Rapid Tool Heating

Final Project Report

June 2013

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CHAPTER 1: INTRODUCTION

SPONSOR NEEDS

Quatro Composites creates various molded parts for an array of industries. They are seeking to improve their thermoplastic molding process by decreasing the amount of time to heat up the steel tool that molds the thermoplastics. Currently, it takes approximately 1 hour to heat up their 120 pound steel mold from room temperature to approximately 700°F. The goal of this project is to create an optimum heating method that will minimize that heating time to about 20 minutes or less. It is critical for the stakeholders (Quatro Composites) to have a faster heating time in order to increase their production capabilities.

OBJECTIVE

The goal of this project is to create an optimum heating method for the steel tooling. The method will need to heat up Quatro Composites' largest tool to approximately 700°F from room temperature in 20 minutes. There cannot be any changes to the current tooling itself, but through our research and analysis, suggestions for tooling changes will be considered for the company's production future.

Infrared, induction, conduction, convection, microwave, and a combination of the heating methods will be modeled using a transient and finite difference model. The top 2-3 heating methods (based off the models) that can be manufactured and meet Quatro Composite's specifications will be prototyped, tested, approved, and built. In order to evaluate and choose the most viable heating methods, a variety of techniques will be used to brainstorm and compare ideas. After compiling a list of

current specifications for the project, we will consider each method against each other based on individual specification weightings and ratings. Our main tool to make these comparisons is a quality function deployment (QFD) table (Appendix A). The current list of specifications and targets is meant to be a living document that is subject to change in the form of more specifications to be considered in order to further evaluate heating methods.

The most difficult specifications to achieve will be heating time and heating consistency. We are aiming to heat the tools as quickly as possible, but cannot exceed a temperature of approximately 750°F. We will need to find a method that can add heat quickly, but not in a way where the temperature gradient between the surface of tool and the internal mold surface is too large.

In order to analyze various heating systems we will be modeling the mold starting at a basic level to get general requirements and abilities of each heating method. The system will be modeled and analyzed using Microsoft Excel to calculate energy requirements and heating times (while staying within physical constraints). From there, the better performing systems will be analyzed in a more complex manner using MATLAB to model the heating system and assess performance. These models will provide data to be used in the final decision process, and then further used when a final design for implementation is created.

CHAPTER 2: BACKGROUND

The main focus of our background research was to explore all possible heating methods that would be viable and sufficient for the materials and size of the molds that we will be working with. Initially we started exploring general theory for several methods of heating in order to gain an understanding of their strengths and drawbacks. General information publications as well as technical journals were used to learn about each of the heating methods.

Once a basis of each method was understood, we looked out to various industry applications using a variety of heating methods. Through communication with engineers utilizing different processes, we were able to develop an understanding of how analysis can be performed with different heating methods, as well as some of the technical limits of the heating methods.

The main focus we looked at with each different heating method was how rapidly it was capable of heating a mold that is the material and size of those used at Quatro Composites.

Some newer focus in industry has been put on induction heating as a source of very rapid and efficient heating. This seems like a good potential option for mold heating and is already currently being tested and used by some other companies around the world for composite mold heating. Potential concerns are raised with how consistently and evenly it can heat the tool all the way to the surface of the mold (without getting the outer faces too hot) as well as its effectiveness with the steel alloy currently used to construct the tools.

Alternatively, a currently emerging technology for industrial heating applications is microwave heating. Its ability to heat to the temperatures we need with the currently tooling size and material is questionable and no current operations on this scale were

discovered. The microwave method however, does show hopeful statistics and will be considered as a heating option.

The current process used at Quatro Composites, convection oven heating was explored to see if faster times can be achieved through different or multiple pieces of equipment. While we may not be able to heat faster, the possibility of preheating tooling could be explored, to decrease final heating time requirements.

Further methods such as resistance heating, conductive heating methods, and infrared/furnace heating were also explored and analyzed through current industry applications. Some these raised possible concerns regarding current tool geometry or heating consistency, but the methods will still be considered and evaluated against other possible methods.

CHAPTER 3: DESIGN DEVELOPMENT

CONCEPTUAL DESIGNS

This project depended mainly on analysis of various heating methods in order to choose an ideal solution to the problem presented. The process relied heavily on analytical methods through Excel and MATLAB to get detailed and useful data on each possible heating method.

Extensive background research was conducted and utilized to develop a firm understanding of our constraints and specifications. Research into the industries that Quatro Composites operates within was also conducted to understand expectations, standards, and the overall process.

Through analytical models created using tools like Excel and MATLAB, a quantitative compilation of results can aid qualitative analysis, as well as the QFD comparisons in order to decide upon a final heating method to be used.

Induction Heating

Induction heating is a process of heating an electrically conducting object by electromagnetic induction, where eddy currents are generated within the metal which heats the object. For modern manufacturing, this method provides a potential of a combination of speed, control, and consistency.

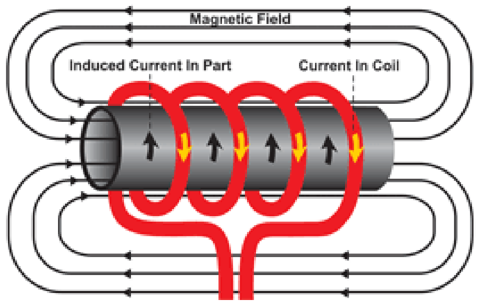

Figure 1. Eddy currents induced in work piece (Gh-Ia)

Figure 2. Steel billet heated by induction heating (Yuelon)

Induction heating was chosen as one of the top choices because of its ability to heat up metal quickly, which was one of Quatro Composites' main requirements. The heating process also had to be safe and easy to use for the operator. An induction system is safe because it does not have an open flame or furnace. Additionally, non-

conductive materials are not affected and can be placed close to the heating zone without damage.

Consistent heating and the ability to monitor temperature was another requirement. With a properly calibrated system, the heating pattern is repeatable and consistent. In modern induction systems, power can be instantly turned on and off, and precise temperature control provides uniform results. Furthermore, these induction systems have the capability to measure the part's temperature with its closed-loop temperature control. The benefit of induction heating is that the heating results are repeatable as long as the induction settings are held constant. Additionally, the same heating patterns can be applied to different sized tools by scaling the induction system accordingly. Linear dimensions of a coil and the load can be changed by a factor "k." When scaling, the following steps occur:

1. The frequency is changed by $1/k^2$
2. The number of coil turns is maintained
3. The applied voltage is maintained
4. Power factor and efficiency are retained
5. Coil and work power input and coil losses are changed by the factor "k."
6. Heating pattern is retained
7. Surface power density is changed by 1/k.
8. Heating time to a given temperature is changed by k^2.

