Investigation of Integrally-Heated Tooling and
Thermal Modeling Methodologies For the Rapid Cure
of Aerospace Composites

by

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Submitted to the Department of Mechanical Engineering and the MIT Sloan School of
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Abstract

Carbon Fiber Reinforced Polymer (CFRP) composite manufacturing requires the CFRP part on the associated tool to be heated, cured, and cooled via a prescribed thermal profile. Current methods use large fixed structures such as ovens and autoclaves to perform this process step; however heating these large structures takes significant amounts of energy and time. Further, these methods cannot control for different thermal requirements across a more complex or integrated composite structure.

This project focused on the below objectives and approaches:

- Gather baseline energy and performance data on ovens and autoclaves to compare with estimations of new technologies

- Determine feasibility, applicability, and preliminary thermal performance of proposed heated tooling technologies on certain part families via heat transfer analyses.

The project yielded the below results and conclusions:

- Proved the capability of the modeling software to mimic an oven cure with less than 3% error in maximum exothermic temperature prediction

- Provided guidelines on when to use 1D, 2D, and 3D heat transfer analyses based on part thickness

- Concluded which size/shape of parts would work best for the single sided integral heating technologies

- Calculated energy intensity of incumbent technologies for comparison of future experiments on integrally heated tooling

Overall, this project helped steer the team into the next phase of their research of the technology and its applications. It provided recommendations on what type of parts the technology can be used as well as quantified the energy intensity of incumbents for comparison.
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Contents

1 Introduction 17
  1.1 Discussion, Problem Statement, and Hypothesis 17
  1.2 The Voice of the Customer: The Airline Industry 18
  1.3 The Aircraft Manufacturer’s Response to Customer Needs 19
  1.4 The Aircraft Manufacturer’s Response to Competition 20

2 Background 22
  2.1 Composite Manufacturing 22
    2.1.1 Materials 22
    2.1.2 Prepreg Carbon Fiber-Reinforced Polymer Fabrication 23
    2.1.3 Resin Infused CFRP Manufacturing 29
  2.2 Conclusion 31

3 Literature Review 32
  3.1 Energy Usage in Composite Manufacturing 32
    3.1.1 Life Cycle Analyses 33
    3.1.2 Conclusion 35
  3.2 Integrally Heated Tooling for Composite Manufacturing 35
    3.2.1 Conclusion 38
  3.3 Heat Transfer in CFRP Composites 38
    3.3.1 Discussion 38
    3.3.2 Material Characterization 39
    3.3.3 Coefficient of Thermal Expansion 39
6.2 Capital Costs

6.2.1 Material Costs

6.2.2 Controller Costs

6.2.3 Engineering Costs

6.2.4 Installation and Commissioning Costs

6.2.5 Incumbent Costs

6.2.6 Incumbent vs Integral Heating

6.2.7 Rate Tools and High-Rate Production

6.3 Reliability

6.3.1 Conclusion

6.4 Support and Safety Systems

6.5 Conclusion

7 Conclusions and Recommendations

7.1 Conclusions and Recommendations for Future Initiatives
List of Figures

2-1 CFRP Example Fabrication Process Flow .......................................... 24
2-2 Example of Ultrasonic Cutting of Roll Material ................................. 25
2-3 Basic Diagram of an Autoclave ...................................................... 28

3-1 Quickstep Diagram of Technology [48] .............................................. 36
3-2 QPoint Photo of Technology [47] ................................................ 37

4-1 Nitrogen Pressure Response During a Cure ........................................ 51
4-2 Breakdown of Energy Use for Autoclaves of Different Types ............... 57
4-3 Simple Diagram of Power Usage During a Cure .................................. 59

5-1 Diagram of Oven Data Validation ...................................................... 65
5-2 Diagram of Air Flow Over a Skin Tool .............................................. 65
5-3 Model vs Experimental at 15 Points in Laminate ................................. 69
5-4 Oven Data Validation Full Results .................................................. 70
5-5 Oven Simulation - Mid Laminate of Thickest Portion .......................... 71
5-6 Typical Resin Infusion Temperature Profile ...................................... 72
5-7 Generic 1D Single-Sided Heating Model Diagram .............................. 73
5-8 Generic 2D Single-Sided Heating Model Diagram .............................. 74
5-9 Maximum Temperature in a Skin Laminate for 1D, 2D, and 3D Models ... 75
5-10 Error of Maximum Temperature from 1D and 2D Models Compared to 3D
     Model ......................................................................................... 77
5-11 1D, 2D, and 3D prediction of Exotherm on Skin Part .......................... 78
5-12 Profile of a Rib and Tool .............................................................. 80
<table>
<thead>
<tr>
<th>Page</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-13</td>
<td>Rib Tool Output</td>
<td>80</td>
</tr>
<tr>
<td>5-14</td>
<td>Profile of a Spar and Tool</td>
<td>81</td>
</tr>
<tr>
<td>5-15</td>
<td>Spar Tool Output</td>
<td>82</td>
</tr>
<tr>
<td>5-16</td>
<td>Profile of a Skin and Tool</td>
<td>83</td>
</tr>
</tbody>
</table>
THIS PAGE INTENTIONALLY LEFT BLANK
List of Tables

3.1 Energy Intensity of Different CFRP from Witik et al. [67] ............... 34
3.2 Selection of Material Properties [34, 15, 29] .......................... 41
4.1 Regression Statistics .................................................. 49
4.2 Uncontrolled Pressure Response During an Example Cure ............... 51
4.3 Energy Intensity Ranges ............................................ 60
5.1 Relative computational time for an average desktop computer ............ 63
6.1 Tooling Area, Complexity vs Channels Needed .......................... 91
Chapter 1

Introduction

1.1 Discussion, Problem Statement, and Hypothesis

Major aircraft manufacturers have seen significant growth in their backlog of orders for new aircraft in recent years. This has come not only from emerging markets and new state-owned airline expansion, but from legacy carriers upgrading ageing fleets [63]. Competition between Airbus and Boeing for market share has also driven down the purchase price of new aircraft [22, 37]. This has put the pressure on Airbus and Boeing to not only produce more aircraft per year to keep up with demand, but to cut costs at the same time.

To make matters more difficult, the customer is also demanding more fuel efficient aircraft. One response to this need from manufacturers is to use advanced aerospace composites in their new generation of aircraft.

The problem faced by aircraft manufacturers is how to produce composites at faster rates, with lower cost and higher thermal precision. One option proposed and investigated in this paper is to use integrally heated tooling to cure resin infused carbon fiber-reinforced polymer (CFRP) composites instead of using the conventional oven or autoclave.

This could potentially provide energy savings through thermal mass reduction, and improve cure precision by bringing the heat source closer to the part needing the heat with local active temperature control. This active temperature control could then enable faster cure times and thus higher throughput.

This paper investigates how different resin infused composite part families would perform
in a cure if cured with a single-sided integrally heated tooling versus an oven. This paper also provides energy usage context of the incumbent oven and autoclave technologies for comparison for future experimentation of this technology.

This paper hypothesizes that integrally heated tooling would enable faster cure rates with better thermal uniformity for the part families investigated. It is also hypothesized that although 3D modeling will give the most accurate thermal model, 1D or 2D models would suffice for thinner laminates.

1.2 The Voice of the Customer: The Airline Industry

The US airline industry has struggled to make sustained profit over the past few decades [46], with even the profitable years still yielding very thin margins. Reasons for this are well researched and debated; but one need not look further than fuel prices as the most significant driver to airlines’ bottom line. The International Air Transport Association cites that 30% of airline costs are for jet fuel [24]. As a response, the major aircraft manufacturers like Boeing and Airbus have tried to focus on fuel efficiency in their next generation of aircraft. This has been accomplished via many different initiatives such as weight reduction and engine design. One of the simplest ways to reduce fuel burn (in principle) is to reduce aircraft weight. Boeing utilized advanced aerospace composites extensively in the innovative 787 aircraft, saving roughly 20% in weight over what the design would have weighed if built from aluminum [21]. Some airlines have even gone to unprecedented lengths to control fuel costs. Delta Airlines bought an ageing jet fuel refinery to help better control its jet fuel costs [36]. Every dollar saved in jet fuel for an airline is a dollar they can invest more wisely in other places, such as new aircraft.

Other pressures for many legacy carriers is the need to replace ageing, fuel-inefficient aircraft with new fuel-efficient models. This is not only a cost pressure, but a temporal pressure. The sooner they can receive the new aircraft, the quicker they can start saving in fuel and maintenance costs (and thus have a cost advantage to competitors if they can take delivery sooner). One high profile example of this is the recent switch by the US legacy carrier Delta who canceled $6B worth of new 787 orders, citing that Airbus could provide
them new airplanes sooner than Boeing [17].

More state-owned and international airlines and low cost carriers (LCC’s) are also creating stiff competition on long haul flights for incumbents [12]. They are trying to dip into the more profitable long haul market, but their advantage on administrative costs and labor rates don’t translate as easily to long haul flights, where fuel contributes a larger chunk of total operating costs [1]. So one way they can edge into the market is by getting the more fuel efficient aircraft like the Boeing 787 and Airbus’ A350 before competitors. These examples clearly show that customers are wanting more plane for less money and they want delivery of the new aircraft as soon as possible.

1.3 The Aircraft Manufacturer’s Response to Customer Needs

The aforementioned challenges faced by customers have led to a significant response by manufacturers. Boeing’s new 787 aircraft family and Airbus’s A350 are saving (or poised to) save airlines significant fuel costs. In addition, changes and redesigns to existing families like the Boeing 777X, the Airbus A320neo and the Boeing 737MAX are all answers to this increasing cost pressure on the global airline industry. Design changes, however don’t fully solve the problems of the customer. The cost of the new plane itself also has a huge impact on airline’s profitability, so any and every decrease in cost of manufacturing is crucial not only for the customer, but for the manufacturer’s profitability as well. Steep discounts given to airlines for bulk orders are putting downward pressure on costs to ensure profitability even at the discounted price [22, 37].

Aircraft manufacturers are also increasing rates to keep up with demand and deliver planes to the customer sooner. Boeing is increasing its 737 line to 52 airplanes per month (up from 42) by 2018, while Airbus is increasing the A320 production rate to 46 airplanes per month [53]. Boeing’s 787 production has already increased 30% to 10 aircraft per month, but has plans to increase another 40% to 14 per month by the end of the decade [52]. It is apparent then, that aircraft manufacturers are not only facing cost pressure from customers,
but also time pressure. This means they need to decrease cycle times and total costs of manufacturing at the same time to meet demand.

1.4 The Aircraft Manufacturer’s Response to Competition

The customer isn’t the only stakeholder that is affecting commercial aircraft manufacturers’ decisions on investment, production, and R&D, however. Competition is coming not only from the emerging market, such as China’s rapidly growing aircraft company, Comac [27], but also from below. Bombardier and Embraer are starting to try and crack the lower end of the 100-240 seat single-aisle airplane market. Historically they have stayed in the smaller regional and private jet market, but see potential for growth in the 100-149 seat market [42].

This adds pressure for both Airbus and Boeing to innovate in their small single-aisle airplanes such as the 737 and the A320. Boeing, cognizant of the threat from Embraer, Bombardier, and Comac, has plans to create a new single aisle aircraft by 2030 made of composites, to stay ahead of the competition [42]. This completely new design would “replace the 737MAX” which is Boeing’s already fuel efficient, but aluminum, single aisle workhorse [42].

To fully replace the 737MAX, one would expect the need to maintain the same high rates of production to keep up with customer demand. High production rates on a composite aircraft, however will pose many challenges. Technological, material, and process improvements will be necessary to not only increase current production of the 787 composite aircraft to 14 per month, but certainly for a future composite aircraft delivered at rates similar to those of the the 737 and A320.

