain alignment)



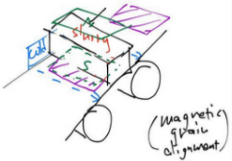
Standard R2R setup continuous slurry deposits (electric grain alignment)



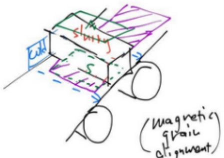
Standard R2R combined setup w/ lateral casting direction & discrete slurry deposits (electric grain alignment)



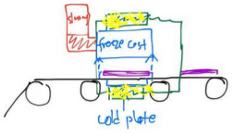
Standard R2R combined setup w/ lateral casting direction & continuous slurry deposits (electric grain alignment)



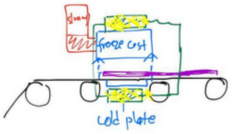
Standard R2R combined setup w/ lateral casting direction & discrete slurry deposits (magnetic grain alignment)



Standard R2R combined setup w/ lateral casting direction & continuous slurry deposits (magnetic grain alignment)

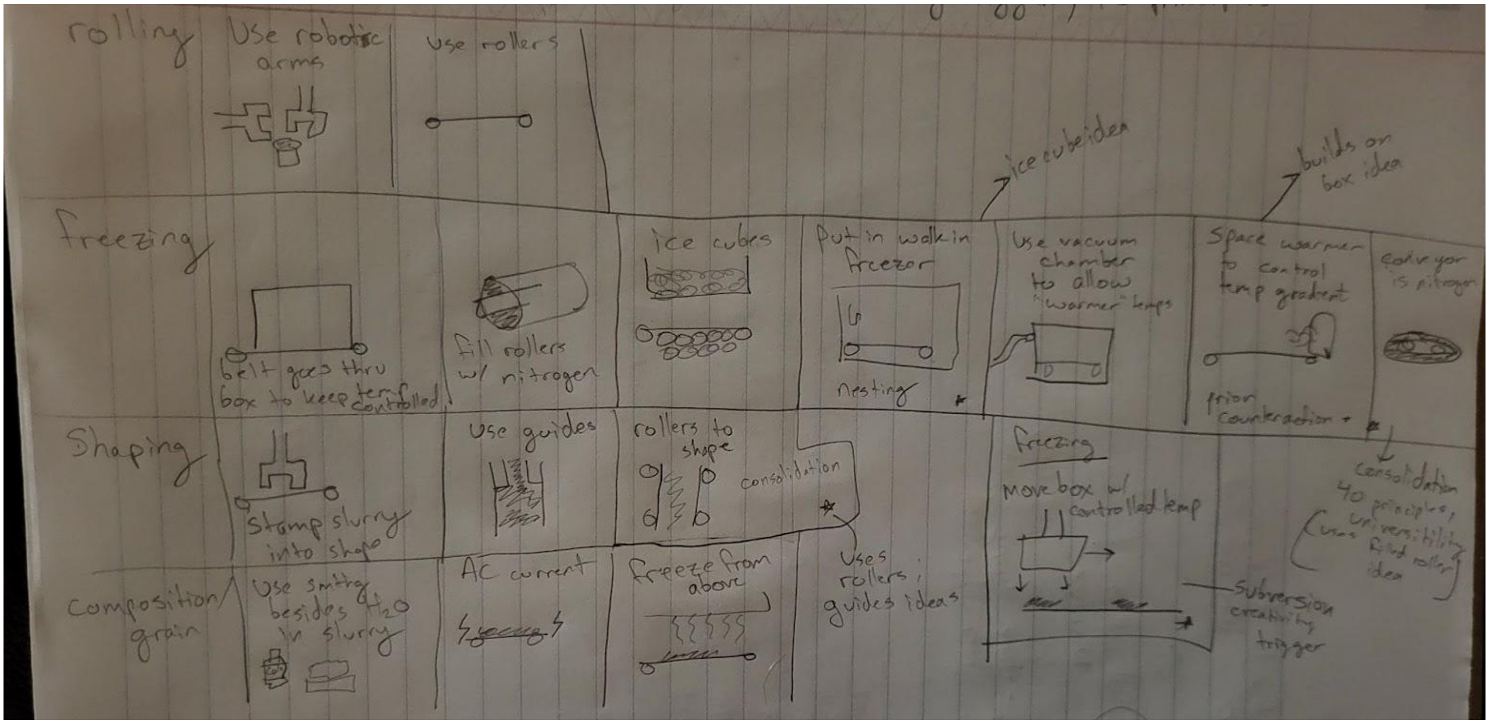


Standard R2R combined setup discrete slurry deposits (ultra-sonic grain alignment)