For example, after a correct frequency is determined for a certain size tool based on depth of penetration and testing, a system can be scaled accordingly by a factor "k." If a frequency of 50 Hz worked for a certain tool, changing that frequency to 3000 Hz would result in k = 1/8 based off the following calculation:

$$1/k^2 = 3000/50$$
$$k = 1/8$$

(Davies and Simpson)

Extensive testing is needed to select the optimum induction heating system. However, approximate specifications were determined from research. For through-heating, a low frequency is needed (1-30 kHz) to achieve optimum results. A frequency that is too high will only heat the surface and fail to penetrate to the core. The temperature distribution for a round-cornered steel billet is shown in the Figure 3 below.

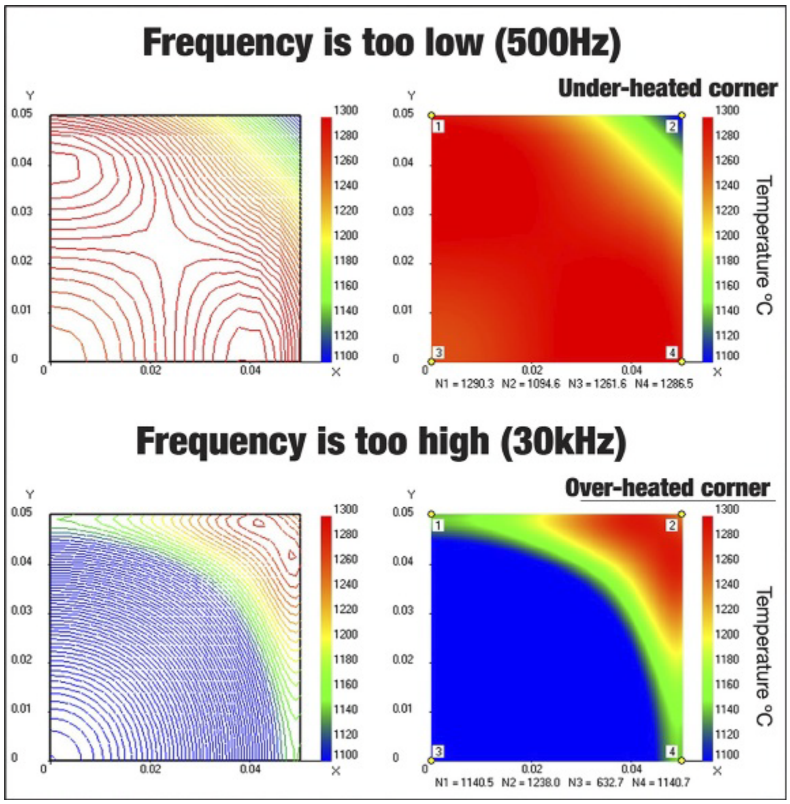

Figure 3. Temperature distribution of steel billet at different frequencies (Inductoheat)

From Davies and Simpson's "Induction Heating Handbook," system parameters were estimated.

The power density needed for the steel tool was calculated as follows:

$$P = \theta_m * b * \gamma/2 * t$$

Where: mean temperature (θ_m) = 644.25K (700F)

Thickness of slab (b) = 0.305 m (12 in.)

Density (γ) = 7850 kg/m^3

Time (t) = 1200 s (20 min.)

P = 175185 W/m^2 or **175.19 kW/m^2**

This is only an estimate, and testing is required to get the correct power density.

Induction heating tends to heat the outer surface much more rapidly than the core. The temperature distribution is parabolic and remains in such a state when P is applied. To equalize the temperature, the power must be removed and the material must be allowed to "soak" (allow material to reach an even temperature distribution in the environment) (Davies and Simpson 27). The time for the material to reach 10% of the outer and core temperature difference is given by the following relationship:

$$T_{10\%} = 0.154 * (c * \gamma) * R^2/k$$

Where: thermal conductivity (k) = 44.7 W/m?C

Radius (R) = 0.305 m (12 in.)

With the approximate frequency range and power density, an appropriate induction heating system can be constructed to test the tool. Quatro Composites will lend us a 3in. x 3in. sample of their steel tool to test. We will test the sample under various frequency ranges and power densities and construct a solid mathematical model.

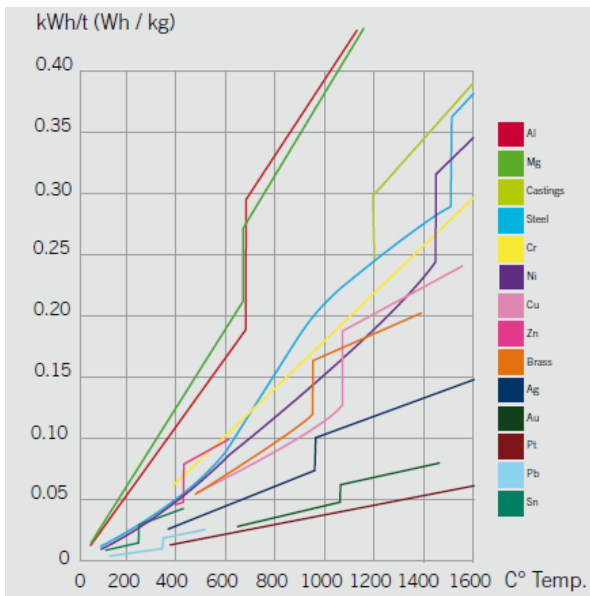

Figure4. Energy absorption rates for different materials (Efd-induction)

Convection Heating

The convection heating method was selected as one of the most likely and viable options for a more rapid heating process. Convectively heating the tools is the process currently used at Quatro Composites. By altering the process currently used, the heating time of the molds can be sped up.

Possible ways to improve the process lie in the oven used for the heating, as well as other pieces of equipment. By looking into parameters like airspeed and temperature in the oven, changes can be made to speed up the heating time. An additional possibility lies in the idea of multiple ovens for the tools. Having each tool preheated to a certain temperature, so that when it is ready to be used, a secondary oven can bring it to its final temperature in the goal time of about fifteen minutes.

Analysis for convective heating started with simplified two dimensional models in order to develop a base of analysis. From there, the model is being converted into a three dimensional finite difference model where different parameters can be changed in order to see results on a time dependent temperature curve. The idea is to see what variables have the largest effect on the heating rate, and see if the changes that would be required are feasible with the current ovens or would require additional equipment.

Currently, an accurate and functional three dimensional model (with simplified geometry) is nearly complete. With the coming months of gathering some empirical data, the model will be able to be compared to experimental results to check its functionality and reliability, along with helping with scaled analysis, using the small scale mold model.

CHAPTER 4: FINAL DESIGN

OVERALL DESIGN

In general, the system recommended to be implemented for Quatro composites is a full scale induction heating system. Multiple components come into play when compiling an inductive system, but each piece plays an important role in the success of the system. At its core though, the system comes down to a few major components: the power generation (power supply), energy transfer (induction coil), and cooling (water pump).