Further, inevitable cost pressures from a Chinese competitor will force companies like Boeing and Airbus to find ever more efficiency gains in their supply chains and manufacturing lines to decrease the costs of production. The aircraft industry is moving toward the use of more complex and integrated advanced aerospace composite structures in the aircraft. This in turn, means that cutting cost and cycle time in the composite fabrication process will be
paramount to staying competitive globally.
Chapter 2

Background

2.1 Composite Manufacturing

2.1.1 Materials

A composite material is defined roughly as “a solid material which is composed of two or more substances having different physical characteristics and in which each substance retains its identity while contributing desirable properties to the whole.” [11] Common examples of composite materials are concrete (stones and cement) reinforced concrete (rebar and concrete), plywood (wood and glue), and of course carbon-fiber and glass-fiber reinforced plastics. Composites are used in a wide variety of industries and most commonly in civil construction, aerospace, and energy. In the case of aerospace, and specifically commercial aircraft, carbon-fiber and glass-fiber reinforced composites have been used extensively and (as stated previously) are growing in their use.

For the case of this study, carbon fiber-reinforced polymer composite (CFRP) parts will be discussed. There are two main formats that the carbon fiber material comes in from a supplier (the manufacture of the raw material and resin will not be covered): carbon fiber that is pre-impregnated with a resin matrix and partially cured (prepreg), and dry carbon fiber (no resin). The majority of material purchased in the global market is the pre-impregnated material [54], but dry fiber is growing in use.

Raw carbon fiber material can come in many different formats. The fibers can be short,
discontinuous fibers in random orientation, or long, continuous fibers in long unidirectional strands. The material can also come in woven patterns similar to other standard fabrics. The orientations of the woven fibers to one another (0°, 45°, 90°, etc.) is dependent on the final product's desired strength in each direction. Where traditional steel and aluminum materials are isotropic (their strength is essentially the same in any direction), carbon fibers are anisotropic. The strength in the longitudinal direction of a carbon fiber is much higher than in the radial direction [34].

Material originating from individual carbon fibers can come in many different formats. From thin individual fiber tows, to flat rolls of tape (fractions of an inch to a few inches across), or full sheets that usually come in rolls (3 feet across or so).

Each thin sheet of woven fabric or unidirectional fibers is called a ply. Fiber orientations in each ply as well as the stacking order and orientation of each ply can be tailored to achieve specific physical and mechanical properties [34] of the final part. These properties can be achieved by a woven material tailored with fibers in the desired orientations, or unidirectional sheets stacked in the quantities and directions needed to achieve the desired strength properties. In any case, the basics of different carbon fiber materials, their properties, and how they stack to become carbon fiber laminates is widely published, and can be found in Mallick's 2008 book "Fiber Reinforced Composites" [34].

For this case, dry woven carbon fiber fabric and unidirectional prepreg rolls will be discussed. Hand layup from roll stock material will be the process investigated. Although there are many new and exciting materials and methods for layup, this study is restricted to these materials and technologies.

2.1.2 Prepreg Carbon Fiber-Reinforced Polymer Fabrication

The basic flow for the fabrication of a part from prepreg material is shown in Figure 2-1.

Cutting

If the material comes in a roll, it needs to be cut into the desired shapes needed to stack and build up the part. This is usually done with automated ultrasonic cutters that have the
2D cut shapes and orientations on the material pre-programmed. The layout of these thin fabric shapes (called plies) on the bulk fabric is optimized to reduce waste of the material. Then, these cutout shapes are removed from the bulk material and readied for the next step which is layup.

Figure 2-2: Example of Ultrasonic Cutting of Roll Material

Layup

Automated Fiber Placement and Automated Tape Layup are two examples of advanced layup methods that are gaining in popularity for prepreg materials. These two technologies use fibers and/or tape for the material input. Hand-layup using rolls as the feed material, however, is still popular for many layups due to the high quality produced [34]. Hand-layup involves stacking and forming the shaped plies created during the cutting step in the proper order so as to produce the desired 3D final part. This is done on a forming tool in the shape of the final part. For hand-layups, the stacking and positioning of each ply is often done with a laser guided visual cue system that projects the outline of the expected ply on the proper location of the tool. This informs the operator which ply to put in which location.

For prepreg material, there are periodically “de-bulkling” steps. De-bulkling is done to remove any remaining air between plies, and is basically a compression of the plies. This
is done by pulling and maintaining a vacuum on the plies for a set period of time, or until a certain vacuum pressure is achieved and maintained. The vacuum is then removed, and layup is resumed. Because the plies stick to one another, the removal of the external vacuum doesn’t introduce air back in between the plies. This layup-debulking cycle is repeated periodically until all the plies are laid down and the final part with desired shape and thickness is created.

The final part is then covered in a vacuum bag and other “consumables” used to facilitate keeping the plies under vacuum. Pulling a vacuum on the system is important so the proper fiber-volume fraction can be achieved and also to prevent voids or pockets of air from being trapped inside of material. Voids can be stress-concentrators and weaken the overall strength of the material, so they are to be minimized as much as possible [33]. Sometimes facilities keep a vacuum on the plies overnight (most often for out-of-autoclave prepreg materials) which adds significant cycle time and energy usage to the layup [67].

**Autoclave Curing**

The autoclave cure step involves placing the laminate and tool in a pressure vessel and applying a temperature and pressure profile to transform the uncured prepreg material into a fully cured composite part or structure. The elevated temperature from ambient is needed for the resin to undergo a chemical reaction that turns it from a viscous liquid into the hard plastic end state required. The pressure, in the case of a prepreg material, is required to maintain a proper fiber volume fraction and to inhibit void formation to achieve the sufficient material properties [34]. The pressure and temperature profile required varies depending on the chemistry of the resin and the make up of the material itself.

The pressure in an autoclave can be assumed to be applied uniformly across the outer surfaces of the tool and part, however, the heat in an autoclave or oven is not quite uniform across a tool/part. The sheer size of an autoclave leads to a temperature gradient from top to bottom and front to back of the autoclave as it is heating up. For example, in a larger diameter autoclave, the warmer air will be near the top and the cooler air will be near the bottom until the autoclave reaches a steady state and temperatures can equalize. This can cause a problem if many parts are stacked in a large autoclave. The top parts may cure
differently than the ones near the bottom.

It is also important to note that the airflow travels from front to back of the autoclave. For wings and wing subcomponents, this means the portion of the wing near the circulation fan may have different heat transfer coefficients than the side near the door. P.F. Monaghan et al. shows that the convective heat transfer coefficient does not vary much through the length of an 8m autoclave, but acknowledges discrepancy with prior experiments [35].

The design of the autoclave can have significant effects on the overall heat transfer coefficient. If it is electrically heated, the band heaters are often in the walls of the autoclave, but if it is gas-fired, then the combustion chamber is outside of the autoclave and the warm air is then sent through a heat exchanger to interact with the pressurized atmosphere in the autoclave. Monaghan et al. suggest that having the electric heaters within the autoclave walls may increase the radiative component of the overall heat transfer coefficient [35].

One of the main drawbacks to an autoclave is the single zone heating approach, and this is a main contributor to the increased curing times. The thickest laminate is often the slowest to heat up and cool down during the curing process. No additional heat can be added to that portion of the part without adversely affecting the thinner portion of the laminate. Much of the part may have already been cured to specification, but the autoclave or oven still has to wait until that thickest part of the laminate reaches the set temperature for the specified amount of time.

Often, to determine where these leading and lagging portions of the tool and part are located, companies have to do repeated tests on the various tool and part families before full production. This is often an iterative process to determine which ramp rates, dwell times, and set pressures/temperatures yield the best quality part.

Typical cure times can range from 6-7 hours to over 12 hours. Because final material properties depend heavily on the temperature profile (and not just the set temperature), this profile is a very critical aspect of producing a quality part. The rate of temperature increase has a significant impact on the chemical reaction rate, and thus the final part integrity [34]. The cool down rate has an impact on the final mechanical integrity due to internal stresses introduced by cooling. This is discussed more in Chapter 3. One example of an autoclave cure profile is shown in Chapter 4.
Although Figure 2-3 shows only one tool in the autoclave, a cure in an autoclave typically involves a batch of tools, because of the relatively high cost of operation for each cure cycle and the long cure cycle time. Placing as many parts as will fit in the autoclave better utilizes the costs incurred during each cure. This does, however, increase set up time. Sometimes difficult and time-consuming stacking of heavy tooling needs to occur before loading into an autoclave. This adds cost and risk of damage to a tool.

Thermocouples are attached to each part/tool combination to monitor the temperature profile and ensure that each tool meets the specifications of the cure. The pressure is also monitored and controlled to ensure proper pressure is applied throughout the cure. These pressure and temperature set points differ depending on the material system used in the composite part.

Although industry has been trying to get out of the autoclave for decades, (to some success), autoclave cures and prepreg materials continue to dominate the aerospace composite fabrication landscape due the repeatable high quality of the process [40]. This is made evident recently by the fact that Boeing has decided to build some of the largest autoclaves in the world to make its new 777X fully composite wing [18].

Following the cure, the part is de-moulded from the tool and consumable parts such as the vacuum bag. It is then sent to quality and final assembly. This study will not discuss
the assembly process; but instead focuses on the fabrication and specifically the composite cure step.

2.1.3 Resin Infused CFRP Manufacturing

Resin Infusion is a process that is less commonly used than the traditional autoclave process. It is similar but has two distinctive differences. First, no external pressure is required during the cure. Second, the resin is not pre-impregnated into the carbon fiber material, but is introduced to the dry carbon fiber during the cure step. This introduces challenges and complexities to the cure, as now resin viscosity, infusion temperature, and resin supply pressure are all new variables that must be controlled during the cure. These all affect final part quality and can lead to a processing failure if not properly monitored and controlled. The basic flow for this study of the fabrication of a part from prepreg material is shown in Figure 2-1.

Cutting

The cutting step in resin infusion is very similar to that as discussed previously. It is important to note, however that because the carbon fiber is dry, when it is cut, the fibers fray more than prepreg material would. To combat the material fraying too much, there is often a very thin thermoplastic material (colloquially called a “veil”) that keeps the woven fibers together even after it is cut into the desired shapes.

Layup

For the resin infusion process, dry fiber is laid up. This means each ply won’t necessarily stick to the ply before it (because of the lack of tacky resin), and thus may not stay in place when laying down subsequent plies. Because of this, the veil is often used to temporarily tack the plies together before they are enclosed in the vacuum bag. This can be done simply with a soldering iron. The veil is a thermoplastic, and will melt together with the previous ply to temporarily keep it in place. This is done in a few spots only; just to maintain the position of the ply. The completed ply stack is then put under vacuum only when the layup
is complete. This saves significant time and energy in layup over a prepreg layup process because there is no need to debulk in the middle of the layup process nor is there a need for the final long (and sometimes overnight) debulk step after layup and before cure [67].

Curing

The cure step for resin infusion is the step that is most different from an autoclave prepreg cure step. The main difference, again, is the lack of pressure required on the laminate. This means the part can cure in an atmospheric industrial oven instead of a pressure vessel. Removing the need for pressure not only saves energy during the cure, but significant upfront capital costs [40, 67]. There are downsides to resin infusion such as poor dimensional control (due to one-sided tooling) [16].

As discussed previously, it is at this point where the resin is introduced into the carbon fiber reinforcement. This is accomplished in most cases with a “resin pot” external to the oven that maintains a control pressure to inject the resin into the layup (which itself is still under vacuum). Consumable materials placed during the layup provide a path for the resin to reach all portions of the part. The location and quantity of these “flow media” materials are often designed to reduce the time required for the resin to wet the entire part (and thus keep cycle time to a minimum). Excess resin is caught in an exit reservoir [43]. This is all done at elevated temperatures to provide the right viscosity for infusion. Once the resin has been infused into the part, the oven is then brought to cure temperature, per the prescribed thermal profile.