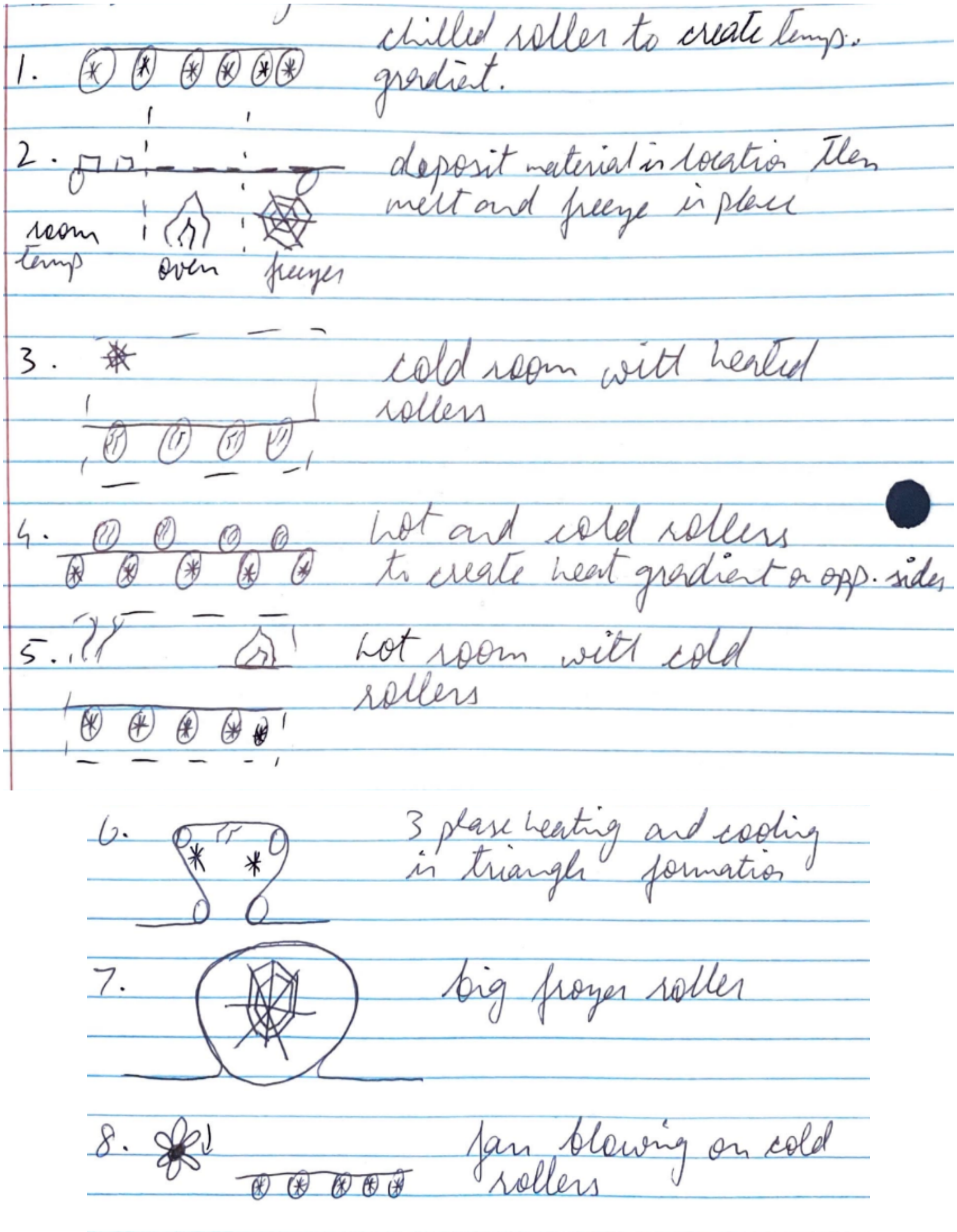


Standard R2R combined setup continuous slurry deposits (ultra-sonic grain alignment)

Michael’s Designs



Rohit's Designs



1. chilled roller to create temp. gradient.

2. deposit material in location then melt and freeze in place

3. cold room with heated rollers

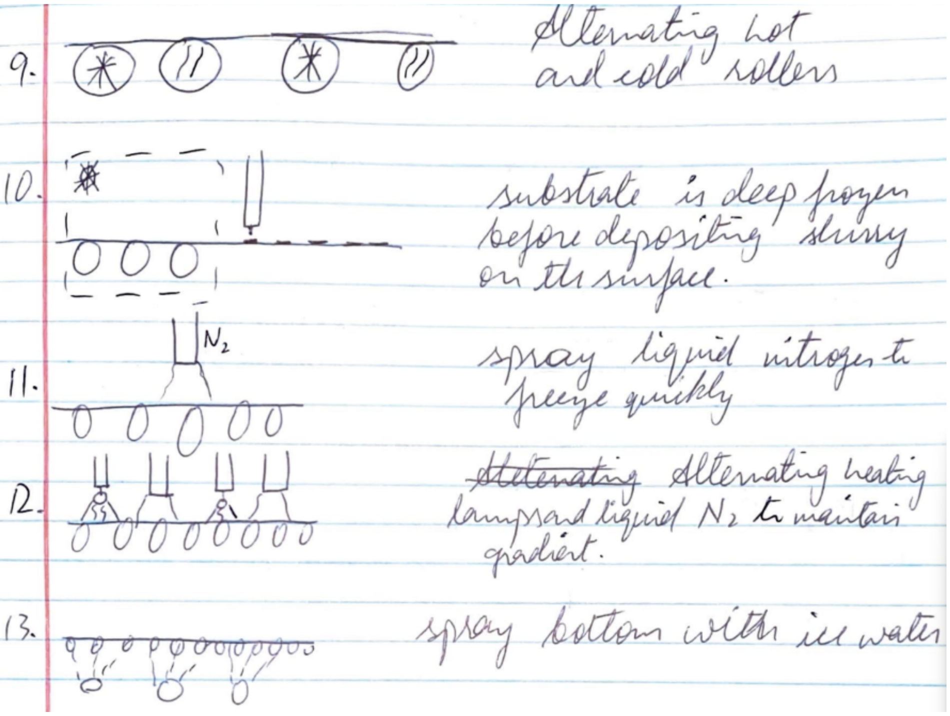
4. hot and cold rollers to create heat gradient on opp. sides

5. hot room with cold rollers

6. 3 phase heating and cooling in triangle formation

7. big freezer roller

8. fan blowing on cold rollers



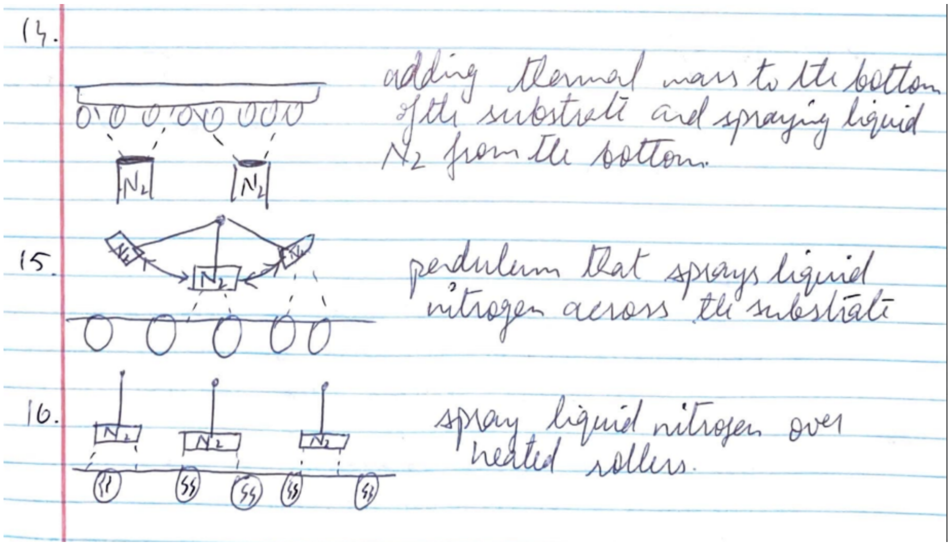
9. Alternating hot and cold rollers

10. substrate is deep frozen before depositing slurry on the surface.

11. spray liquid nitrogen to freeze quickly

12. ~~Alternating~~ Alternating heating lamps and liquid N_2 to maintain gradient.