Power Supply

The power supply is where some of the most important success factors, power and frequency, are tuned. Power supplies generally come with a range rating of power and frequency. The difference is, frequency is often tuned in the generator inside, and not changed ‘on the fly’, whereas power can be altered during heating or by the user more easily. The ability to change either setting is not overly necessary for the application, as each tool will have an optimized parameter listing and heating cycle. Additionally, it is expected that each tool will likely operate at a single frequency, with varied power settings and heating times.

The power supply required would range from about 30kW to 50kW in power requirement for sufficient range to be able to power each different tool geometry that may be encountered. Frequency values would need to be tuned with a final vendor upon an order of system, but they would be low, near 5kHz. There is the option of

running the system at line frequency (60Hz), which would certainly offer a very slow wave and highly penetrative heat; whether or not that would be an optimum choice will require further testing and discussion with an induction distributor.

Induction Coil

The induction coil used in the heating system is the sole method of transferring energy to the work piece, and getting it perfect is essential to efficient and rapid heating. There is still a lot of unknown in the industry when it comes to number tuning and coil design. There are a small number of research facilities working on theories and formulas that can be applied, but there is not much yet as far as design equations.

The coil comes down to a few different parameters including: number of turns, inner coil diameter (ID), outer coil diameter (OD), coil height, and coil shape. The main goal for a coil is to have it as closely match the geometry of the part as possible. In this application for existing tool geometry, a square coil would be ideal so that it can closely wrap the entire tool. Number of turns, ID, OD, and height would all vary depending on the tool size. Most 'size ranges' would need their own custom coil, meaning, there isn't one single coil that can heat all different tool sizes equally. If it were tried, it could work, but energy transfer drops off exponentially as the distance between the coil and part increase. However, if most tools fit into an approximate 'small, medium, or large' category, a few coils could be designed to effectively fit a set of multiple tools, helping reduce cost and difficulty for system operation. Each tool would at a minimum likely have all 4 of its outside faces fully inside of the coil, ensuring maximum energy transfer, yielding the quickest temperature increase.

Currently, there a many people in the industry who have some very basic 'rules of thumb' about how to design a coil, but it often comes down to their personal instinct and experience, and varies from company to company. Most vendors are similar in the

fact that a lot of work will be done to create the ideal coil and test it to ensure customer satisfaction. The process often starts with an advised geometry test coil, which is tested with, and then altered as needed until the optimal geometry has been created. From there, the coil can be used indefinitely and retain a very good lifetime.

Cooling System

Every induction system operates at very high power, frequency, and temperatures. Aside from the heat generated within the coils, the heat the tool will be experiencing on the surface (1000+ F) can damage the coil and it requires a full time cooling system. Basically, water is pumped through the coils the entire time the system is running to ensure no damage to the coil or system. A cooling kit is generally an inclusive system, included in a quote for a system, and will contain a pump, reservoir, and plumbing kit, all specified for sufficient flow rate and heat removal (generally around 15gpm and 40,000Btu/hr, respectively).

COST ANALYSIS

A lot of cost related factors come into play with any new system, and especially with an induction system. A full system requires a lot of piece of new hardware that all have relatively large upfront costs. Aside from initial costs, there are operating costs as well that are worth considering and comparing to existing methods.

As far as energy costs go, induction brings the real potential to save. The power supply brings about the largest operating cost, especially one with a rating of 30+kW. However, the current convection oven used has ratings not much lower than that, with ratings in the low 20kW range. The cost is lower, and over time can add up, but to heat

just a single tool, that oven needs to be operating in steady state for over an hour, not to mention the time to heat it up each day (potentially multiple times a day). Meaning over a single day, it has 8+ hours of operation. With the induction power supply, it will only be cycled on a few minutes at a time, totaling maybe a couple hours a day. These energy savings will be significant. There are other components in the induction system that require measurable amount of energy, such as the water pump to cycle water through the coil, but the total operating costs will still remain lower we believe when compared to multiple ovens running all day.

The system itself, with all of its components will likely total well over $150,000 initial cost, but we would expect that cost to be paid off in a handful of years if ovens were to continue to be used.

SAFETY

One major benefit of induction heating is its safety, and is often used almost mainly for that reason, especially in field heating applications. When compared to an oven, an induction system is much safer. The coil is continuously cooled with water and cool to the touch when heating is complete, reducing risks of any incidents that may occur. With an oven, an attendant must wear a heat protective suit and equipment to open the oven and transport the tool. The attire is cumbersome, and the environment is still dangerous. With induction the tool can be moved and observed throughout the entire heating cycle with minimal equipment required.

MAINTENTANCE AND REPAIR

A system that may be implemented would not require much maintenance or repair at all. There would likely need to be some regular schedule for swapping out coils for different sized tools, but that training is done upon installation of the system and is easy to accomplish. Any issues that may come up regarding maintenance should be directed to the supplier of the product and/or manufacturer of the component in question.

CHAPTER 5: DESIGN VERIFICATION

Initial Induction Testing

Initial testing of a scale tool was performed with hopes to start developing a predictive model for heating of multiple geometries. In order to test with actual induction heating, Induction Technology Corp, ITC, of Adelanto, CA was generous enough to let us use their equipment and facilities for the day. We tested with a 'puck tool' provided by Quatro Composites, which could be modeled as an approximate 1/3 or 1/4 scale of actual tooling used. For testing, we had access to a single power supply that could not be greatly altered, meaning we had to operate at the frequency it was set to, approximately 2250Hz. It was estimated that we would want to operate this tool and larger, full scale tools, at much lower frequencies (<1kHz), but it was a test we still wanted to perform to get some physical numbers, rather than analytical. Multiple trials were performed at different power settings and all with different amounts of time that power was being applied. We learned there is a significant amount of time that needs to be allowed for the heat to 'soak' through. Basically, because of the thickness of this part or any other that may be larger, a lot of energy can be rapidly transferred into the tool, but finding the right amount is almost a game. If the tool was simply heated until

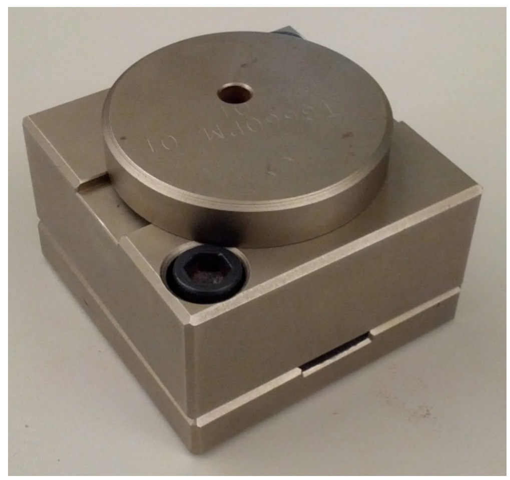

Figure 5: Puck Tool used in test heating

an internal thermocouple read the goal temperature, within seconds and for a continued amount of time, the energy from the outside of the part would continue to soak in and raise the temperature. This is due to the fact that right near the coil, the most efficient energy transfer will occur, and drops off severely as distance from coil increases.