The typical shape for a resin infusion cure is shown in Figure 5-6 in Chapter 5. Note that there is the additional dwell and ramp used for the resin infusion portion of the cure. This is in contrast to the common single ramp and dwell period in an autoclave seen in Figure 4.2.2 in Chapter 4. Specifications for the ramp rates, dwell temperatures, part lead and lag temperatures, and part-tool temperature differential control all determine the resin infusion thermal profile. The part is then removed from the oven, de-bagged and sent to the assembly process.
2.2 Conclusion

Whether in an autoclave or an oven, the cure step is arguably the most important step in the manufacture of aerospace composites. Autoclaves are historically the most often used due to the consistent quality produced, but suffer from high capital and operating costs. Ovens require no pressure, have lower capital and operating costs, but the quality of the final part compared with an autoclave cure is still debated. The temperature and pressures required (or not required) for the cure of a CFRP vary depending on the material system; and their rates of change throughout the cure cycle have a very significant effect on the final part quality [34].
Chapter 3

Literature Review

This chapter describes findings in the literature that are relevant to the three main portions of this paper: Energy Analyses of CFRP Manufacturing, Existing Integrally Heated Tooling Technologies, and Process Modeling/Cure Simulation for CFRP Materials. For the Energy Analysis discussion in the first section of this chapter, data found in literature are presented for comparison with data produced in this paper on the energy intensity of the cure. In the second subsection of this chapter is an industry overview of current integrally heated tooling technologies to provide background on where industry is with regards to the types of technologies used. Finally, information on process modeling of the cure is presented for a better understanding of the maturity of the FEA simulation techniques, and the material characterizations used as inputs into these models.

3.1 Energy Usage in Composite Manufacturing

Data on the energy needed to turn raw fiber and resins into a fully cured and assembled part are present in the literature but somewhat limited. However, as recently as January 2015, there is a new push from the US Department of Energy’s Advanced Manufacturing Office (AMO), to reduce energy usage of advanced fiber-reinforced polymer composite manufacturing by 75%, reduce manufacturing costs by 50% and increase recyclability of these products to over 95% [41]. The energy used in manufacturing composites is gaining more and more attention.
3.1.1 Life Cycle Analyses

Life cycle analyses for different Fiber Reinforced Polymer Composites (FRP) have been conducted for widely disparate FRP materials, manufacturing processes, and end use applications. Although data exists for many different FRP manufacturing processes, multiple sources of data for comparison of each material and process were not found in the literature.

Suzuki and Takahashi from the University of Tokyo have provided one of the most complete estimations of energy usage for different CFRP manufacturing processes [59]. This is, however, a theoretical prediction of energy usage and not a direct measure. Song, Yeung, and Gutowski performed a lifecycle assessment on the pulltrusion process and compared it with values found in literature, including those from Suzuki and Takahashi. They showed that the highly automated process of pulltrusion was on the lower end of energy usage at approximately 3.1 MJ/kg in energy intensity, while on the high end was the autoclave process; estimated at 21.9 MJ/kg [56]. The vacuum assisted resin infusion process (the subject of this study), had an energy intensity value in the middle at 10.2 MJ/kg [59]. Note that these values only represent the manufacturing process and not the full life cycle analysis completed in the Song et al. paper.

Both analyses, however, conclude the same thing: the moulding and assembly process is not the most energy intensive process over the life of the material. Suzuki and Takahashi showed that the vast majority of the energy used to make a CFRP part was in the manufacturing of the raw fiber and resins [59]. Song et. al. also showed that for a pulltrusion process, the most energy usage to create a final part was in the primary production of the fibers and resin, not in the moulding and assembly processes [56].

Possibly the most recent and applicable study was conducted by Witik et al. in 2012. They compared a representative sized CFRP part and manufactured it using 5 different processes for fabrication [67]. They compared the traditional autoclave prepreg process, an out-of-autoclave prepreg process, microwave cured prepreg, oven resin infusion, and microwave resin infusion. They calculated the energy usage from that used to manufacture the raw material all the way through assembly. A summary of their findings of the energy intensity to manufacture their 400mm x 400mm x 4 mm part is shown in Table 3.1.
Table 3.1: Energy Intensity of Different CFRP from Witik et al. [67]

<table>
<thead>
<tr>
<th>Step</th>
<th>Autoclave Prepreg MJ/kg</th>
<th>OOA Prepreg MJ/kg</th>
<th>Microwave Prepreg MJ/kg</th>
<th>Oven Infusion Microwave Infusion MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impregnation</td>
<td>38.1</td>
<td>38.1</td>
<td>41.73</td>
<td>-</td>
</tr>
<tr>
<td>Weaving</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.1</td>
</tr>
<tr>
<td>Cutting</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>De-Bulking</td>
<td>-</td>
<td>17.9</td>
<td>19.6</td>
<td>-</td>
</tr>
<tr>
<td>Vacuum</td>
<td>4.9</td>
<td>7.9</td>
<td>7.4</td>
<td>4.70</td>
</tr>
<tr>
<td>Cure</td>
<td>139.8</td>
<td>40.4</td>
<td>58.9</td>
<td>32.9</td>
</tr>
<tr>
<td>Total</td>
<td>183.3</td>
<td>104.8</td>
<td>128.2</td>
<td>38.9</td>
</tr>
</tbody>
</table>

To derive these numbers from the Witik study, the weights of the fiber and resin reported in Table 3 in [67] were added and then the weight of cutting waste was subtracted to give the final mass of cured part. The weights were all around 1 kg for the size of part they fabricated. The kWh numbers reported in that table were then converted to MJ and divided by the kg of cured part.

Note that the autoclave energy intensity is much higher than reported in Song et al. [56]. Suzuki and Takahashi reported values in their research for an autoclave process in upwards of 600 MJ/kg [59]. This vast disparity in the literature is most likely due not only to material (fiber and resin type) differences, but to the wide array of autoclave sizes, designs, vintages, and loading procedures. For example, if an autoclave is only loaded with a few parts, then the energy intensity will be much greater than if it is filled with as many parts as possible; this is due to the batch process nature of an autoclave. The disparity in values is most likely due to assumptions in part loading and autoclave efficiency.

Further, the numbers for resin infusion from Witik et al. are also over 3 times higher than those reported in Suzuki and Takahashi. This is most likely due to Witik et al. reporting their values in secondary energy (or billed energy), while Suzuki and Takahashi are reporting primary energy. This could also be due to material (fiber and resin) differences, and oven size/loading assumptions. Note that Witik et al. did not include energy required to make the bulk materials like the fiber and resin, but instead started with the combination of the bulk materials.
3.1.2 Conclusion

Numbers given in Song et al., Suzuki and Takahashi, and Witik et al., although different, all agree that the energy intensities of the manufacture of raw material dominates the energy usage in a life cycle assessment of CFRP manufacturing [56, 59, 67]. Some of the numbers reported range from 700-1000 MJ/kg to produce raw carbon fiber [67]. Comparing values, it is obvious that energy used in the manufacture, and even the cure step of a CFRP part, is very small.

Although the fabrication of parts from these raw materials is not the major energy user, it is the portion of the process that still affects aircraft manufacturers costs and the only portion that they can control directly. Because it is a real and persistent cost, it is worth investigating as a point for cost savings for a CFRP aircraft structure manufacturer.

3.2 Integrally Heated Tooling for Composite Manufacturing

As Nickels mentions in her article in Reinforced Plastics, the aerospace industry has been trying to get out of the autoclave for decades, but with only limited success of matching the quality and consistency of that process [40].

Many of the tooling manufacturers in the market have focused on integrally heated tooling to replace an autoclave. One prominent player in this market is Quickstep, an Australian manufacturer of an out-of-autoclave and out-of-oven integrally heated tooling concept [48]. They use flexible membranes filled with liquid as the heat transfer fluid to increase heat transfer rates and help control exothermic temperature spikes seen at faster ramp rates [48]. Their process has been studied to test how well materials hold up under the faster ramp rates achievable with the process. These studies have found that the Quickstep process can produce autoclave or better quality parts on all measures reported, such as void content, fractural toughness, and resultant glass transition temperature, $T_g$ [68, 10]. Davies et al. did report, however, a 10% decrease in flexural strength against the same part cured in an autoclave [10].
Quickstep reports in their product literature that their system can reduce cycle time by up to 75%, while reducing energy usage by 30%-50% compared to an autoclave, all while providing similar quality products. Similar to an autoclave or oven, however, there is only one thermal zone of control, and this doesn’t provide localized heating/cooling for complex layups.

Figure 3-1 shows how the mould tool floats between the two fluid filled chambers. For large parts, the transfer of a tooling face sheet from its backing structure to be placed into this tool can be very difficult and risk damaging the facesheet. This is especially true for metallic tooling.

Induction heating is another technology that has been explored, but is not well represented in the literature. The technology uses metallic tooling materials, and uses changing magnetic fields to generate heat within the tool, which in turn heats the laminate. Many patents were found for this technology, some of the early ones from 1994 describing methods for induction heating to cure composite parts [38, 30]. A recent example of this technology used in industry is from RocTool, a tooling manufacturer. They have demonstrated a rapidly curing induction heated tool for luggage shells. These 1 mm thick shells are claimed to be rapidly cured in 105-310 seconds [55].

Other methods to cure FRP parts vary by technology widely but many do not have widespread use for FRP structures in the aerospace industry. QPoint Composite has a technology that can be used for forming processes and curing processes. They utilize a
textile with carbon fiber interwoven as the resistive heating elements [47]. They are stitched into the textile backing in what looks like a topographic pattern. The density of the stitched carbon fiber resistive heating elements can be designed to match the thickness (and thus heating requirement) of the laminate it will cure. The closer together the fiber heating elements; the fewer heating elements the lower the heating power. This textile is wrapped in a silicone membrane to limit localized heating effects between carbon fibers and the fabric between them.

![QPoint Photo of Technology](image)

This can provide localized control of heating power to provide the right amount of heat to the thickest portion of a laminate, while providing less heat input to the thinner portions of the laminate. Combined with active control, this can limit exotherm potential and enable rapid and precise cure of FRP parts. From their webpage, it appears most of the use of their technology in industry is for preforming the mould, and not necessarily the cure itself [47].

Another company trying to provide localized control of the temperature for a FRP cure is Surface Generation. Their patented technology, utilizing localized heating and control, can also segregate different heating/cooling zones across a single-sided tool and part [58]. Utilizing air heating and cooling in a localized manner, they can provide active control for different thicknesses across a given laminate. The company claims that tailoring their technology to the actual thermal requirements of the composite part can reduce cycle times by up to 95% and energy usage by 90% [58].
Weber manufacturing, based in Canada, is well known in the aerospace tooling market. They make all shapes and types of tooling, but also specialize in heated tooling. One technology they use is a metallic tool with integral piping that can circulate oil or water for heating and cooling. Airbus appears to use this for their overhead storage compartments [65]. For a resin transfer moulding process, North Coast Composites appears to offer a similar design of piping integral to a double sided tool used to circulate fluid and heat/cool a part [9].

3.2.1 Conclusion

Overall, from research and industry experience, it appears that integrally heated tooling use in the market is used much more for forming processes and not necessarily the cure. Localized control of the heating and cooling input is only done by a few tooling manufacturers, but it has the potential to save cycle time and energy.