13. spray bottom with ice water

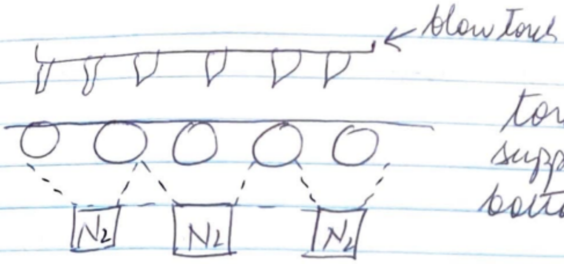


14. adding thermal mass to the bottom of the substrate and spraying liquid N_2 from the bottom.

15. pendulum that sprays liquid nitrogen across the substrate

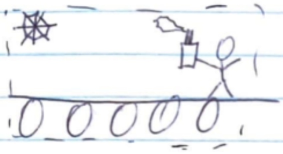
16. spray liquid nitrogen over heated rollers.

17.



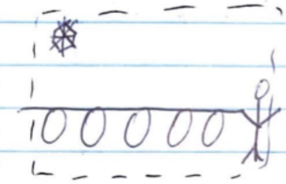
torch top surface and supply liquid N_2 from to bottom

18.



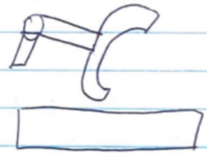
person blowtorches substrate in a cold room

19.



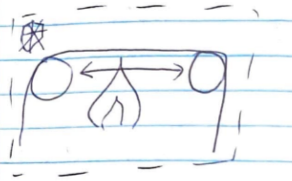
person pulling substrate through once frozen

20.



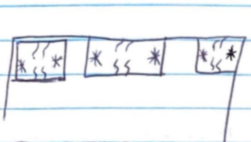
robot arm moving substrate from hot to cold environments

21.



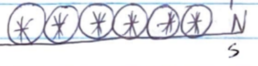
adjustable rollers over fire in cold room

22.



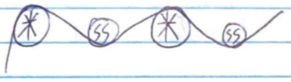
square rollers with hot and cold sides

23.

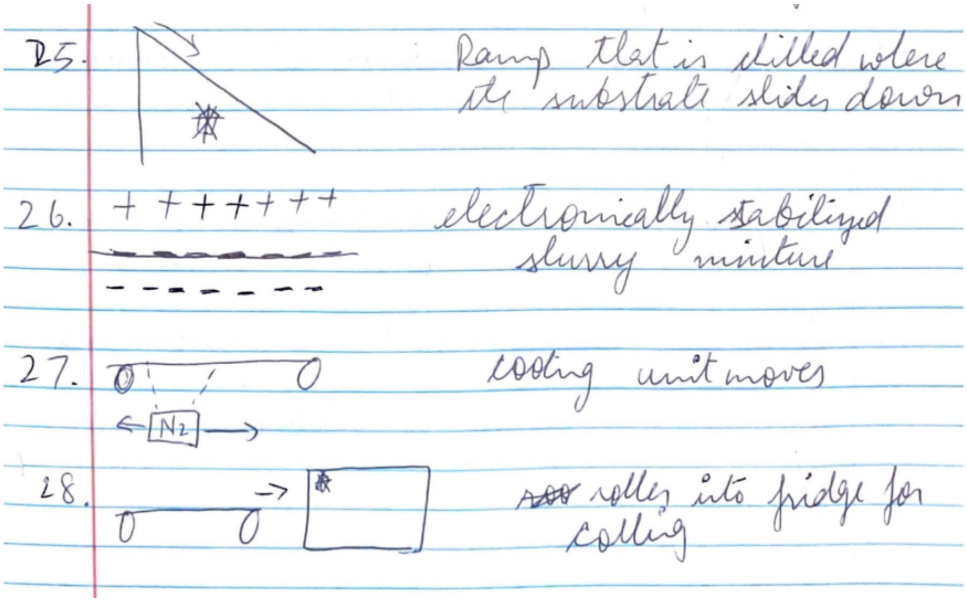


magnetic rollers with cold surfaces

24.



asymmetric rollers with hot / ~~Box~~ cold surfaces.

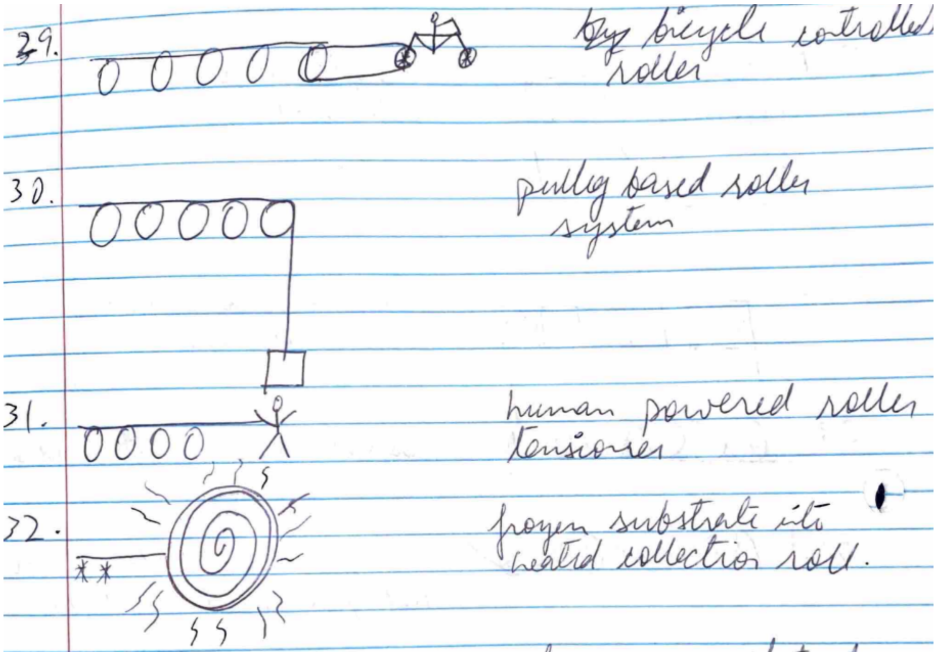


25. Ramp that is chilled where the substrate slides down

26. electronically stabilized slurry mixture

27. cooling unit moves

28. ~~roo~~ rolls into fridge for colling



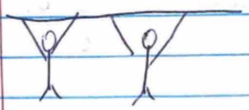
29. ~~by~~ bicycle controlled roller

30. pulley based roller system

31. human powered roller tensioner

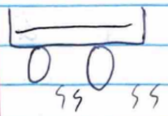
32. frozen substrate into heated collection roll.