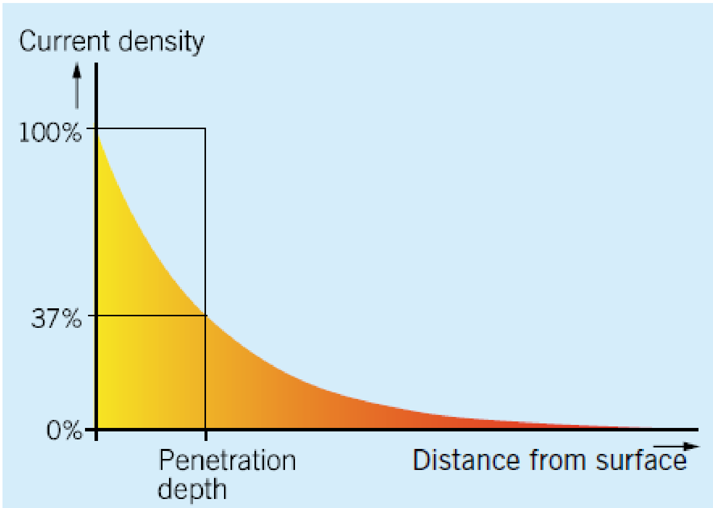

Figure 6. Illustration of depth of penetration for induction heating (Efd-induction)

The depth of penetration is distance from the surface of the heated object where the current density drops to 37%.

$$\delta = 1.98*(p/\mu*\omega)^{1/2} \text{ (Davies and Simpson)}$$

where δ = depth of penetration, p = resistivity, μ = permeability, and ω = frequency

Thus a lower frequency results in a deeper depth of penetration.

This issue can be reduced by tuning the frequency well. If the ideal frequency is found for each individual tool, the percentage of time that is needed for soak time of the heat will be reduced. With each test performed, we had a single thermocouple at the center of the tool, meant to model the mold surface of a full scale tool. We time how long it took for that point to reach between 700F and 750F, while noting when we killed the power through the coil. These trials are shown below on the plot comparing them all.

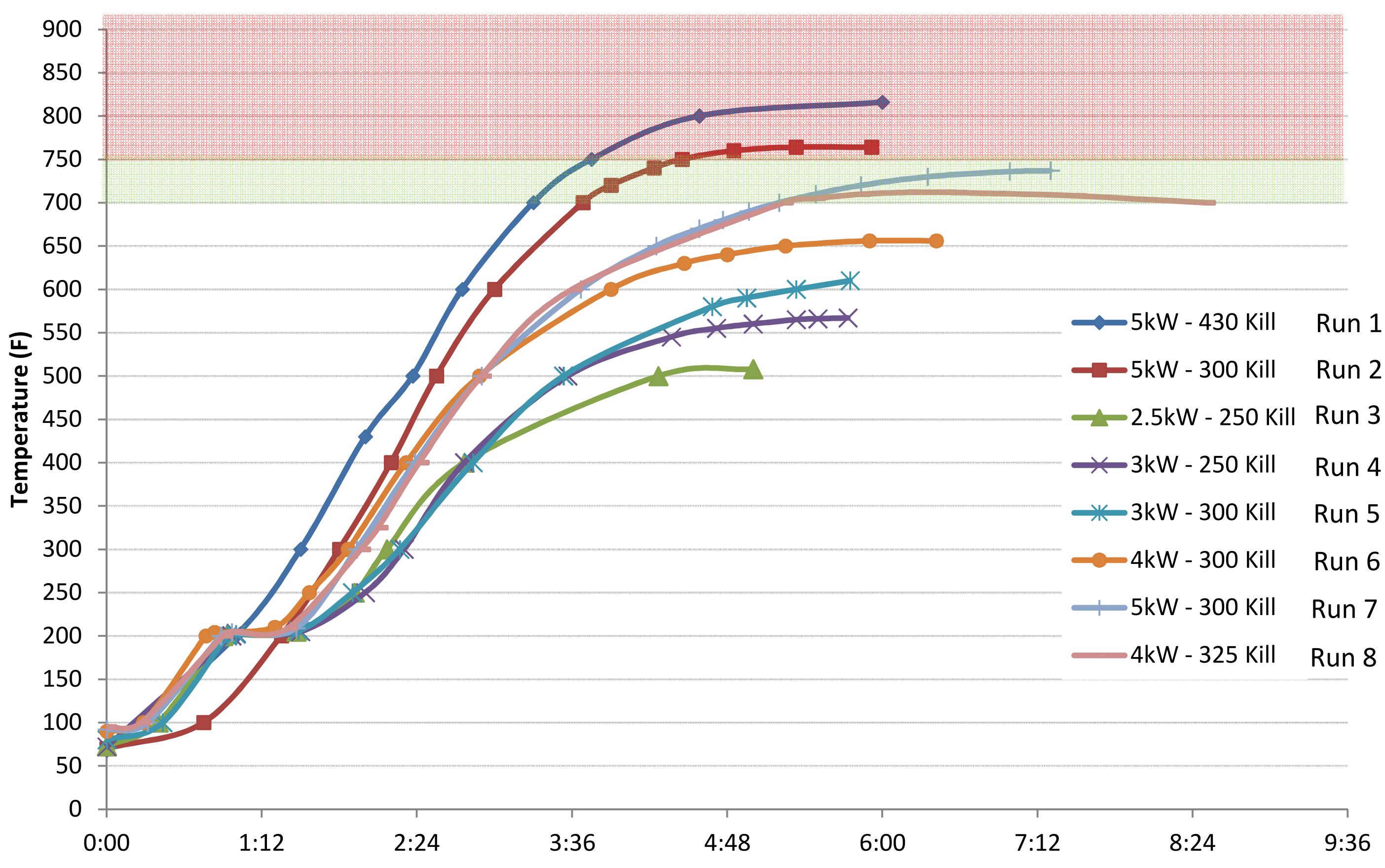

Figure 7: Induction testing with puck tool heating times and temperatures

Through our experiment it can be seen that a small change in parameters can have a large effect on the outcome. Each run shows the power used (kW) and the temperature at which we 'killed' power. We had two identical puck tools for testing, and the first test used one, and the second used the other. Starting in test three, we see a flat spot in the data around 200F. We concluded this to be from the fact that the tools were cooled in water, and right at the boiling point of water, the phase change occurred and caused a brief moment of no temperature change. Overall it did not have an effect on the final outcome. With each test, the power was killed around 3 minutes in, while reaching final temperature took an additional 4 minutes. That is not a negligible amount of time, but as stated, a more ideal frequency can reduce the ratio of power heating time to heat soak time. Our final two trials landed in the 'green zone' to represent being within the target temperature range.