3.3 Heat Transfer in CFRP Composites

3.3.1 Discussion

For this study, energy usage is being evaluated as a means to calculate potential operational and capital cost benefits of integrally heated tools over conventional curing methods. However, just as or more important than cost savings is to prove that an integrally heated tool will actually perform better than the incumbent technologies in dimensions such as part thermal uniformity and heat transfer, cure specification adherence, final part integrity, and quality. In order to determine this, thermal models can be conducted early and provide valuable data into the design and performance of a given part or tool design. To create these models and run cure simulations to test a new heating technology, knowledge of material properties of the part and tool are crucially important. The subsections below discuss material properties of CFRP constituents, tooling, and concerns often investigated in the design phase of a part and associated tool.
3.3.2 Material Characterization

Before any modeling can be conducted, the mechanical and thermal material properties of the resin and the reinforcement must be experimentally determined. There are many different tests that can be conducted on the fibers, the resin, or fully cured composite laminate to understand their behavior. Some tests that can be conducted are tensile, shear, compression tests for single fibers, strands of fibers, unidirectional and woven materials, resins, and full laminate stacks. Thermoelastic tests can be conducted as well to find out the coefficient of thermal expansion (CTE).

Thermal conductivity tests can also be conducted to test how well heat travels through a material. Detailed procedures for these types of tests can be found in the book Experimental Characterization of Advanced Composite Materials by Carlsson et al [5].

These tensile, conductivity, shear strength, CTE, resin modulus, density, etc., values are all required inputs for modeling to be conducted. These define the material properties that dictate the heat transfer into and throughout the tool and part. These values are also needed for boundary conditions in the model. For the case of this study, the resin and reinforcement characterization were completed independently and the results proprietary. Some examples of publicly available resin characterization for certain properties can be found from the manufacturer's websites such as Cytec, Toray, and Hexcel, [8, 62, 23].

The numbers reported by manufacturers are good for a general approximation, but some in the literature point out that very little information exists on the methodologies to obtain the numbers given by the manufacturers. For example, manufacturer data sheets may only report one number for thermal conductivity or CTE of a carbon fiber material. However, for a full 3D thermal analysis the direction of heat transfer is important, and thus the anisotropic numbers for the fibers is important to have. For internal analyses, an independent verification is often completed to determine the properties of material systems used.

3.3.3 Coefficient of Thermal Expansion

The coefficient of thermal expansion for a composite is vitally important for a thermal analysis, determining residual internal stress, springback of a material after a cure, and also
dictates tool design.

On a CFRP constituent level, resins usually have higher CTE’s and carbon fibers very low or negative overall CTE’s. CTE’s for carbon fiber are often negative in the longitudinal direction, but positive in the radial direction. The effect of the resin expanding when heated and the carbon fiber contracting when heated leads to the positive effect of pre-stressing the carbon fibers. When the material cools down after a cure, however, the opposite occurs and the resin wants to contract more than the carbon fiber; if done improperly can lead to warpage of the final part, unwanted residual stresses and damage. Thus, controlled and uniform cooling is important during the cure step.

Internal Stresses and Tool Design

Internal stresses will always be present after a cure, and tool designs can compensate for this. Designers can calculate how internal stresses after a cure will change the shape of the part once it is cooled and removed from the tool. They can then compensate the tool design to yield a net shape part.

The coefficient of thermal expansion for many FRP materials is much less than that of metals [34]. This causes a challenge for tool manufacturers, as tool CTE cannot exceed the composite CTE by too much, or it can warp the part and yield a part that is not of the desired final shape. Composite tooling has the best CTE match, but isn’t as durable for long-term production. Many manufacturers use a nickel alloy called Invar on which to layup the part, but it is also very expensive and very heavy [7]. Below is a table from [34] with various CTE’s for a subset of materials used in this study.

Thermal Conductivity

Heat transfer analyses in composites cannot be conducted without thermal conductivity values for the constituents. Table 3.2 gives some example values of CTE and thermal conductivity of some materials used in aircraft manufacture and composites. It is important to note the high thermal conductivity in the longitudinal direction of raw carbon fibers. The numbers reported are for PAN T300 fibers, but for pitch carbon fibers, the longitudinal thermal conductivity can range from 100-1000 W/mK, and some have measured even higher
Table 3.2: Selection of Material Properties [34, 15, 29]

<table>
<thead>
<tr>
<th>Material/Property</th>
<th>Coefficient of Thermal Expansion $10^{-6}/K$</th>
<th>Thermal Conductivity W/mK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain Carbon Steel$^{a}$</td>
<td>11.7</td>
<td>52</td>
</tr>
<tr>
<td>Carbon-Epoxy Composite (Quasi-isotropic) $^{b}$</td>
<td>0-0.9</td>
<td>10.38-20.76</td>
</tr>
<tr>
<td>PAN T300 Carbon Fibers (longitudinal) $^{c}$</td>
<td>-.6</td>
<td>8.5-76$^{g}$</td>
</tr>
<tr>
<td>PAN T300 Carbon Fibers (radial) $^{c}$</td>
<td>7-12</td>
<td>0.085-76$^{g}$</td>
</tr>
<tr>
<td>Epoxy Resin</td>
<td>50-80 $^{e}$</td>
<td>0.2$^{f}$</td>
</tr>
<tr>
<td>Invar$^{a}$</td>
<td>1.6</td>
<td>6</td>
</tr>
<tr>
<td>Aluminum Alloys$^{a}$</td>
<td>23.5</td>
<td>130-220</td>
</tr>
</tbody>
</table>

$^{a}$ Source: Mallick 2008, Table 1.2, Page 5; $^{b}$ Source: Mallick 2008, Tables 4.16, 4.18, Page 322, 324, Fiber Volume Fraction 60%; $^{c}$ Source: Mallick 2008, Table 2.1, Page 34; $^{d}$ Source: Mallick 2008, Page 53; $^{e}$ Source: Mallick 2008, Table 2.8, Page 74; $^{f}$ Source: Garrett 1974 [15]; $^{g}$ Source: Klett 1999, range for 1100°C and 2400°C heat treatment of fibers [29]

... conductivity [34].

For resin, the thermal conductivity is lower than that of carbon fibers in the axial direction, but greater in the transverse direction.

In effect, for a carbon-fiber epoxy laminate, the thermal conductivity in the longitudinal direction will be dominated by the carbon fibers and in the transverse, or through thickness direction, it will be dominated by the thermal conductivity of the resin [34]. What this means in a heat transfer analysis for a laminate is that heat will travel in the x-y plane readily, but heat will transfer much less quickly through-thickness, or in the z-direction.

However, Gaier [14] challenges the anisotropy under certain conditions for woven fabric laminates.

Farmer, in his Ph.D. thesis, experimentally determined how the thermal conductivity within a laminate changes during the cure based on parameters such as volume fraction of the resin and degree of cure [13].
3.3.4 Conclusion

Heat transfer in composites poses some challenges due to the non-homogeneity of the materials, the anisotropy of the thermal properties, and the mismatch between thermal properties of a CFRP composite and the tool on which it sits. Much is known, however, about the heat transfer in composites, and this knowledge can readily be applied to thermal models. The above sections provided insight into these concerns and discussed material properties required to perform the thermal models discussed in the following section and in Chapter 5.

3.4 Thermal Modeling of CFRP During Its Cure

One-dimensional and two-dimensional thermal modeling of a cure have been discussed in the literature for some time now. Using the Finite Difference Method, Bogetti and Gillesie performed 2D models of “thick thermosetting composites of arbitrary cross section” back in 1991 [3]. Kim et al used 1D thermal modeling to describe a novel continuous curing process [28]. The 1D and 2D methodologies, however, assume temperature uniformity across a boundary and geometrical symmetry. White and Hahn utilized cure thermal models to develop optimal cure cycles to reduce residual stresses in composites due to the cure process [66]. Nawab et al. discuss thermal gradients in a part during the cure and uses models and experimentation to determine cure shrinkage in an epoxy resin [39]. A methodology and code describing how the governing equations of heat transfer in composites and the heat generation of the resin reaction can be combined mathematically in a Finite Element Analysis (FEA) model to produce the final three-dimensional cure simulation [44]. In this paper they compare their simulation with experiments and prove out the model. Park et al. in [44] provide detailed descriptions of the governing equations for 3D models and simulation of CFRP cures.

As recently as 2014, modeling of the cure of aerospace composites was discussed by Carlone et al [4]. In that paper they discuss combining FEA with artificial neural networks (ANN) to design an optimal cure cycle.
3.5 Conclusion

This chapter presented a literature review of energy usage in CFRP manufacturing, existing integrally heated tooling technologies, an overview thermal modeling/simulation of the CFRP cure process, and material properties required to perform such simulations. Thermal modeling, heat transfer in composites, and energy use of the sure cycle has been studied extensively for various curing processes, materials, and applications. Much is known about the heat transfer of a given material, and many thermal models and full composite software has been been developed based on this knowledge. The present work will build off this to evaluate a new curing technology concept; how the material reacts, and if the technology can compete with incumbents. The work in this paper will provide additional energy intensity data from actual industry sources to compare with literature. In addition, it will prove out 3D modeling methodologies for large aircraft CFRP parts to save computational time and still maintain accuracy. Finally, it will provide conclusions on how well single-sided heating of CFRP parts works on actual aircraft part families.
Chapter 4

Energy Data Collection and Analysis

4.1 Discussion

This chapter outlines the methods used to gather energy data on autoclaves and ovens used to create CFRP aircraft parts. The analysis uses limited input data, system energy accounting, and regression methods to tease out how much energy each autoclave uses on average for many different temperature/pressure setpoints, part loadings, and durations.

The collection of energy data is necessary to help better understand how the current system operates and to allow a proper comparison with an integrally heated tool, as well as data presented in the literature review in Chapter 3. Different methods can be utilized to gather energy data. Obviously, the easiest and most accurate method is to measure the energy usage directly. However, in most systems, there are no real-time electricity meters or gas meters from which to get data. Usually, there is just the one meter feeding the site that the utility company uses for billing. So, a combination of utility bills, autoclave/oven run data, estimations on heater and motor operation times, and direct measurements can be used to estimate how much energy is being used by the ovens and autoclaves.

4.2 Autoclave Energy Usage

Most autoclaves have three main energy sources used for the cure: electricity, natural gas, and liquid nitrogen. First, electricity is used to power all the motors driving the pumps and
fans, the control system, vacuum system, and in some cases is also used for heating. Second, natural gas is often used for heating an autoclave in lieu of electrical heating. Finally, liquid nitrogen or a local nitrogen gas generation system is used to apply an inert pressurized atmosphere.

Because there are multiple variables such as temperature set point, pressure set point, number of runs, volume of autoclave, design of autoclave, and only one data point per month of electricity, natural gas, and liquid nitrogen usage, a regression can be used to determine the effect of each parameter on the monthly bills for each of the energy usage constituents. First, however, discussion on how each parameter is calculated or gathered needs to be discussed.

4.2.1 Natural Gas Usage

As stated in the discussion section of this chapter, manual regression using Solver was used to determine how much natural gas was used for each run of the autoclave. In this regression, the independent variables were the number of runs that each autoclave had each month over the time period studied, and matched them with the dependent variable of billed natural gas usage for each monthly billing period. Details into isolating only autoclave natural gas usage from billed usage is outlined below.