33.



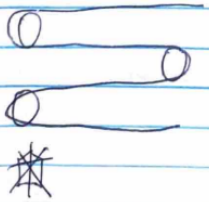
people carry substrate between locations

34.



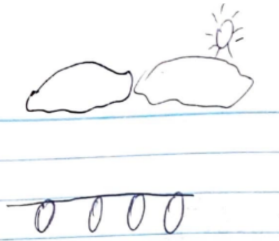
cart for movement between processes.

35.



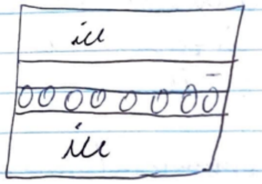
vertical scafolding rollers going from colder bottom to hotter top surface.

36.



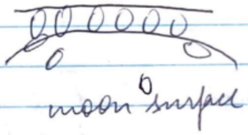
freeze it in the Michigan winter

37.



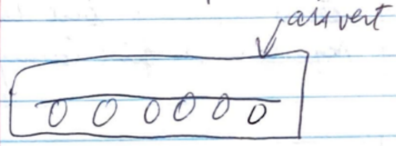
create a tunnel through a glacier to cool.

38.



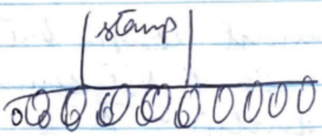
set up manufacturing station on the moon for ≃0K temp.

39.



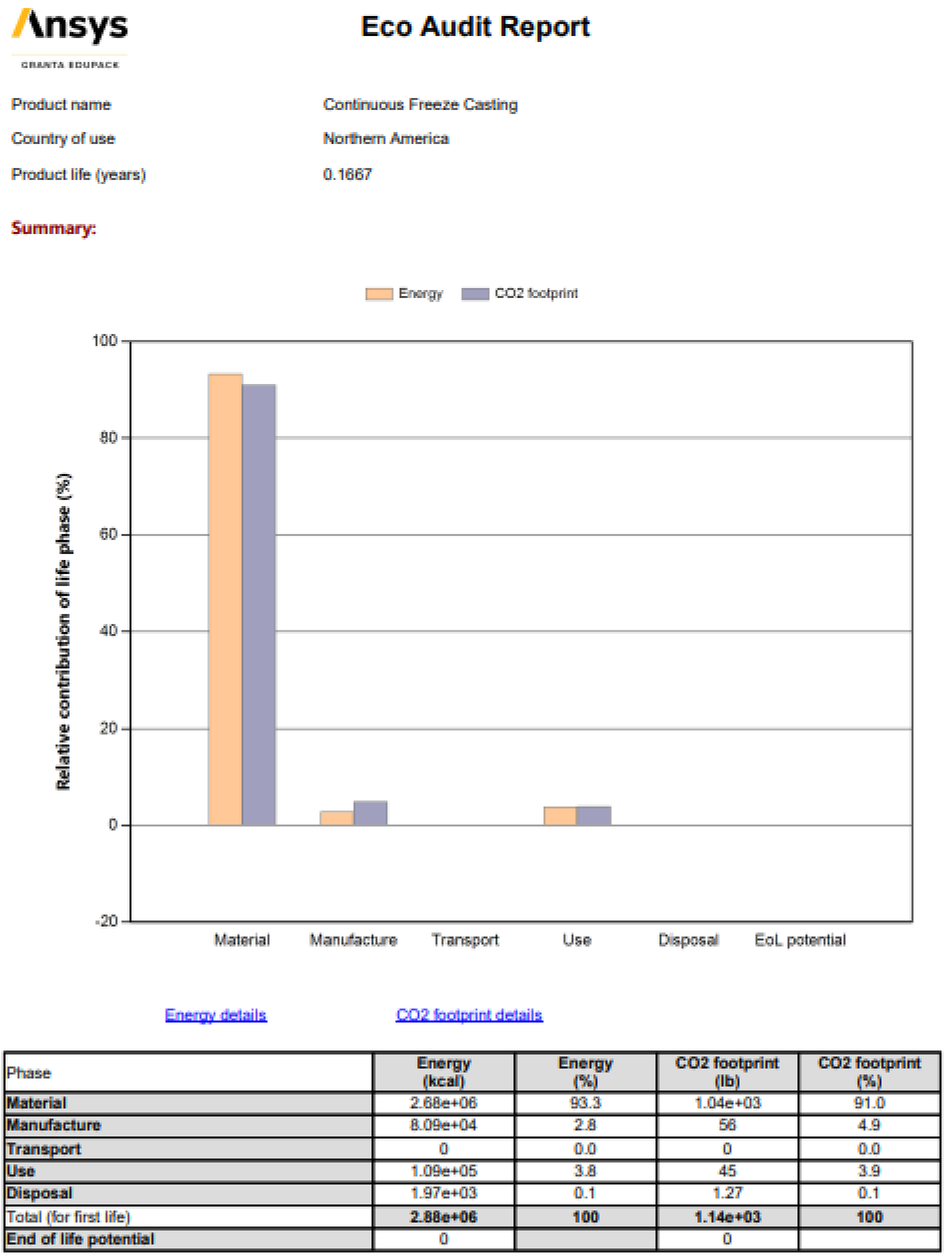
incorporate heat dissipation into HVAC system.

40.



use a super cooled sheet metal stamp.