Figure 8: Test setup showing puck tool inside coil

Figure 9: Visible heat patterns showing the concentration at the corners.

While heating we noticed a few different things physically about the process. The corners got very hot towards the end of the power cycles. When operating at 5kW and heating for more than a couple of minutes, we observed the corners to glow red or orange, and read in on an infrared thermometer at over 1000F. It is for this reason we continued to tune settings with less power and heating time. While it would not be catastrophic to hurt this tool relative to a full scale one, we want to

understand how to tune appropriately, and understand where limiting factors may occur. Too much heat on the outside and we may see a largely decreased tool life, especially when cycling thermal cycles through heating and cooling, and stress cycles when pressed and released. It leads to the recommendation that sharp corners be reduced as much as possible in future tools. We also noticed that the corners with bolt holes concentrated the heat much faster than those without holes. The thin walls created by the bolt holes caused a high heat concentration, much like a stress concentration. This was not something we had predicted due to simplified geometry models and is worth consideration in future tool design, to reduce thin features, especially close to the mold surface. We would like to further investigate the temperature difference in corners with and without bolt holes.

While this test can't give us a final idea what parameters we will need for larger scale tooling, it gives good indication to numbers to expect for soak time. This test was not performed in ideal conditions. As stated, a different frequency would be appropriate, but was not available to us at the time. Additionally, with a final design, a square coil would be the ideal coil geometry for the square tool to ensure maximum efficiency in energy transfer.

Final Induction Testing

Final induction testing was done using a 6-inch solid steel billet. Various holes were drilled and tapped so that thermocouples could be strategically placed to thermally map the billet. In Figure 1 below, thermocouples #1, #2, and #3 were placed 1 inch, 2 inches, and 3 inches from the outside edge of the cube, respectively. The depths of thermocouples

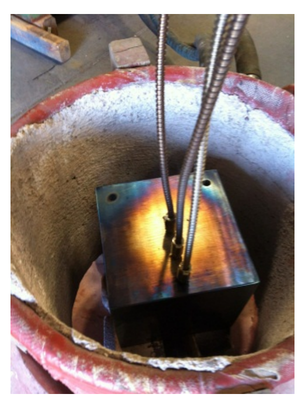

Figure 10: Test setup of 6" cube with visible surface heating concentrations and patterns

#1, #2, and #3 were 1 inch, 2 inches, and 3 inches from the surface, respectively. Additionally, a thermocouple were put in two different corners, one with a simulated bolt hole, and one without, in order to study the temperature difference with the thinner features created by the bolt holes.

The induction setup utilized a 12 inch diameter coil and a 50 kW power supply. For both runs, the frequency was set at 1750 Hz and 7.5 kW. Similarly to our first experimentation, a square coil was not available to us, but would have been ideal. Similarly, this coil did not tightly surround the tool, and that distance does reduce the efficiency of the process and increase the heating time.

Run 1

Schematic:

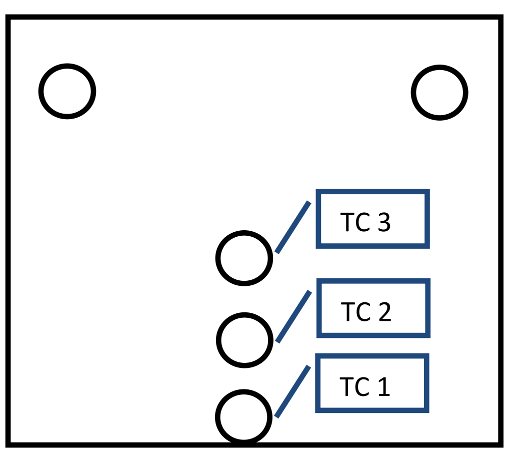

Figure 11. Thermocouple setup on the 6-inch billet for run 1

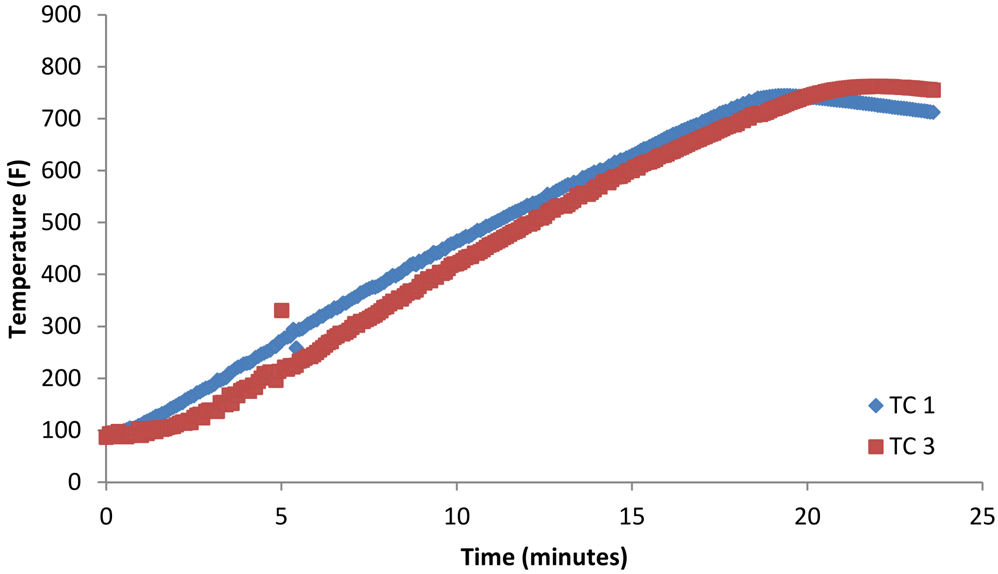

Figure 12. Thermocouple readouts for run 1

During run 1, thermocouple #2 gave faulty readings halfway through the test, and therefore was not included in Figure 12. However, thermocouples #1 and #3 gave accurate readings during the entire test. As shown in Figure 2, the average temperature difference between thermocouple #1 and #3 was approximately 38.2 °F during the heating cycle. After approximately 19 minutes the power was shut off, the heat was allowed to soak through the billet. It took approximately 1 minute for thermocouples #1 and #3 to reach equilibrium, and afterwards the temperature reading on thermocouple #3 continued to increase while thermocouple #1 decreased. Thermocouple #3 reached maximum temperature (762.2 °F) 3 minutes after the induction system's power was shut off before cooling down.