Natural Gas Regression Formulation

The objective function for the regression is to minimize the mean squared error between the predicted value (billed usage, \( B_i \)) and the calculated value \( U_j \). Constraints were placed on the individual usage/run \( U_j \) values with the assumption that the larger autoclaves had to use more natural gas than the smaller autoclaves. These constraints can be informed by gathering the nameplate data from the autoclave gas combustion chamber, which gives values in GJ/hr energy usage rate for each autoclave. These constraints were also removed and the results came out to be the same.

\[
\text{obj} \quad \min \quad \epsilon
\]
\[ e = \sum_{i}^{m} \sum_{j}^{n} (A_{i,j}U_j - B_i)^2 \]

In the below matrix describing the calculation, everything is known but the Usage per Run values for each autoclave. In the \( A_{m,n} \) matrix, the rows represent each month, and the columns each autoclave. Knowing that the numbers would not be exact due to deviations in run time, set temperature, and external atmospheric conditions; an optimization was used to minimize the error between results from the predictions of \( U_j \) and what the monthly bills showed. Getting precise numbers for each run was not possible or useful given all the variables involved. However, an overall average of usage per run, even with error, is more useful in predicting future natural gas usage, due to the ease in multiplying one average number by an estimated number of runs. In contrast, for more accuracy, knowledge of exactly how long each future run will be, at what temperature and pressure, under what system losses, and under what environmental conditions would be required.

\[
\begin{bmatrix}
  A_{1,1} & A_{1,2} & \cdots & A_{1,n} \\
  A_{2,1} & A_{2,2} & \cdots & A_{2,n} \\
  \vdots & \vdots & \ddots & \vdots \\
  A_{m,1} & A_{m,2} & \cdots & A_{m,n}
\end{bmatrix}
\times
\begin{bmatrix}
  U_1 \\
  U_2 \\
  \vdots \\
  U_n
\end{bmatrix}
\approx
\begin{bmatrix}
  B_1 \\
  B_2 \\
  \vdots \\
  B_m
\end{bmatrix}
\]

where:

\( A_{m,n} \) is the number of runs in Autoclave \( n \) during Month \( m \), in runs

\( U_n \) is the unknown parameter of Usage Per Run of Autoclave \( n \), in GJ/run

\[ \sum_{j}^{n} A_{m,j}U_j \quad , \text{for all } m \]

**Natural Gas Usage Discussion**

For natural gas-fired autoclaves, there is a combustion chamber where the natural gas is fed an ignited. This is almost always external to the main body of the autoclave. The output air from this combustion chamber is then mixed with dilution air at atmospheric temperature via blower fans in the proper ratios to achieve the desired temperature in the autoclave. This air is then directed to an internal heat exchanger where it transfers heat to the pressurized...
nitrogen atmosphere inside the autoclave. This is usually a once-through process, where the heat generated is dumped to atmosphere after going through the heat exchanger one time.

There are significant inefficiencies in this process, as it uses a methane flame at temperatures near 1500 degrees Fahrenheit to heat air to a few hundred degrees Fahrenheit. There is an exergy-related inefficiency in this process as that 1500 degree flame could be used to do much more work than is it is actually doing. Further, the once-through process is inefficient, as the heated air is exhausted to atmosphere and not fully recirculated. Nevertheless, it is a simple and effective way to achieve the proper temperature control.

One method to calculate natural gas usage in this configuration would be to use a bottom-up approach. This would involve calculating the mass of a given autoclave, assumed heat losses through the insulation and autoclave walls, part and tool masses, and assumptions in the efficiency of both the combustion chamber and the internal heat exchanger. Since nearly all of that information was not readily available, a top-down approach was employed.

Often, there are no local gas meters on the feeder lines to the autoclaves, so it is usually unknown exactly how much natural gas is used for each autoclave during any given run. Other methods to estimate the natural gas usage have to be employed to get reasonable results. To determine this, the total gas usage for the site can be gathered from historical monthly utility bills. When trending the natural gas usage over the past decade or so, it was found that natural gas usage varied cyclically almost perfectly in line with the seasons. Up until a few years ago there were other major users of natural gas such as boilers used in processes on site. These were decommissioned and this left very few natural gas users on site, save for the autoclaves.

To determine if these monthly bills could be used to calculate autoclave usage, a survey of all the end users of natural gas was conducted. The main natural gas users on site were hot water heaters, radiant heaters in the rafters of the manufacturing bays, and the autoclaves. Using calculations based on the nameplate of the radiant heaters, and assumptions of how long per day they were in use, it was confirmed that they accounted for nearly all of the peak usage in the spring, winter, and fall months. In a typical summer, where temperatures range between 90 to over 100 degrees Fahrenheit, no heating is required and these heaters are all turned off. The seasonal trough in natural gas usage always coincided with the summer
months. It was these months that were used under the assumption that the natural gas usage was dominated by the autoclaves. Using simple calculations based on the nameplate of the hot water heaters, it was determined that these only account for low single digit percentages of the natural gas usage during these months. So, it can be assumed that the monthly natural gas numbers from the summer utility bills could be directly correlated to the natural gas used on site.

Given the above analysis of the site, natural gas utility bills from the past 5 years were analyzed. It was fortunate that during the summer months of one year, a subset of the autoclaves were being upgraded and not utilized. A different subset of the autoclaves were out of service for upgrades over a different year. This allowed for an easier task in determining how much each autoclave used because the remaining autoclaves could be isolated from those that ran zero times over the given period.

To determine how often the autoclaves ran during these discrete monthly time periods, run data from the systems data historian were pulled, and pivot tables in Excel were used to isolate how often each autoclave ran during the given period. This gave the numbers of runs for each autoclave in a given period, the set pressure, set temperature, and duration. Using this data, the calculations described above were used to set up the problem. The instances of an autoclave beginning a run on the night of the last day of one month and finishing the morning of the first day of the next month were minimal and ignored. The start date of the run was used to determine what bill to assign the run towards.

**Natural Gas Regression Results**

The linear regression model gave an $R^2$ of 0.995, an F-Test value above 500, with the P-Values for the explanatory variables (usage/run for each autoclave studied) at or below 0.02, with most at or below 0.001. The residual plots for each of explanatory variables were roughly evenly distributed about the mean, and the normal probability plot was linear. These values shown below provide confidence between the monthly bills and the number of runs that each autoclave had during the period. This supports the assumptions stated above about billed values during the summer time period being nearly completely driven by the autoclaves.
Table 4.1: Regression Statistics

<table>
<thead>
<tr>
<th>Regression Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>0.995</td>
</tr>
<tr>
<td>$R^2_{adj}$</td>
<td>0.851</td>
</tr>
<tr>
<td>F-stat</td>
<td>512</td>
</tr>
<tr>
<td>P-values</td>
<td>Range: $1.2E^{-6} - 0.02$</td>
</tr>
</tbody>
</table>

4.2.2 Liquid Nitrogen Usage

As stated above, most autoclaves that cure aerospace-grade composites use nitrogen for pressurization and to provide an inert atmosphere. This can either be accomplished with liquid nitrogen delivered to the site, or via an on-site nitrogen generation system. Typically, for the large volumes needed on a regular basis, liquid nitrogen is preferred over on-site generation. For this study, liquid nitrogen usage is explored.

To determine how much liquid nitrogen is used per run of each autoclave, run data from the autoclaves and theoretical calculations of how much nitrogen should be used can compared with bills for the delivery of nitrogen to the the site, and the Solver function in Excel can then be used to find the scale factor that minimizes the error between billed and calculated values. The billing invoices for every delivery of liquid nitrogen can be collected and organized temporally as the independent data that needs to be matched to run data (volumes, pressures, number of runs).

This method is similar to the one used above in Subsection 4.2.1 for Natural Gas Usage, but with the added parameter of the different pressure set points for each cure and volume of each autoclave. Obviously, different set pressures and different volumes require different amounts of nitrogen.

A standard regression like for Natural Gas usage was attempted, but because there is not a 1:1 match of dependent and independent variables, manual calculations and aggregation of variables were used. For example, for each month, a 5X5 matrix of values may need to be matched with one number (monthly billed volume of liquid nitrogen), and then each month over time would be used to find the dependent variables. This is because there are
multiple autoclaves operating many times at multiple pressure set points all being combined to match to one billed value. However, once all the variables are calculated, aggregated, then a scale factor can be applied by minimizing a simple sum of squares error (as in a regression) between calculated and billed values can be used. Once the error is minimized via a scaling factor, the individual liquid nitrogen usage for a given autoclave at a given pressure set point can be back calculated. The calculations are described via two methods below.

**Cure Pressurization Description**

A standard industry cure specification could have a 90 psig pressure and approximately 356°F temperature set point. A typical autoclave will maintain 90 psig before it begins the temperature increase, and after the cool down period. This is because many cure specifications require the pressure to be applied to the material throughout the cure cycle. However the pressure, if uncontrolled, would increase above 90psig as the temperature increases and would drop below 90psig as the temperature decreases (thus \(N_2\) needs to be vented or added back to maintain the set point). For this analysis, the compressibility factor \(Z\) of nitrogen is ignored because these calculations do not require that level accuracy. Therefore, nitrogen will be assumed to be an ideal gas. Table 4.2 shows typical steps in an autoclave cure, and what the pressure would do if the control system did not maintain a set pressure throughout the cure.

To calculate the Pressures shown in Table 4.2, the simple relationship \(P = \rho R_s T\) can be used to calculate what the nitrogen pressures would be with and without the control system holding the pressure at 90psig at each temperature change step. This can be seen in Figure 4.2.2 showing the pressure increasing above 90psig between Steps 2 and 3, and decreasing below 90psig between steps 4 and 5. The reason for including this is that it feeds into the calculation on how much liquid nitrogen is needed per run for each autoclave, and shows that more nitrogen is required than just the initial pressurization to 90psig.

**Volume Method**

To begin, the calculation of the working volume of the autoclave is required. Using the working volume over the actual total volume is used in this analysis because it is more likely
Table 4.2: Uncontrolled Pressure Response During an Example Cure

<table>
<thead>
<tr>
<th>Step</th>
<th>Pressure psig</th>
<th>Temperature °F</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>70</td>
<td>Assume standard atmospheric conditions</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>90</td>
<td>Pressurize Period. Add nitrogen to reach 90 PSIG with a nominal temperature increase.</td>
</tr>
<tr>
<td>3</td>
<td>140.6</td>
<td>356</td>
<td>Temperature Ramp Period. Assume no nitrogen is vented (constant density), and pressure naturally rises with rising temperature.</td>
</tr>
<tr>
<td>4</td>
<td>140.6</td>
<td>356</td>
<td>Cure Dwell Period. Conditions held throughout cure. Temperature only added to counteract losses from autoclave walls to atmosphere.</td>
</tr>
<tr>
<td>5</td>
<td>62.2</td>
<td>140</td>
<td>Cool Down Period. This calculation assumes the Pressure in Step 4 was actually 90psig to better show the effect of needing to add nitrogen to maintain 90psig pressure. If it was truly uncontrolled and at 140.6psig, like stated above, the pressure would drop to 99.5psig during this step. Pressure is allowed to drop naturally from 90psig to 62.2psig as the autoclave cools from 356°F to 140°F.</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>70</td>
<td>Pressure is bled off and autoclave returns to atmospheric conditions.</td>
</tr>
</tbody>
</table>

Figure 4-1: Nitrogen Pressure Response During a Cure
that one will know the working dimensions (say a 10ft X 30 ft autoclave) over knowing the full dimensions of the autoclave. Some of the internal volume is taken up by the internal fans, heating elements, heat exchangers, etc. Calculating the simple volume of a cylinder is quicker and easier than determining the actual dimensions of the autoclave and estimating the volume of hemispherical or ellipsoidal heads, etc, of an autoclave. Knowing that the working volume does not equal the total pressurized volume, one can just apply an unknown factor in Solver to the working volume to account for this difference.