Appendix F: Eco Audit

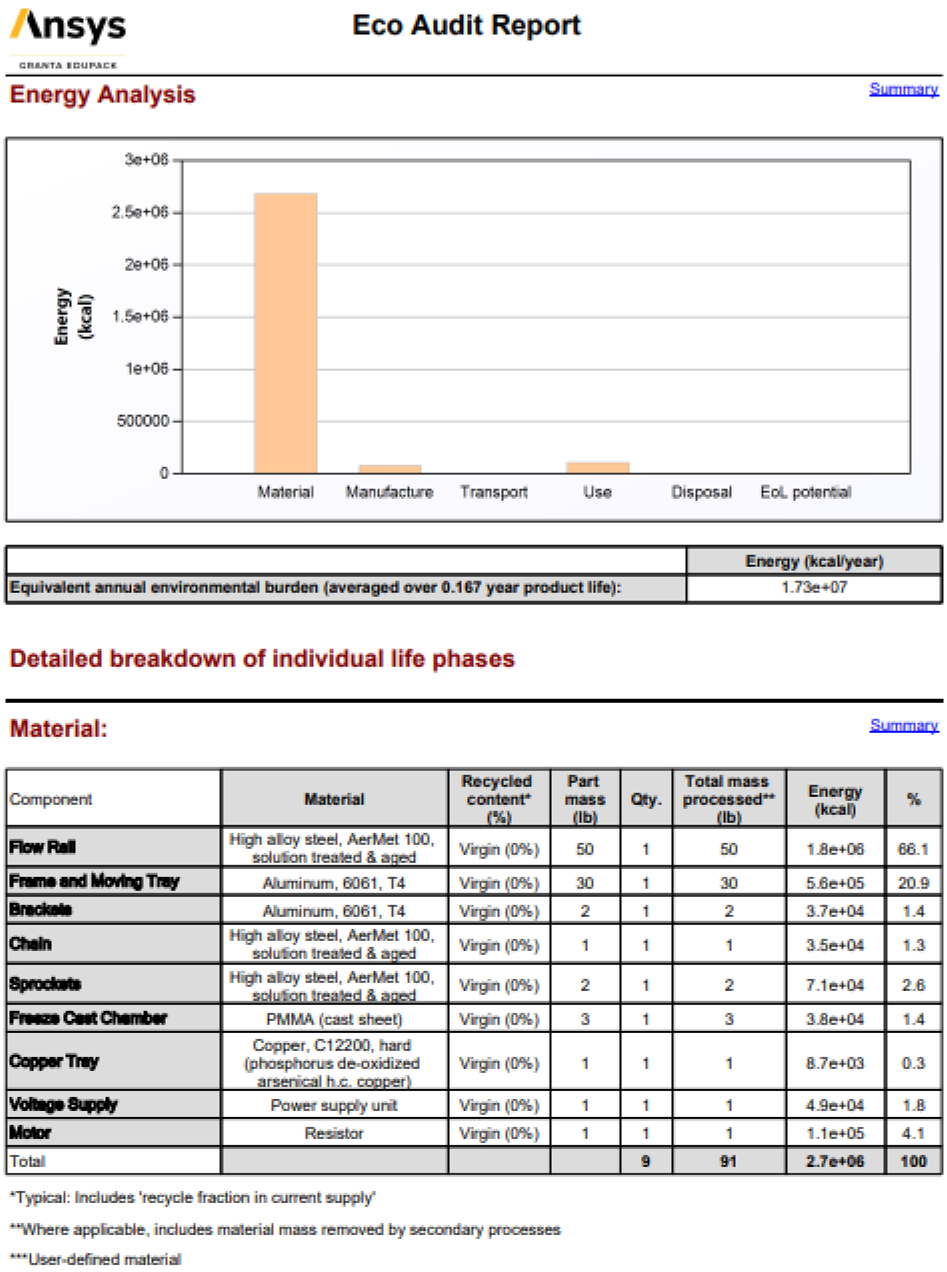


Eco Audit Report

Product name	Continuous Freeze Casting
Country of use	Northern America
Product life (years)	0.1667

Summary:

Phase	Energy (kcal)	Energy (%)	CO2 footprint (lb)	CO2 footprint (%)
Material	2.68e+06	93.3	1.04e+03	91.0
Manufacture	8.09e+04	2.8	56	4.9
Transport	0	0.0	0	0.0
Use	1.09e+05	3.8	45	3.9
Disposal	1.97e+03	0.1	1.27	0.1
Total (for first life)	**2.88e+06**	**100**	**1.14e+03**	**100**
End of life potential	0		0	



Eco Audit Report

Energy Analysis

Summary

	Energy (kcal/year)
Equivalent annual environmental burden (averaged over 0.167 year product life):	1.73e+07

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (lb)	Qty.	Total mass processed** (lb)	Energy (kcal)	%
Flow Rail	High alloy steel, AerMet 100, solution treated & aged	Virgin (0%)	50	1	50	1.8e+06	66.1
Frame and Moving Tray	Aluminum, 6061, T4	Virgin (0%)	30	1	30	5.6e+05	20.9
Brackets	Aluminum, 6061, T4	Virgin (0%)	2	1	2	3.7e+04	1.4
Chain	High alloy steel, AerMet 100, solution treated & aged	Virgin (0%)	1	1	1	3.5e+04	1.3
Sprockets	High alloy steel, AerMet 100, solution treated & aged	Virgin (0%)	2	1	2	7.1e+04	2.6
Freeze Cast Chamber	PMMA (cast sheet)	Virgin (0%)	3	1	3	3.8e+04	1.4
Copper Tray	Copper, C12200, hard (phosphorus de-oxidized arsenical h.c. copper)	Virgin (0%)	1	1	1	8.7e+03	0.3
Voltage Supply	Power supply unit	Virgin (0%)	1	1	1	4.9e+04	1.8
Motor	Resistor	Virgin (0%)	1	1	1	1.1e+05	4.1
Total				**9**	**91**	**2.7e+06**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

***User-defined material

Manufacture:

Summary

Component	Process	% Removed	Amount processed	Energy (kcal)	%
Flow Rail	Casting	-	50 lb	6.2e+04	76.7
Flow Rail	Fine machining	-	0 lb	0	0.0
Frame and Moving Tray	Roll forming	-	30 lb	1.1e+04	13.9
Frame and Moving Tray	Cutting and trimming	-	0 lb	0	0.0
Brackets	Roll forming	-	2 lb	7.5e+02	0.9
Brackets	Cutting and trimming	-	0 lb	0	0.0
Chain	Roll forming	-	1 lb	1.8e+03	2.2
Chain	Cutting and trimming	-	0 lb	0	0.0
Sprockets	Casting	-	2 lb	2.5e+03	3.1
Sprockets	Fine machining	-	0 lb	0	0.0
Freeze Cast Chamber	Polymer extrusion	-	3 lb	2e+03	2.4
Freeze Cast Chamber	Cutting and trimming	-	0 lb	0	0.0
Copper Tray	Roll forming	-	1 lb	2.3e+02	0.3
Copper Tray	Cutting and trimming	-	0 lb	0	0.0
M6 Bolts	Fasteners, large	-	20	3.4e+02	0.4
M2 Bolts	Fasteners, small	-	5	33	0.0
Total				**8.1e+04**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (miles)	Energy (kcal)	%
Total				**100**

Breakdown by components

Component	Mass (lb)	Energy (kcal)	%
Flow Rail	50	0	
Frame and Moving Tray	30	0	
Brackets	2	0	
Chain	1	0	
Sprockets	2	0	
Freeze Cast Chamber	3	0	
Copper Tray	1	0	
Voltage Supply	1	0	
Motor	1	0	
Total	**91**	**0**	**100**