Run 2

Schematic:

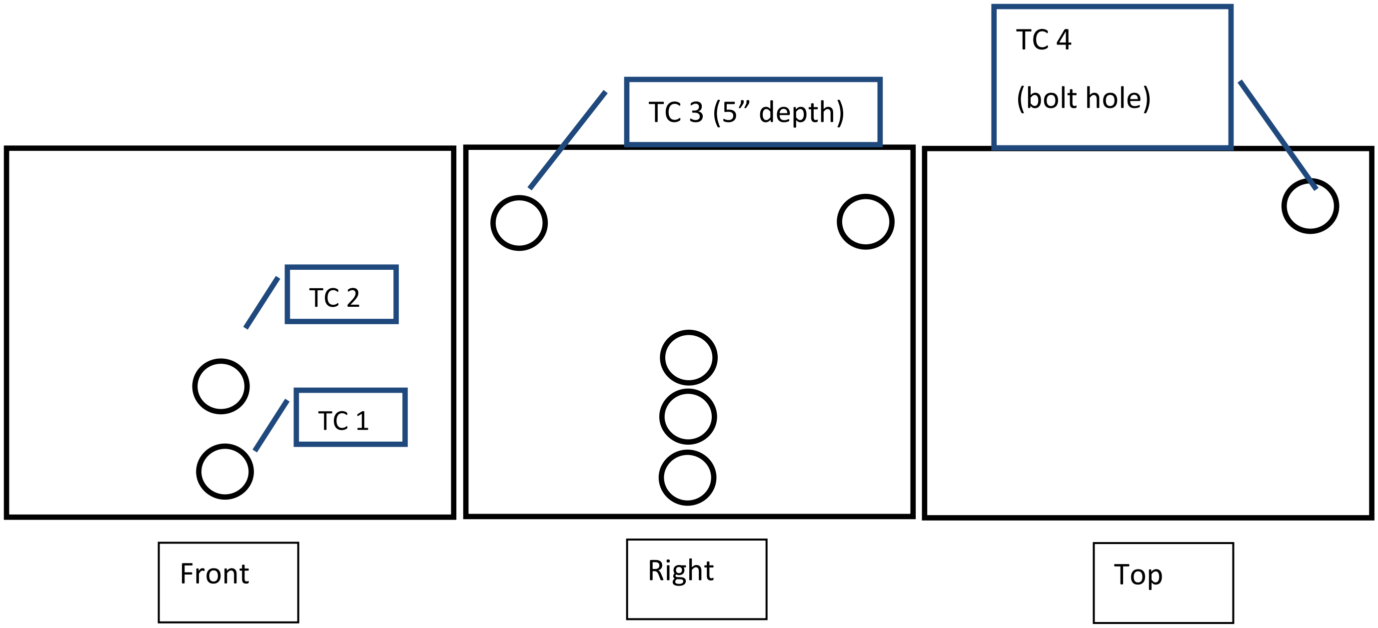

Figure 13. Thermocouple setup on the 6-inch billet for run 2

In Figure 13, thermocouples #1 and #2 were placed 1 inch and 2 inches away from the outside edge, respectively. The depths of thermocouples #1 and #2 were 1 inch and 2 inches from the surface, respectively. Thermocouples #3 and #4 were both placed 1 inch away from the outside edge. Thermocouple #3 was at a depth of 5 inches from the surface (1 inch from the edge) and thermocouple #4 was at a depth of 1 inch from the edge with a hole drilled perpendicular to it.

The main purpose of run 2 was to compare thermocouples #3 and #4 to see the effects of a bolt hole near the edge of the billet. From initial testing on the puck tool, the thin-walled bolt hole areas were red hot compared to the edges without bolt holes. The goal was to quantitatively observe the effects that a bolt hole has on the billet's temperature.

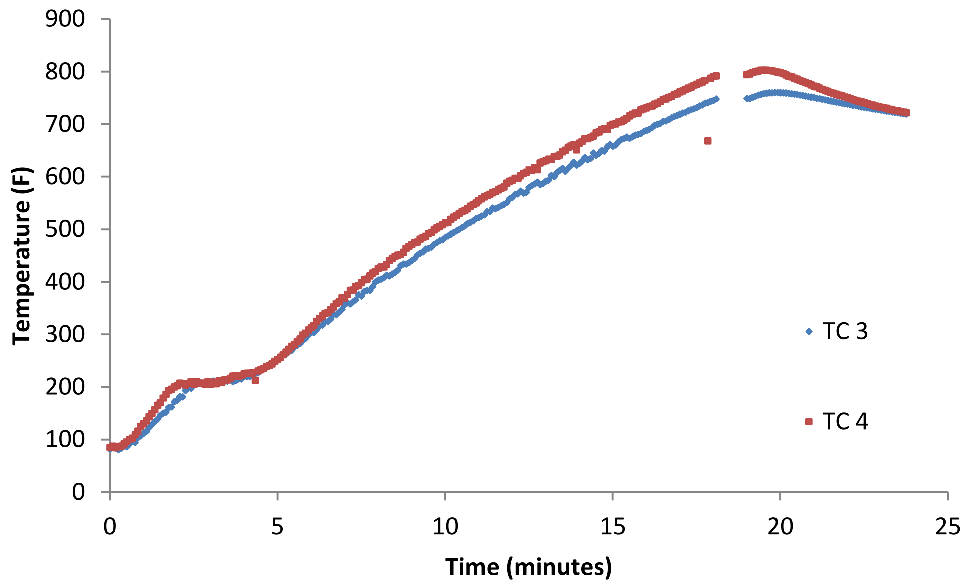

Figure 14. Thermocouple readouts for run 2

As shown in Figure 14, the average temperature difference between thermocouples #3 and #4 was approximately 25 °F during the heat cycle. This test shows that there is a quantifiable temperature difference between areas that have bolt holes and areas that do not. The discontinuity in Figure 3 is from the thermocouple wires being temporarily disconnected when the data logger was moved.

Testing Conclusions

From experimental testing at ITC for both the puck tool and the 6-inch steel billet, induction proved to be a viable option for Quatro to pursue to rapidly heat their steel molds. Even under non-ideal setups for both tools, induction rapidly heated up the steel test tools to target temperature. With custom optimization of frequency, power input, and coil size for each of Quatro's tools, the heating results will be better in terms of heating time and temperature distribution.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Throughout all of the research and studies, induction heating has proved quite well that it is worth serious consideration for implementation in this application. We ultimately conclude that induction heating should play a part in the future of this mold heating process and will greatly increase the production capabilities of the company, allowing larger contracts, and future growth. Ultimately, with the ability to heat, even larger tools, in approximately 20 minutes, production could see a great increase (3, 4, or even more times larger in a day), which makes this system instantly worth it. With this system we do offer certain suggestions, concerns, and visions all for consideration in future use of this technology.