Optimizing the error between the calculated nitrogen volumes and billed nitrogen volumes using this factor can assist in better accuracy than trying to fully understand what volume is actually pressurized inside the autoclave (total internal volume minus fans, heat exchangers, parts/tools, etc). Therefore for all following equations, the working volume \( V \) for autoclave \( j \) \((A_j)\) will be denoted as \( V_j \) and equal to the simple volume of a cylinder \( V_j = \left( \frac{\pi}{4} \cdot (ID_j)^2 \right) \cdot L_j \), where \( ID_j \) and \( L_j \) are the working internal diameter and working length, respectively, of autoclave \( j \) \((A_j)\).

**For Step 1 - Step 2:** First, assume this is an adiabatic process (confirmed by data trends for multiple autoclave runs). Also assume that the atmosphere of air inside the autoclave at the start of the cure is not purged, but remains in the autoclave. Therefore, the volume of \( N_2 \) required to pressurize autoclave \( j \) \((A_j)\) to pressure set point \( i \), \((P_i)\) can be determined simply via Equation 4.1:

\[
V_{N_2,i,j,press} = \left( \frac{P_{i,abs}}{P_{init,abs}} \right) \cdot V_j
\]

**For Step 2 - Step 3:** First, assume this is an isobaric process, because the control system maintains the autoclave at the set point pressure. Therefore, the volume of \( N_2 \) bled from autoclave \( j \) \((A_j)\) to maintain pressure set point \( i \), \((P_i)\) can be determined via Equation 4.2:

\[
V_{N_2,i,j,heat} = \left( \frac{T_{i,abs}}{T_{init,abs}} \right) \cdot V_j
\]

**For Step 4 - Step 5:** This process is isobaric again, because the control system will keep the pressure at the setpoint. Therefore, the volume of \( N_2 \) required to maintain pressurize autoclave \( j \) \((A_j)\) a pressure setpoint \( i \), \((P_i)\), while the temperature decreases from temper-
ature setpoint \( i (T_i) \) to the final temperature before the autoclave can be opened \((T_{cd})\) can be determined simply via Equation 4.3:

\[
V_{N_2,ij,cool} = \frac{T_{cd,abs}}{T_{i,abs}} \cdot V_j
\]  

(4.3)

Combining Equation 4.1 with Equation 4.3 yields the total theoretical volume of \( N_2 \) needed to be added to autoclave \( j (A_j) \) for a given run at pressure set point \( i (P_i) \). This is shown in Equation 4.4.

\[
V_{N_2,ij} = \left( \frac{T_{cd,abs}}{T_{i,abs}} + \frac{P_{i,abs}}{P_{init,abs}} \right) \cdot V_j
\]  

(4.4)

Now that the volume of nitrogen required for any pressure and temperature set point \( i \) has been calculated, multiply those values by the number of runs \((R_{ijk})\) that each autoclave \( j \) had at each set point \( i \) during the billing period \( k \). So, for any autoclave \( j \) during billing period \( k \):

\[
V_{N_2,jk} = \sum_{i} V_{N_2,ij} \cdot R_{ijk}, \quad \text{for each Autoclave} \quad j
\]  

(4.5)

However, as stated previously, the working volume used in these calculations is not equal to the actual volume that gets pressurized during the cure. There are general system losses, and extra volume surrounding the fans and heat exchangers that make up the difference between working volume and total pressurized volume. So the unknown factor \( \alpha \) is applied to Equation 4.5, yielding Equation 4.6. It would make sense to apply an \( \alpha_j \) to each autoclave (because the difference between working and total volume would be different for each depending on design) and then multiplying that corrected volume by the number of runs. This was also tried, but only a marginal benefit was gained in the error between calculations and billed values. This method was determined to be sufficient for this analysis.

Assuming the site has more than one autoclave that uses liquid nitrogen, this process must be completed for each autoclave up to \( n \) number of Autoclaves. Therefore Equation 4.5 becomes:

\[
V_{N_2,Total,k} = \sum_{j} V_{N_2,jk} \cdot \alpha
\]  

(4.6)
So, knowing total theoretical volume that should be required for \( n \) number of Autoclaves, operating \( R_{ij,k} \) times at each of their own \( m \) number of pressure/temperature set points, compare this total value with the billed volume \( B_k \) for the month \( k \), and then minimize the error using the \( \alpha \) variable and the “Total Sum of Squares” equation:

\[
\epsilon_{N2,k} = \sum_{k} (B_k - V_{N2,Total,k})^2
\]  

(4.7)

Now, using optimization software, minimize \( \epsilon \) to achieve the optimal factor \( \alpha \) to calculate the Volumes of nitrogen each Autoclave used over the period for each set point.

\[
\min \quad \epsilon_{vol}
\]  

(4.8)

With the proper \( \alpha \), Equation 4.4 can calculate the volume of nitrogen needed per run of Autoclave. Bringing all the Autoclave usages together made the optimization easier. Now use the proper \( \alpha \) to multiply Equation 4.4 and back calculate how much nitrogen each Autoclave used on average per run with the below Equation:

\[
V_{N2,ij,\alpha} = \alpha \cdot V_{N2,ij}
\]  

(4.9)

**Direct Cost Method**

If there are only 1 or 2 different set points across the autoclaves (say 45psig and 90psig), a much faster and equally effective way of calculating volumes used is to use Solver on the billed cost only, and then back calculate the volumes of nitrogen. All that is needed to use this method are the number of runs of each autoclave \( j \) at each set point \( i \) during the billing period \( k \) and the working Volume \( (V_j) \) for each autoclave, which can be simply calculated as shown above. The preliminary assumption is that each set point has a different cost per run (i.e. a 90psig run costs more than a 45psig run because it uses more nitrogen), which is fairly intuitive. Therefore a factor \( \beta_i \) can be used as the variable in the Solver calculation.

If there are many different pressure/temperature set points \( i \), the number of variables in the Solver increases and accuracy for each factor will decrease. So, as a reminder, this works best with only a couple \( \beta_i \) factors. In this equation, \( \beta_i \) is in $/m^3/\text{run}$ To begin, the billed
cost for period \( k \) is defined as \( C_k \). Knowing that each set point will have a different cost per run, but to account for different sized autoclaves, the working volume must be included so as to weight each autoclave by size, otherwise the optimization won’t know which autoclave uses more and which uses less because of its respective volume. To calculate the estimated cost \( C_{estimated,k} \) in period \( k \):

\[
C_{estimated,jk} = \sum_{i}^{m} (V_j \cdot R_{ijk} \cdot \beta_i)
\] (4.10)

\[
C_{estimated,k} = \sum_{j}^{n} \sum_{i}^{m} (V_j \cdot R_{ijk} \cdot \beta_i)
\] (4.11)

\[
\epsilon_{cost} = \sum_{k}^{p} (C_k - C_{estimated,k})^2
\] (4.12)

Now, to minimize the “Total Sum of Squares”:

\[
\min \epsilon_{cost} \quad \text{by changing each} \ \beta_i
\] (4.13)

Then, dividing each portion of the expanded Equation 4.10 with the appropriate \( \beta_i \) factor for each setpoint \( i \), by the unit cost (\$/m\(^3\)) from the bills yields the volume used for each Autoclave \( j \) for each setpoint \( i \).

The Volume and Direct Cost methods were utilized with similar success. The average absolute error between the calculated values and billed values was between 3% and 4% for each method. These calculations were conducted over 8 months of data. This is because prior to this there were known leaks in the nitrogen system, thus skewing the results. The analysis only used data after the leaks were fixed.

Although minimal electricity is used to deliver liquid nitrogen from the on site tank to the autoclaves, significant electricity is used in the production of liquid nitrogen, and this must be taken into account when calculating the total energy usage. To convert the volume of liquid nitrogen used per run of autoclave into MJ of energy, numbers from Theobald’s 1980 patent for production of liquid nitrogen can be used. He states that approximately 850kWh (3,060MJ) are used to produce 1 MT of liquid nitrogen [61]. Knowing that the
density of liquid nitrogen is about 0.8kg/m$^3$, and that 680.4m$^3$ of gaseous nitrogen is equal to 1m$^3$ of liquid nitrogen [32], then one can calculate how much electricity it takes to produce the volume of gaseous nitrogen for each cure via the below equation:

$$E_{\text{iq}N2} = V_{N2,ij} m_{\text{gas}}^3 \cdot \frac{1 m_{\text{iq}}^3}{680.4 m_{\text{gas}}^3} \cdot \frac{0.8 kg}{m_{\text{iq}}^3} \cdot \frac{1 MT}{1 kg} \cdot \frac{850 \text{ kWh}}{1 MT}$$  \hspace{1cm} (4.14)

4.2.3 Electricity Usage

As stated previously, some autoclaves use electricity for the heating elements as well as to drive the pumps, fans, control system, hydraulics, and lighting. Others use natural gas for the heating and electricity just for the mechanical and control systems surrounding the autoclaves.

To estimate energy usage, simple methods were used. Readings were taken from dial gauges on electrical cabinets supplying power to the various motors that drive the pumps and fans while in operation. This information, coupled with data trends on when the heating and when the cooling systems are started/stopped within a cure can be utilized to estimate the power supplied to the mechanical systems.

Similarly, heat ratings of the electrical heaters coupled with trend data that provides a percentage of the total electrical heat rating can be used to estimate electrical heating power consumption. The assumption when calculating the energy used by the vacuum system was that it runs throughout the cure. This is a reasonable assumption, as maintaining vacuum is an integral part of the recipe for any autoclave cure. The methodology used in this analysis was fairly standard energy calculations, and will not be discussed in detail.

4.2.4 Results

Figure 4.2.4 is a normalized representation of the findings, and should not be interpreted that a natural gas fired and electrically heated autoclave use the exact same amount of energy. Rather, the average make-up of total energy use is presented in Figure 4.2.4 for each heating type as a fraction of total energy. It should be noted that a 1:1 comparison between similar sized and similarly designed electrical vs natural gas autoclaves was not possible in
Although the Liquid nitrogen only makes up a modest portion of the energy usage (in this case, the energy required to produce that amount of Liquid nitrogen at a supplier facility), it makes up a much larger portion of the total costs. This is because the bill accounts for much more than just the energy costs to produce the liquid nitrogen when purchased from a supplier.

4.3 Oven Energy Usage

Industrial ovens for composite curing are usually convective ovens that use radiant heating and large fans to circulate air across heater banks and the tool/part to heat them up. However, they can also be heated via natural gas. These ovens operate at atmospheric conditions, so no nitrogen is needed for pressurization; thus taking away a significant portion of the energy used in a cure. The ovens investigated in this study are entirely electrically heated and powered. This made it much easier to directly measure how much energy was being used for each run. A power logger can be hooked up to the electrical leads for each
oven to provide a direct output of power usage.

There are three main sizes of ovens located on this site; sized for the three main part families discussed above (skins, spars, ribs). The Skin Oven is the largest and usually only cures one part/tool combination but sometimes has two smaller skin parts cured at once. The Spar Oven is the medium sized oven and usually cures a couple part/tool combinations at once. The Rib Oven is the smallest oven and cures all the ribs, with multiple part/tool combinations at once.

There are a large number of ovens, so gathering data on them all is impractical. So, one was selected for each oven size. The specific ovens to gather energy data were determined by which parts they typically cure. It was desired to get an oven that cures the parts that were also analyzed in the heat transfer analysis discussed below. This would give the best 1:1 comparison between energy usage in an oven compared with an integrally heated tool. Each oven measured was connected to the power logger for a minimum of 4 days, with some connected for over a week. This duration was decided on based on how many cures occur over this time period, and the variability of part loading of the oven. For ovens that cure the same parts over and over without much variation, a shorter duration is needed because each cure is essentially the same. For ovens that cure a wider variety/combination of parts, gathering power data over a longer time period is necessary to catch that variability.