Use:

Summary

Static mode

Energy input and output type	Electric to mechanical (electric motors)
Country of use	Northern America
Power rating (W)	2.4e+02
Usage (hours per day)	4
Usage (days per year)	2.5e+02
Product life (years)	0.17

Relative contribution of static and mobile modes

Mode	**Energy (kcal)**	**%**
Static	1.1e+05	100.0
Mobile	0	
Total	**1.1e+05**	**100**

Disposal:

Summary

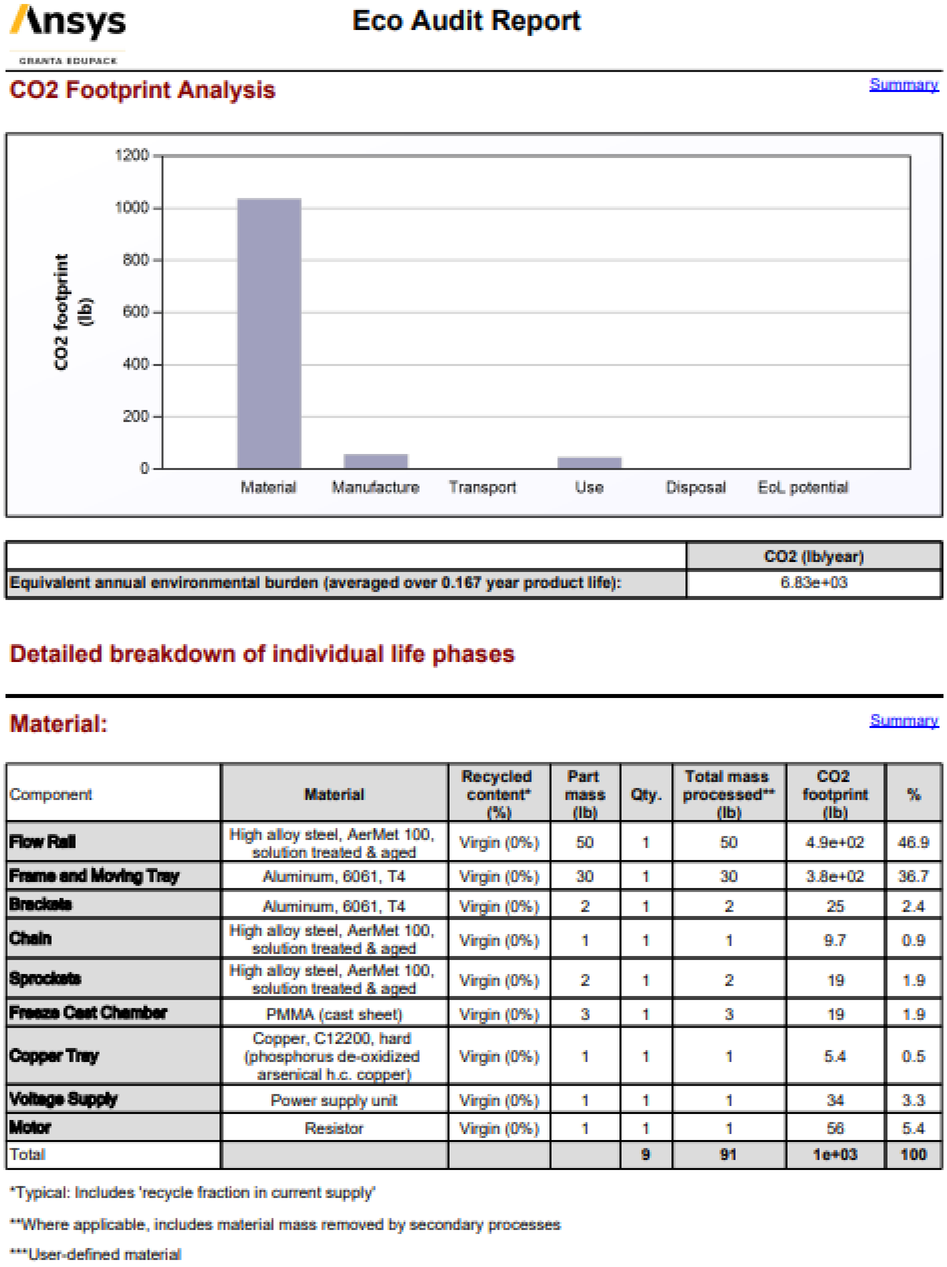
Component	**End of life option**	**% recovered**	**Energy (kcal)**	**%**
Flow Rail	Landfill	100.0	1.1e+03	54.9
Frame and Moving Tray	Landfill	100.0	6.5e+02	33.0
Brackets	Landfill	100.0	43	2.2
Chain	Landfill	100.0	22	1.1
Sprockets	Landfill	100.0	43	2.2
Freeze Cast Chamber	Landfill	100.0	65	3.3
Copper Tray	Landfill	100.0	22	1.1
Voltage Supply	Landfill	100.0	22	1.1
Motor	Landfill	100.0	22	1.1
Total			**2e+03**	**100**

EoL potential:

Component	**End of life option**	**% recovered**	**Energy (kcal)**	**%**
Flow Rail	Landfill	100.0	0	
Frame and Moving Tray	Landfill	100.0	0	
Brackets	Landfill	100.0	0	
Chain	Landfill	100.0	0	
Sprockets	Landfill	100.0	0	
Freeze Cast Chamber	Landfill	100.0	0	
Copper Tray	Landfill	100.0	0	
Voltage Supply	Landfill	100.0	0	
Motor	Landfill	100.0	0	
Total			**0**	**100**

Notes:

Summary



Eco Audit Report

CO2 Footprint Analysis

Summary

	CO2 (lb/year)
Equivalent annual environmental burden (averaged over 0.167 year product life):	6.83e+03