When it comes to actual tool geometry, how the tool is designed can have an effect on the heating time and efficiency. We recommend to round out any corners as much as possible, essentially try to make it as close to a cylinder shape as possible. The cylindrical shape offers the best energy transfer properties and does not see the high heat concentrations that were seen in the corners of the cubes. Additionally, because these tools are multiple pieces in order to make de-molding possible, keep fastening holes as far away from the mold surface as possible. These holes create thin features and those areas see a high heat concentration during heating. Near the outer surface of the tools this should pose no issue, but it could cause a temperature differential internal to the part and create non-uniform heating. Make the tools as symmetric as possible. The internal cavities will be complex and asymmetric, but locate it as central to the tool as possible, and keep the geometry and features surrounding the cavity as symmetric as possible in order to help ensure a consistent temperature across the entire cavity wall. The main concern with this system is the inconsistencies in heating patterns that may be seen. Because of the way it is heated, one side of the cavity inside the tool may see more heat than another. This poses an issue if that side of the mold exceeded an

allowable temperature range, but this can be eliminated with the initial tuning of the system and heat cycle. The heating cycle will be defined upon order of the system, and can ensure that the tool gets to the minimum temperature, but no single part of the cavity exceeds a maximum temperature. Ideally, a tool could be placed into a coil in any orientation (meaning, there does not need to be a "top" or "right side"), but if certain tool geometry has the potential to create too large of a temperature difference, and it is tuned in a certain orientation, it may be necessary to have a consistent orientation each time. Overall, it would likely be worth it to have all variables, including orientation, be consistent each and every time, to ensure consistent and acceptable results with the minimum amount of inconsistencies between parts.

We do have remaining experimentation thoughts that may prove useful if more information is desired before purchasing anything. It would likely be worth doing a day of full scale testing, with at least the modular test tool used in our second testing day using a test coil more accurate to what a final coil may look like. It would also be nice to be able to actually tune a full scale tool for power and frequency as if it were a final process, to get more 'exact' numbers for heating time and cost estimates. Through our experimentation, we are comfortable suggesting the approximate cost analyses, parameter settings and heating times.

There is a lot of emerging technology in the field of controlled heating, and even for that of an application similar to this (compression mold heating). There are 'advanced' areas that may be interesting to explore further than we were able to. Those include the ideas of multi-material tools. That could mean a mold surface lined with a material that responds well to induction heating, and a tool constructed of a material that does not absorb the energy through inductive heating. This would completely eliminate the long heating times as only the surface would need to be heated. With this comes the issue of the distance between the volume to be heated and the coil. It would likely prove very inefficient at that distance. This could be

combated with heating sources somehow internally mounted into the tool, to locally heat the mold surface. Additionally, a more material science based approach could be one of having a sealed layer of a certain material (that would need to be determined) that either has a phase change or ceases to heat at a certain temperature. The idea is that there would need to be less 'control' over the heating, to not have to wait as long for the 'soak time' of the heat. Certain materials cease to heat very rapidly or efficiently at all at a certain temperature due to their magnetic properties, at lease while inductively heated. If a material could be found or some sort of alloy created that has this property around 700F, then it could see great benefits. There is certainly a lot to explore when it comes to experimental processes that could revolutionize this type of molding, but, the reason we ultimately focused on induction was due to its history and community. As a controlled heating method it is still relatively new, but it has proven to be a very viable and consistent process, perfect for this application.

While investigating this technology and how it could be applied to Quatro Composites, we have had various visions for potential layouts of this system and how it could greatly help the production process. After seeing and learning of the existing process, it seems as though it could greatly benefit from more automation, and ease of interaction. One of the largest burdens on the process is the tool itself, being so heavy, it is difficult and slow to move from one place to another. How we could envision this system working is an adaptive, modular, and 'station' based system. An assembly line style is what seems to make sense, made up of roller or belt tables, eliminating the need for human lifting or moving of the tool. All tools could be stationed at the beginning and ready for use at any moment. The path a tool would follow would be one of moving from one workstation to the next, each where a different process happens. Immediately, a tool could be disassembled and prepped for molding, and a charge of material added. It could then be moved to a heating station, where an induction coil could be simply lowered or placed around the tool, and when clear, the attendant could

start the heating process, with a preset for each tool type. Because different geometries require different coils, each day would need a setup of the system. Coils can be relatively simply interchanged, and depending on the power supply purchased, 2, 3, or more coils can be attached, and in certain circumstances, even heat simultaneously. With this being the case, at the beginning of the day or week, the line can be set up for whatever parts will need to be made that day or week (assuming one day does not see multiple different tools). Once the part(s) is heated, the attendant, with gloves, can push the part into the following stations of pressing and cooling. Here is where a future thought of automation may be considered, to increase safety regarding the tool being hot. A benefit of this though, is that the tool is the only thing hot after this process, the equipment is all continuously water cooled and cool to the touch after the process is complete. When it comes to the press and cooling stations, after seeing the process used, we would recommend further research and project time into improvements. We think that tool geometry could be altered to help cooling without inhibiting heating; in addition, the cooling process [water cooled platens in the press] could be improved and sped up. After the whole process is complete, the tools can offload into a de-molding station, and can be cycled right back to the beginning of the line. This is one idea of how induction heating could work for Quatro Composites, but we believe it is at least a direction viable of consideration to vastly speed up the overall process, and significantly improve production rates.

We do believe upgraded technology with induction heating will prove to be the future of this process at Quatro Composites, and will bring great improvements to the company.