The data can then be cross referenced with the specific cure data (temperature profile) that occurred over that same time period, and the energy usage can be determined for each portion of the cure.

### 4.3.1 Power Analysis

The power draw during each step of the cure is not equal. In Figure 4.3.1, normalized data for an oven cure is presented. As shown, the initial ramp usually records the highest peak power draw, but is the shortest duration. This simplified representation of the actual measurements shows how the power output changes as the cure progresses. Increasing ramp rates to decrease overall cycle times can actually increase the power draw during the ramp and thus possibly increase the energy usage if the percent increase in power draw to achieve
a faster ramp rate is greater than the percent decrease in time of the ramp; given that:

\[ E_{t_2-t_1} = \int_{t_1}^{t_2} P \cdot dt \]  \hspace{1cm} (4.15)

Decreasing the dwell duration does decrease energy usage by decreasing \( t \), but it also has a lower power draw, and thus the savings of reducing the dwell has a smaller effect on overall energy usage.

This interplay of the two methods of decreasing cycle time (increasing ramp rates and decreasing dwell times) is important with regards to energy usage. Increasing ramp rates can increase energy usage to a larger effect than decreasing dwell times.

### 4.4 Conclusion

Table 4.3 gives a normalized energy intensity range for the autoclaves and ovens studied. Values from the above calculations were combined with average weights of parts cured (excluding tool weights) to get the energy intensity numbers. As shown, the autoclaves are the most energy intensive per unit mass of part on average, but has a large spread as well. This is due to their large size with the most parasitic losses, and the most variable part loading.
Table 4.3: Energy Intensity Ranges

<table>
<thead>
<tr>
<th></th>
<th>Energy Per Unit Mass (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autoclave</td>
<td>150-270</td>
</tr>
<tr>
<td>Large Oven</td>
<td>55-75</td>
</tr>
<tr>
<td>Small Oven</td>
<td>100-125</td>
</tr>
</tbody>
</table>

In addition, for this specific study, the autoclaves were of varying vintages, with some having recent upgrades and others not.

The large oven is the least energy intensive (most energy efficient), which may be counter intuitive. One would expect the small oven to be the least energy intensive because it cures smaller and lighter parts. Although they are small and light, their associated tooling is large and heavy. This means the tool weight/part weight ratio is much larger for the small oven than for the large. So, more energy has to be put into the tooling to keep its temperature close to the part temperature than on a larger skin.

The oven cure energy intensity looks high relative to the values reported in the literature review, but when compared to overall cost of a part, it is actually quite low. The autoclave energy intensity numbers fit between the numbers reported by Song et. al, [56]; Witik et. al, and Suzuki and Takahashi [59]. Taking the average of the different autoclaves investigated with this study, an autoclave at industrial scale still looks to be 2-3 times more energy intensive than an oven.
Chapter 5

Case Study Modeling: Single-Sided Integrally Heated Tooling

5.1 Discussion

In ovens and autoclaves, heat and pressure is applied to the part and tooling from 360° surrounding the part and tool. This is beneficial in that heat can travel through the tool underneath a laminate, but also directly into the laminate from the exposed top and sides of a single-sided layup. For single-sided integrally heated tooling, the idea is to only heat from underneath the tool face, effectively heating only from 180° beneath the part, and insulating the top. This means the heating devices are permanently installed in the layup tool and leaves the top surface of the tool face clean for layup. After the layup and before the cure, insulation would then be placed on the top of the laminate to limit heat transfer out of the top during the cure.

In Figure 5-1, the heating technologies would be installed within the backing structure and under the tool face. This heat transfer study is impartial to the specific heating technology and a basic assumption is that any technology used would be able to meet the temperature profile required. Figure 5-7 shows a simplistic representation of the single-sided heating concept for this study with a temperature profile applied beneath the tool, and a heat transfer coefficient (HTC) on the top and sides to mimic insulation or free-air interaction.

Single-sided heating has the theoretical advantage of using less energy because of the
lower thermal mass that must be heated. The idea is to only heat the tool and part instead of also heating the walls and floor of an oven or autoclave, which can lead to parasitic losses. It also has the potential to provide multi-zone thermal control to a specific area. Although completely independent thermal control is not possible since the laminate and tool are contiguous bodies and heat can travel freely between zones, localized control can be applied.

5.2 Software Selection

A novel way to approach the design of the cure profile, and even the design of the tooling and part, is to perform a 3D thermal model of the part to see how it will perform in a cure.

With thermal modeling and simulation software, the designer can be better informed of the cure performance and design the tooling more robustly to allow for better heat transfer, and/or allow for heated tooling to be better utilized. The software utilized for this combines 3D Finite Element Analysis (FEA) with thermal and resin cure models and is discussed in the following section.

Many different models were run for the heat transfer analysis, consisting of one dimensional, two dimensional, and three dimensional analyses. Two pieces of software were used to complete these models. For the 1D and 2D modeling, a product called Raven was used. Raven is a stand-alone software package created by Convergent Manufacturing Technologies based in Vancouver, British Columbia [25]. For the full analyses of 3D models of actual parts, the Abaqus [60] modeling software with the COMPRO add-in was used [26]. COMPRO is also a product from Convergent Manufacturing Technologies.

Both Raven and COMPRO utilize input files that provide data categorizing the properties of the resins and carbon fiber constituents in the composite. This data is generated through external experiments, as discussed in Chapter 3 that determine values such as thermal conductivity, density, specific heat capacity, resin modulus development, glass transition temperature development, etc. The experiments conducted to gather this data were completed prior to this study and are proprietary for the materials used.

These set of input files would provide data similar to that in Table 1 of Reference [45].
This set of input files would have one each for the resin, the fiber, the composite as a whole, the tooling, and in this case, the insulation as well. For the 3D analyses, this input data is called out in Abaqus when defining materials. Abaqus is then used for things such as supplying dimensional data and model boundary conditions. For all the models discussed, dry woven fabric and thermoset resins were used. All models were conducted at atmospheric pressure.

These software packages allow the designer to see how a part and tool design will react to any temperature profile or applied thermal and/or mechanical loading. The COMPRO add-in to Abaqus adds significant computational time to a simple heat transfer analysis because it now has to compute all the extra material properties throughout the cure such as Degree of Cure, Cure Rate, Internal Heat Generated, Resin Modulus, Glass Transition Temperature, Resin Poissons Ratio, Resin Cure Shrinkage Factor, Resin CTE, Resin Viscosity, Resin Density, Resin Specific Heat, etc. However, the visibility gained through these material properties are invaluable when determining how well a material will behave under cure conditions. It can help inform a subsequent Design of Experiments (DOE) when testing the performance of a given material system in a given cure profile and tool configuration.

To add insight into computational time required for the three different methods, Table 5.1 shows how long an average desktop computer would take to run models over a full length cure for aircraft sized parts.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Computational Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D</td>
<td>Seconds</td>
</tr>
<tr>
<td>2D</td>
<td>Tens of Seconds To Minutes</td>
</tr>
<tr>
<td>3D</td>
<td>Varies depending on part size and complexity of mesh, but for aircraft sized parts/tools can be hours to days</td>
</tr>
</tbody>
</table>

Table 5.1: Relative computational time for an average desktop computer
5.2.1 Oven Cure Data Validation

Discussion

To first validate the 3D modeling methodology, a model is set up to mimic what occurs in an oven, i.e. 360° heat transfer to a tool/part combination. If the values in the model match those measured in previous experiments conducted back when the ovens and tooling were being qualified, then the conclusion is the methodology is sound, and that it can replicate real-world events inside an oven or autoclave.

Experimental Data Description

The experiment and associated data used to validate the modeling methodology were conducted prior to this study, and the author did not conduct the experiment. Details are only provided for comparison to the model. For the prior experiment, a skin laminate and tool were placed in an oven with 15 different thermocouples placed throughout the part. These were placed in important locations throughout the laminate. This included bottom of laminate, mid-laminate, and top of laminate locations of varying thickness. This data was gathered for the entirety of a typical cure profile to measure the how the part temperature changed as the resin cured.

Oven Model Geometry

To try and match this experimental data, a model of what occurs in an oven was created. The skin part family was chosen as a representative part-tool to model. This was done because the skins have the thickest lay-ups and thus the most potential for a high exotherm. This means if the model can capture the internal part temperatures (inclusive of the heat of reaction) in a complex lay-up such as a skin, then it can capture the proper parameters in the more simple spar and rib part families. The full 3D model of a skin and its associated tool were used in the heat transfer analysis. A simplistic geometric representation of the model set up is in Figure 5-1. The actual half-airfoil shape of the tool and laminate were used in the 3D model, but for the heat transfer and boundary layer calculations, the geometry was assumed to be a flat plate.
Only the tool face and composite layup were used in the model, as can be seen in Figure 5-2. The longer side of the tool would be in and out of the page, and the short side of the tool is shown left to right in the diagram. The backing structure and associated components was
determined to be too complex and would add too much computational time to the model, so they were not included. The tool face sheet is mechanically separate and simply supported from the backing structure; so it is able to thermally grow without affecting the backing structure. Although the backing structure could act as a minor heat sink, keeping it in the model would make things more complex than necessary.

**Meshing**

Simple 3D meshing techniques were used within the Abaqus software. Tetrahedral elements for the tool were used due to the complex local geometries and ease of creating mesh. Twenty-node non-linear heat transfer bricks were utilized for the laminate. The non-linear bricks were used to get mid-laminate temperature outputs. The laminate was only one mesh element thick because the aspect ratio of the elements had to be maintained even in the thinnest portions of the laminate. The laminate and tool were thermally and mechanically tied together using a tie constraint.

**Boundary Layer HTC calculations**

Heat transfer in a convection oven has two components: convective heat transfer and radiative heat transfer. For the convective heat transfer calculations, the below methodology was used.

Air is known to be flowing horizontally over the laminate and through the tool backing structure from the circulation fans in the oven. The heat transfer coefficients on the top, sides, and bottom were not assumed to be the same because of a few factors. First, the tool backing structure has many pockets and beams that partially impede the air flow on the underside of the tool. A lower HTC is used to reflect the limited air flow below the tool face. Air hitting the sides of the laminate and tool face is minimal, but is assumed to have the same HTC as the top of the tool and laminate. The vacuum bags and other consumables used the in the resin infusion process were not modeled.

The air velocity values were gathered from actual velocity measurements. One air velocity was chosen for the top (more free flow), and one for air flow under the bottom of the tool (restricted air flow). Both air velocities were assumed constant over the duration of the cure.
and then used, along with the known temperature gradient, (see Figure 5-6, to calculate the convective HTC seen across the part at each time step. The temperature, air velocity (assumed constant over the duration of the cure), and associated fluid properties (thermal conductivity, kinematic viscosity, and Prandtl number) of dry air were used as inputs to the heat transfer calculations.

\[
Re_L = \frac{V_{air} \cdot L}{\nu} \quad (5.1) \\
Pr = \frac{c_p \cdot \mu}{k} \quad (5.2) \\
Nu = 0.0296Re_L^{\frac{4}{5}}Pr^{\frac{1}{3}} \quad (5.3) \\
h = \frac{Nu \cdot k}{L} \quad (5.4)
\]

In the above equations, \(Re_L\) is the Reynold’s Number over flat plate, \(L\) is the length of the plate in the direction of the air flow, \(\nu\) is the kinematic viscosity of dry air, \(c_p\) is the specific heat capacity of dry air, \(\mu\) is the dynamic viscosity of dry air, \(k\) is the thermal conductivity of dry air, \(Pr\) is the dimensionless Prandtl Number, \(Nu\) is the Nusselt Number, and \(h\) is the convective heat transfer coefficient of air over a flat plate. All the air properties were provided at each temperature throughout the cure via a table of dry air properties at different temperatures.