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (lb)	Qty.	Total mass processed** (lb)	CO2 footprint (lb)	%
Flow Rail	High alloy steel, AerMet 100, solution treated & aged	Virgin (0%)	50	1	50	4.9e+02	46.9
Frame and Moving Tray	Aluminum, 6061, T4	Virgin (0%)	30	1	30	3.8e+02	36.7
Brackets	Aluminum, 6061, T4	Virgin (0%)	2	1	2	25	2.4
Chain	High alloy steel, AerMet 100, solution treated & aged	Virgin (0%)	1	1	1	9.7	0.9
Sprockets	High alloy steel, AerMet 100, solution treated & aged	Virgin (0%)	2	1	2	19	1.9
Freeze Cast Chamber	PMMA (cast sheet)	Virgin (0%)	3	1	3	19	1.9
Copper Tray	Copper, C12200, hard (phosphorus de-oxidized arsenical h.c. copper)	Virgin (0%)	1	1	1	5.4	0.5
Voltage Supply	Power supply unit	Virgin (0%)	1	1	1	34	3.3
Motor	Resistor	Virgin (0%)	1	1	1	56	5.4
Total				**9**	**91**	**1e+03**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

***User-defined material

Manufacture:

Summary

Component	Process	% Removed	Amount processed	CO2 footprint (lb)	%
Flow Rail	Casting	-	50 lb	43	76.7
Flow Rail	Fine machining	-	0 lb	0	0.0
Frame and Moving Tray	Roll forming	-	30 lb	7.8	13.9
Frame and Moving Tray	Cutting and trimming	-	0 lb	0	0.0
Brackets	Roll forming	-	2 lb	0.52	0.9
Brackets	Cutting and trimming	-	0 lb	0	0.0
Chain	Roll forming	-	1 lb	1.2	2.2
Chain	Cutting and trimming	-	0 lb	0	0.0
Sprockets	Casting	-	2 lb	1.7	3.1
Sprockets	Fine machining	-	0 lb	0	0.0
Freeze Cast Chamber	Polymer extrusion	-	3 lb	1.4	2.4
Freeze Cast Chamber	Cutting and trimming	-	0 lb	0	0.0
Copper Tray	Roll forming	-	1 lb	0.16	0.3
Copper Tray	Cutting and trimming	-	0 lb	0	0.0
M6 Bolts	Fasteners, large	-	20	0.23	0.4
M2 Bolts	Fasteners, small	-	5	0.023	0.0
Total				**56**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (miles)	CO2 footprint (lb)	%
Total				**100**

Breakdown by components

Component	Mass (lb)	CO2 footprint (lb)	%
Flow Rail	50	0	
Frame and Moving Tray	30	0	
Brackets	2	0	
Chain	1	0	
Sprockets	2	0	
Freeze Cast Chamber	3	0	
Copper Tray	1	0	
Voltage Supply	1	0	
Motor	1	0	
Total	**91**	**0**	**100**

Use:

Summary

Static mode

Energy input and output type	Electric to mechanical (electric motors)
Country of use	Northern America
Power rating (W)	2.4e+02
Usage (hours per day)	4
Usage (days per year)	2.5e+02
Product life (years)	0.17

Relative contribution of static and mobile modes

Mode	CO2 footprint (lb)	%
Static	45	100.0
Mobile	0	
Total	**45**	**100**

Disposal:

Summary

Component	End of life option	% recovered	CO2 footprint (lb)	%
Flow Rail	Landfill	100.0	0.7	54.9
Frame and Moving Tray	Landfill	100.0	0.42	33.0
Brackets	Landfill	100.0	0.028	2.2
Chain	Landfill	100.0	0.014	1.1
Sprockets	Landfill	100.0	0.028	2.2
Freeze Cast Chamber	Landfill	100.0	0.042	3.3
Copper Tray	Landfill	100.0	0.014	1.1
Voltage Supply	Landfill	100.0	0.014	1.1
Motor	Landfill	100.0	0.014	1.1
Total			**1.3**	**100**

EoL potential:

Component	End of life option	% recovered	CO2 footprint (lb)	%
Flow Rail	Landfill	100.0	0	
Frame and Moving Tray	Landfill	100.0	0	
Brackets	Landfill	100.0	0	
Chain	Landfill	100.0	0	
Sprockets	Landfill	100.0	0	
Freeze Cast Chamber	Landfill	100.0	0	
Copper Tray	Landfill	100.0	0	
Voltage Supply	Landfill	100.0	0	
Motor	Landfill	100.0	0	
Total			**0**	**100**

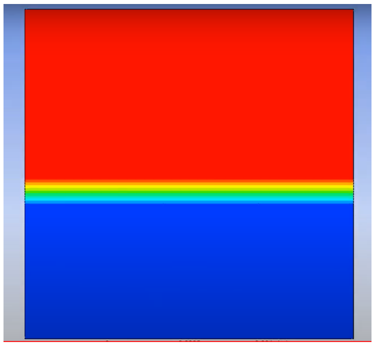
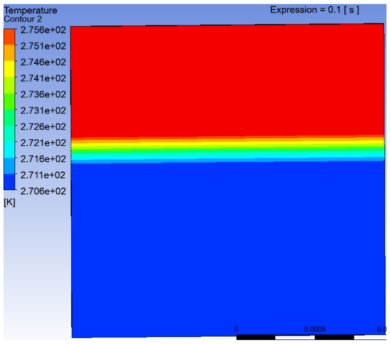
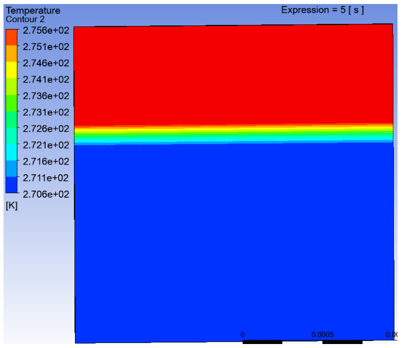
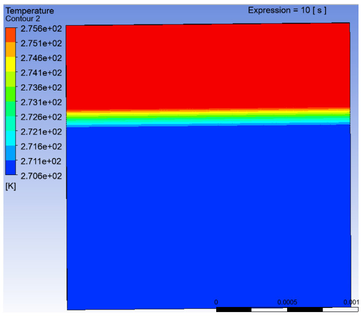
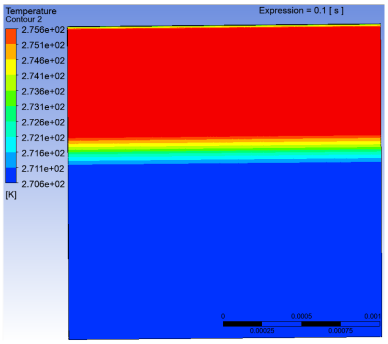
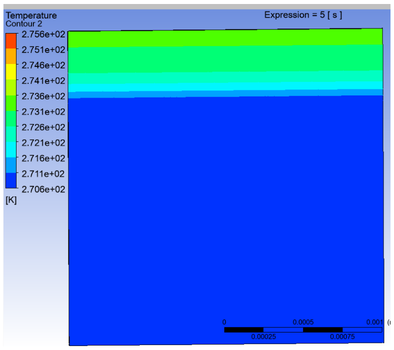
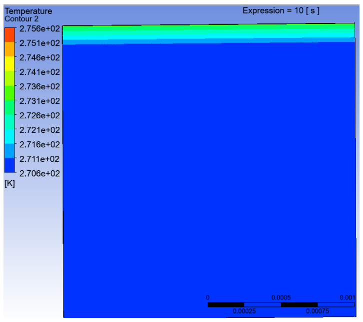
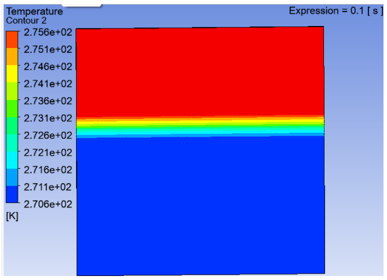
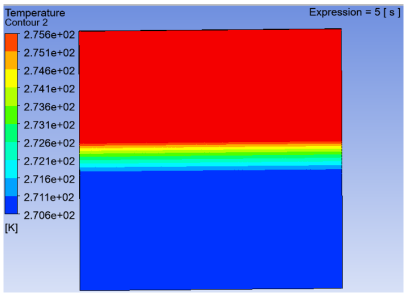
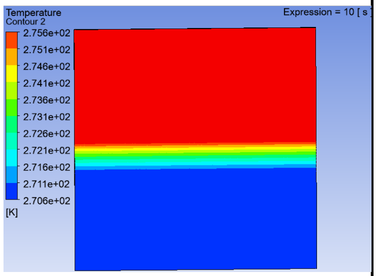
Notes:

Summary

Appendix G: Bill of Materials

Part No.	Part Title	Material	Dimension(s)	Supplier	Quantity	Price per unit (USD)	Total price (USD)
1	Flow Rail	Galvanized Steel	5 ft long	Mcmaster	2	92.05	184.10
2	Chain	Steel	10 ft long, 1/4" pitch	Amazon	1	16.25	16.25
3	Motor L bracket	6061 Aluminum	2" x 2" x 2.5"	Mcmaster	4	8.02	32.08
4	Sprocket	Steel	1.97" x 5/8", 1/4" pitch	Mcmaster	2	18.60	37.20
5	Frame	6061 Aluminum	48" x 6" x 1/4"	Mcmaster	2	60.18	120.36
6	Hot Plate	Acrylic	12" x 12" x 1/8"	Amazon	1	9.99	9.99
7	Cold Plate	Acrylic	12" x 12" x 1/8"	Amazon	1	9.99	9.99
8	Freeze Cast Containment Box	Acrylic	24" x 36" x 1/8'	Amazon	1	45.99	45.99
9	Tray	Copper	4" x 10" x 1/4"	Amazon	1	20.00	20.00
10	Motor	N/A	4.7" x 1.25" x 1.25	ServoCity	1	39.99	39.99
11	Tray and Frame L bracket	6061 Aluminum	1" x 1" x 1-1/4"	McMaster	4	7.81	31.24
12	M6 Screws	Alloy Steel	M6-1.0 x 15mm	McMaster	100	13.98	13.98
13	M6 Nuts	Steel	M6-1.0	McMaster	100	5.21	5.21
14	M6 Washers	Stainless Steel	M6-1.0	McMaster	100	6.58	6.58
15	Varialble Voltage Source	N/A	4.8" x 2.6" x 2.48"	Amazon	1	10.39	10.39
16	MISC Hardware	NA	NA	Carpenter Bros	1	63.13	63.13
17	Sprocket 2.0	Steel	1.97" x 5/8", 1/4" pitch	Mcmaster	2	18.60	37.20
18	Chain 2.0	Steel	10 ft long, 1/4" pitch	Mcmaster	1	63.88	63.88
19	Bearing 2.0	Steel	1/4 ID 1/2 OD	Mcmaster	1	6.12	6.12
20							**753.68**

Appendix H: Fluent

30℃ & -30℃			
30℃ & -40℃			
0℃ & -30℃			
30℃ & -15℃			

Appendix I: Manufacturing Plan

Step	Material	Speed	Tools
1. Cut out aluminum for frame to size with vertical band saw	¼” aluminum	Default	Ruler, calipers
2. Deburr all cut edges	¼” aluminum	NA	File
3. Waterjet the aluminum for the moving tray	¼” aluminum	Default	Waterjet
4. Mark holes on the flow rail and frame pieces based on CAD	¼” aluminum, flow rail	NA	Ruler, calipers, sharpie
5. Center drill the flow rail holes	Flow rail	1000 RPM	#2 Center drill, drill press, vice
6. Center drill the frame holes	¼” aluminum	1200 RPM	¼” drill bit, drill press, vice
7. Drill the flow rail holes	Flow rail	1000 RPM	¼” drill bit, drill press, vice
8. Drill the frame holes	¼” aluminum	1200 RPM	¼” drill bit, drill press, vice
9. Deburr all holes	¼” aluminum, flow rail	NA	Deburring tool
10. Bolt frame pieces and flow rail together	¼” aluminum, flow rail, M6 fasteners	NA	Socket wrench, allen key
11. Mark and drill holes in copper tray	Copper tray	1000 RPM	#2 Center drill, ¼” drill bit, drill press, vice
12. Attach tray brackets to copper tray	Copper tray, M6 fasteners	NA	Socket wrench, allen key
13. Mark and drill holes in motor bracket	Motor bracket	1200 RPM	#2 Center drill, ¼” drill bit, ⅛” drill bit, drill press, vice
14. Attach sprocket and	Motor bracket, motor,	NA	Socket wrench, allen

motor to motor bracket on the driving side.	sprocket, M2 fasteners		key
15. Attach sprocket and bearing to motor bracket on the non driving side.	Motor bracket, sprocket, ¼ fasteners	NA	Socket wrench, allen key
16. Attach both motor brackets to the frame	Motor bracket, frame, M6 fasteners	NA	Socket wrench, allen key
17. Measure chain length using the existing setup and trim chain to size	Sprocket Chain	NA	Chain link tool
18. Adhesive bond fastener to chain	M2 fasteners	NA	Hot glue gun
19. Place copper tray on moving plate, and align hole on moving tray with the M2 bolt on the chain	NA	NA	Socket wrench, allen key
20. Wire up motor to the voltage supply, set voltage to 6V and test drive motor	Wires, motor, voltage supply	NA	Wire stripper