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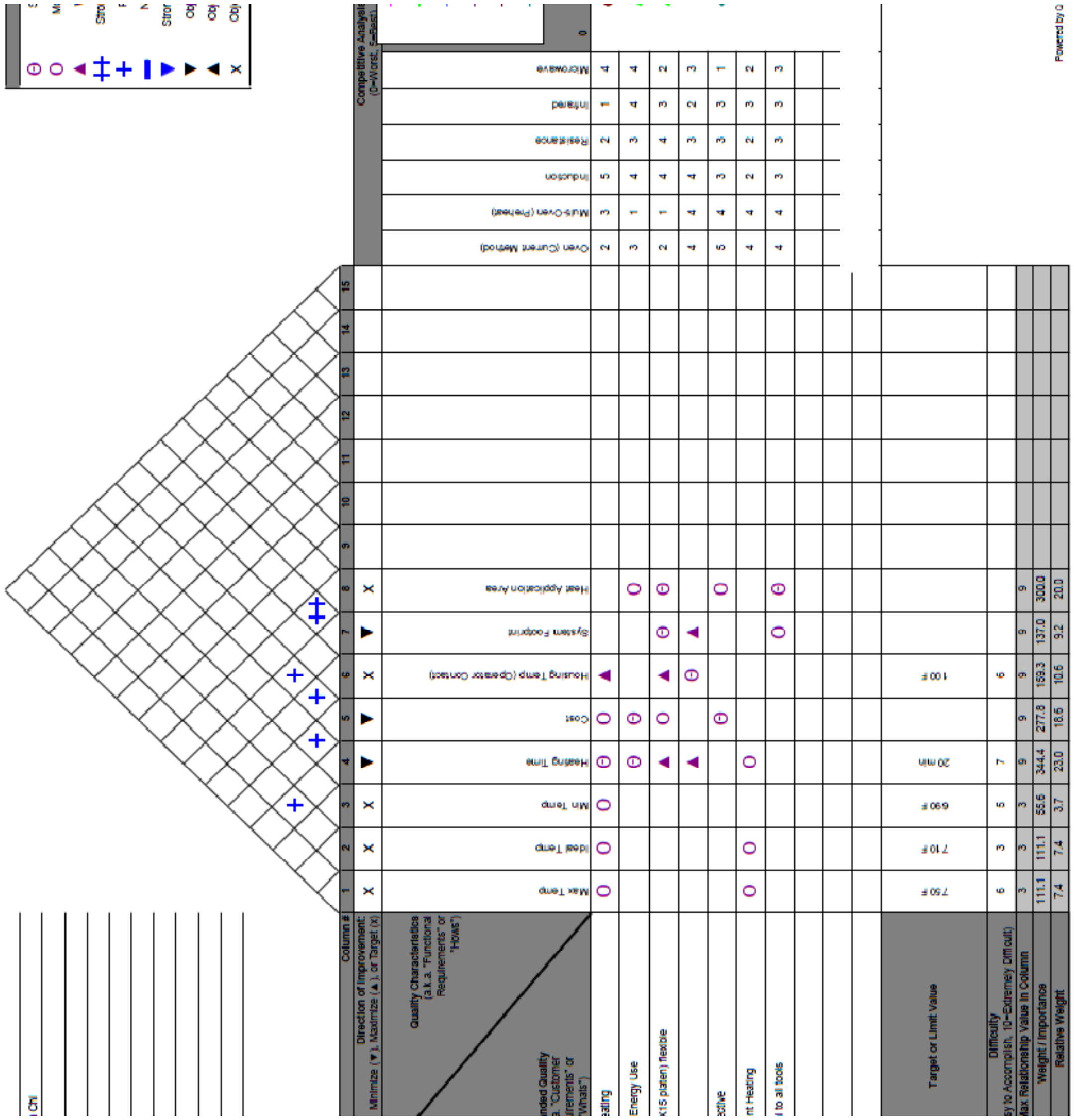
APPENDIX A: QFD



APPENDIX B: DRAWING PACKET

APPENDIX C: SYSTEM QUOTE

AMBRELL®
An AMERITHERM Company

39 Main Street
Scottsville, NY 14546
Phone 585-889-9000
Fax 585-889-4030

Proposal

Valid for 60 Days *

Proposal #	32842
Date	2013-02-08

Estimated Lead Time:

10 to 12 weeks

Payment Terms:

40% with order, bal net 30

Rep Info

Ameritherm Inc.
Win Ballou
12335 Oahu Street
Victorville, CA 92392
USA

wballou@ambrell.com
Phone: 1.760.948.6388
Fax: +1.760.948.6388

Proposed To:

Bobby Dodge
IME Dept. Cal Poly State University
1 Grand Ave
San Luis Obispo, CA 93407

dodge.bobby@gmail.com
Phone: (805)756-1114
Fax:

Item #	Qty	Part Number	Product	Unit Price	Ext. Price
1	1	300-0904	EKOHEAT 20/10 solid state induction power supply, CE rated 432mm wide, 711mm deep, 732mm high (17.0" wide, 28.0" deep, 30.0" high) Water-cooled, requires external heat station Input: 360-440 or 440-520 VAC, 3 phase Output: 20 kW terminal, 5-15 kHz Weight: 32 kg (70 pounds) VOLTAGE RANGE MUST BE SPECIFIED PRIOR TO SHIPPING	$21,170.00	$21,170.00
2	1	301-0325	Remote Heat Station, EKOHEAT 305mm wide x 610mm high x 762mm long (12" wide x 24" high x 30" long) (1) 53.6 uF oil filled tapable capacitor 53.6 uF max at 800 Vrms, 2130 kVAr @ 10 kHz Specify test coil 018-2388 separately non-Triax RF cables called out separately	$13,500.00	$13,500.00
3	1	010-0764	RF/sense cable assembly, EKOHEAT, 15 feet (uses raw cable 011-0112), includes RF and sense leads Price included with workhead	$0.00	$0.00
4	1	018-2388	Test coil, 7 turn, 7.0" ID, 8.20" high, 5.30 uH, large bypass blocks, price included with workhead	$1,195.00	$1,195.00
5	1	018-yyyy	Custom water-cooled work coil, multi turn helical to heat a steel die, 120 pounds to 750F within 20 minutes. Please Note: The customer technical contact will receive a coil approval packet from Ambrell. A response is requested within three (3) days in order to meet your ship date. If the customer response is extended beyond three (3) days, Ambrell reserves the right to extend the equipment ship date.	$6,895.00	$6,895.00

Item #	Qty	Part Number	Product	Unit Price	Ext. Price
6	1	052-0235	WV3000, 12.0 kW, non-CE 34.0" wide, 37.0" long, 70.0" high Air cooled, horizontal & vertical air discharge Input: 396-484 VAC, 60 Hz, 3 phase, 17.5 AAC Heat Removal: 40,980 BTU/hr (12.0 kW) (60 Hz)@ 50-95 degrees F ambient, 70 degrees F Leaving Fluid Temp. Flow Rate: 15.0 gpm @ 50 psi (60 Hz) 36 gal reservoir approx. empty weight 570 lbs. (259 kgms) Flow rate and heat removal derate 17% at 50 Hz	$8,705.00	$8,705.00
7	1	064-yyyy	Plumbing kit, price included with chiller	$0.00	$0.00
8	1	CRATING1	Crating and handling charge, for EKOHEAT bench top (20 to 50 kW) systems. Does not include shipping cost, which is normally best way PP&A (prepay and add) unless customer specifies a carrier and provides an account number. Product cannot be shipped freight collect without the account number.	$150.00	$150.00
9	1	STARTUP	Start-up assistance and technical support, 1 day (8 hours maximum) on-site, customer is responsible for all travel and living expenses. Additional time charged at $200.00 per hour.	$1,600.00	$1,600.00

Total: $53,215.00

This proposal is subject to Ambrell's Terms and Conditions of Sale, accompanying this proposal and incorporated herein by reference.
*** Lead times are subject to change based on availability at time of order.**

Customers in CA, CT and NY are subject to Sales Tax. If your purchase is exempt, please provide appropriate documentation with purchase order.

NOTE 1) LSR S5997 CO.

Commodities, technology or software exported from the United States must be in compliance with Export Administration Regulations. Diversion contrary to U.S. law is prohibited.

APPENDIX D: GANTT CHART