The Reynolds Number for flow over a flat plate was calculated at every temperature \(T\) (it varies based on \(\nu\) of dry air at different temperatures). From this, it was determined to be below the \(Re_{cr}\) during the whole cure, and thus assumed to be laminar flow. The tool and laminate are not actually flat, but have an airfoil shape. The flat plate assumption is only used to simplify the calculations. This is mainly due to the relatively short cross-wise distance across the tooling that the air has to flow.

Effects from crosswise fluid flowing at sufficiently high velocity over a convex or concave shape can lead to vortices at the boundary layer; this was originally shown by Rayleigh, and are called Gortler Vortices [49]. These effects are being ignored for this study because the laminate isn’t perfectly concave or convex (half-air foil shape), and the velocities aren’t known exactly at all points along the leading edge of the tool, so trying to calculate the effect due to Gortler Vortices would not be beneficial for the accuracy needed for this study.
Using the calculated Reynolds number and Prandtl number of dry air at each given temperature, the Nusselt Number could be calculated via Equation 5.3. Using these values, the convective HTC can be calculated as per Equation 5.4 at each time step and corresponding temperature.

Convective heat transfer is only one of the heat transfer mechanisms at work in an oven, however. Radiative heat transfer from the walls, floor and ceiling into the tool and part also need to be taken into account. Monohan et al. estimate that up to 60% of the heat transfer in an autoclave is from radiation [35], and in an oven this would be similar. Park et al. found that the overall heat transfer coefficient in a convective oven can be described via the empirical equation 5.5 using velocity and temperature as an input [50]. This equation is shown in Equation 5.5, where $T$ is the air temperature in this case, and $v$ is the air velocity.

\[
h = 14.8v^{5.4} + 0.05T + 1.9 \quad [50]
\]

This equation was used to describe the overall heat transfer coefficient in a standard home oven, but the set-up was strikingly similar to the industrial oven. The experiment used an oven with cross-wise airflow across a loaf of bread (above and below), and the view factors to calculate radiative heat transfer from walls into an elevated loaf of bread for this experiment and what is seen in the present study with a skin tool in an oven would be very similar.

The above calculations then would output a top HTC and a bottom HTC (using two different air velocities) at every time/temperature step throughout the duration of the cure. These three values; time, air temperature, and top/bottom HTC, were then input as boundary conditions at the outer mesh surfaces of the 3D model.

The material characterization files were used to input the values needed in the heat transfer governing equation discussed in Chapter 3. All these inputs are sufficient for the model to run and output the variables described in the discussion section of this chapter for every time step.

Analyzing the output data at the exact same locations as those that were fitted with thermocouples in the previous experiment conducted could then show how well the model
performed. As can be seen in Figure 5-4 and Figure 5-3, the model appears to predict the maximum exotherm temperature quite well with all errors below 3% and the average error of 1.5%.

Figure 5-3: Model vs Experimental at 15 Points in Laminate

Because multiple fans are blowing air across the part, the velocity is probably different between the portion of the part in front of a fan outlet versus the portions between fan outlets. Additionally, the top and bottom velocities measured and used as an input could vary temporally and spatially during the cure, especially the lower air velocity, as the backing structure inevitably restricts air flow non-uniformly across the underside of the tool. What the model does not predict as well is the spread of temperatures as the temperature increases from the infusion dwell to the cure dwell (seen in Figure 5-4). This is most likely due to the assumption of one global HTC for the top and one global HTC for the bottom.
Figure 5-4: Oven Data Validation Full Results
5.2.2 Conclusion

The maximum exotherm temperature prediction agrees well with the experiment, despite the issues discussed in the previous section relating to the global top and bottom HTC assumption. What is important to note as well is that the locations P01, P03, and P09 in Figure 5-3 are from the bottom, middle, and top of the thickest portions of the laminate. They also have some of the least error in maximum exotherm prediction. This is a good result because it means the model predicts the temperature in the hottest portion of the laminate that is most likely to exceed the upper temperature limit in the cure specification. With a good prediction in the thick portions of the part, mitigations can be put in place to ensure they stay within specification. A single temperature measurement from the mid
laminate point of the thickest portion of the skin is shown in Figure 5-5. Overall, the model is in fairly good agreement, although the timing of the peak is slightly delayed, and graphs of the derivatives of each temperature plot show the experiment has higher rate of change leading up to the peak than the model.

5.3 Single-Sided Heating Model Formulations

5.3.1 Discussion

Three part families were chosen for the heat transfer analyses. Each represented a group of common part profiles seen in composite parts for commercial aircraft. These part families are ribs, spars, and skins. The goal of the modeling is to see how heat flows from a single-sided heating/cooling source through the tool and part at the fastest cure rates allowable by the material specifications, as shown in Figure 5-6. These accelerated cure cycles could have a 25% to 33% quicker process time than the current process.

A uniform temperature is applied to the nodes on the underside of the tool face sheet. This assumes any integrally heated technology would have to be installed on the underside of the tool face, and would be capable of achieving the fastest cure cycle rates of the material
specification. On the top and edges of the laminate, a heat transfer coefficient was used to simulate different insulative conditions. An effective HTC was varied and applied to the top of the laminate. The HTCs were applied as interactions to the element mesh surfaces in the model, as opposed to the heating profile applied directly to the element nodes.

5.3.2 Parametric Study on 1D vs 2D vs 3D Modeling

To begin, a parametric study was conducted to see how much a 1D, 2D, and 3D analysis differed on the same tool/part thickness and boundary conditions. For the 1D analysis, the only inputs needed are the material characterization files, the thicknesses of each component and the boundary condition. The HTC boundary conditions for the 1D analysis is basically shown in Figure 5-7, with the laminate thickness varied and a fixed tool thickness of approximately 12 mm. For the 2D analysis, the dimension in the x direction is also needed, and the model assumes symmetry about a central axis, see Figure 5-8. For this x dimension, 100 mm was used as the dimension from the central axis. This was used because of knowledge of realistic x-dimensions of pad-ups on a skin. The HTC boundary conditions on each of the sides of the stack shown in Figure 5-8 were calculated from the respective thermal conductivities of the laminate and tooling material, and the x-dimension. The top interaction was free air interaction of $\frac{W}{m^2K}$ was the baseline, and HTCs representing different insulation
thicknesses were used reducing the HTC down to \(0.5 \frac{W}{m^2\cdot K}\) as a minimum. The laminate thickness, \(t\), was varied from 1 mm to 12 mm, keeping the tool thickness, \(L\) at a nominal 12 mm.

Figure 5-8: Generic 2D Single-Sided Heating Model Diagram

The maximum exothermic temperature reached in the laminate was used as a proxy for model accuracy against the full 3D thermal model of a skin part. This is because control of this exotherm temperature is very important to stay within the cure specifications for the material system. Both 1D and 2D were compared against the baseline 3D model on this maximum temperature prediction. The full 3D model was only run for \(1 \frac{W}{m^2\cdot K}\) and \(5 \frac{W}{m^2\cdot K}\) top HTC. Different laminate thicknesses were represented within the full skin model, because of the long computational times of the full 3D model.
Figure 5-9: Maximum Temperature in a Skin Laminate for 1D, 2D, and 3D Models

Shown in Figure 5-9, the overall trend is that with increasing laminate thickness, the maximum internal temperature increases. This is expected, as the exothermic reaction is a function of the volume of resin, which increases with thickness. Also shown in Figure 5-9, the 1D model always overpredicts the maximum temperature as compared to the 2D and 3D model. This is due to the inability for the heat generated by the resin reaction to travel in the x-y plane (where the carbon fiber has the best thermal conductivity), but is forced to travel only through thickness. As discussed in Chapter 3, the through thickness heat transfer is dominated by the resin’s thermal conductivity. So, in the case of a 1D analysis where heat is only allowed to travel in the z direction, the heat transfer out of the laminate
will be relatively low, thus leading to higher internal temperatures. In addition, the variation of maximum temperature in the 1D models as the top HTC is changed is low. This is most likely due to the infinitesimal area over which the top HTC is applied, thus having little effect in wicking away heat even at $5 \frac{W}{m^2K}$. The 2D models (green lines), as expected, has a maximum internal temperature prediction between that of the 1D and 3D models. Another notable trend is that the values have a larger spread as the top HTC is increased. This makes sense, as now there is a larger area over which the HTC can wick away heat in the model.

Finally, the 3D model for $1 \frac{W}{m^2K}$ and $5 \frac{W}{m^2K}$ shows that on a full scale model, a free air interaction of $5 \frac{W}{m^2K}$ will take too much heat out of the laminate and it won’t actually reach the set temperature, except for in the case of the thicker laminates of 10 mm or greater.

This data gives an idea of when 1D, 2D, and 3D models can be used based on part thickness. The avoidance of the complex 3D model is paramount, given the computational and set-up time required to run the model.
Figure 5-10: Error of Maximum Temperature from 1D and 2D Models Compared to 3D Model

Figure 5-10 shows the average error of the 1D and 2D methods compared with the 3D method for the 1 $\frac{W}{m^2K}$ and the 5 $\frac{W}{m^2K}$ top HTC interactions. Depending on the accuracy desired for the analysis, this can delineate certain thicknesses where a 1D, 2D, or 3D analysis is sufficient. For example, if a maximum 3°C error or less is desired, then 1D can be used for up to 4 mm, 2D for up to 8 mm, and 3D for anything above that.
5.3.3 Parametric Study Conclusion

The parametric study was conducted to save computational time in subsequent analysis, and the results are presented above. An added reason this was conducted was to see the insulation effect on the maximum internal temperature of different thicknesses of laminates.

What can be concluded is that for single-sided integrally heated cures of a laminate with different thicknesses, different insulation requirements exist. For example, a thin section may need significant insulation to keep the heat in, while a thick portion may need less insulation so the extra internal heat generated can escape and not overheat the material. A 'spotty' or average thickness insulation may then be required to account for the different heat generation and removal requirements.

It is evident that the top heat transfer coefficient, and thus the insulation thickness has
a significant effect on the internal temperature, and thus cure performance. Deciding the
proper insulation thickness for a given thickness could be part of follow on work.

For an example thickness and top HTC, Figure 5-11 shows the difference in the tem-
perature trend and maximum exotherm temperature for a 1D, 2D, and 3D model for a 7.5
mm thick laminate. The 2D trend looks truncated due to the period in which the software
outputted data. The general trend, however is that the maximum exotherm temperature
will be highest for a one-dimensional, then two dimensional, then three-dimensional analysis.

5.3.4 Ribs

Now that basic geometric and boundary condition trials were conducted, the modeling
methodology can be applied to actual parts in order to investigate the results.

Ribs are internal structural components that, in this case, refer to the shorter fore-aft
supports seen in wings and wing sub-assemblies. For this case study, trailing edge ribs were
investigated because of the unique tool geometry required to support the narrow end of the
rib. A C-channel shaped rib was investigated for this study.

An important note is that as the c-channel profile of the rib becomes narrower towards
the trailing edge of the airfoil shape, the tooling beneath must get thicker. This means that
underside tooling thicknesses vary from the wide portion of the rib, to the narrow trailing
ing edge. A diagram of a rib profile can be seen in Figure 5-12. The optimal temperature
profile was applied at the underside of the tool, and an effective HTC representing 100mm
insulation was applied across the top. As shown in Figure 5-13, the performance of the rib
varies across the length of the part. On the narrow end, the tooling thickness prohibits rapid
heat transfer from below, and the part cures worse than in an oven. On the wider portion of
the rib (Element 1), the rib can cure more rapidly than in an oven. This disparity, however,
means that the overall part cannot cure as evenly as an oven. The temperature profile varies
too much from end to end of the rib.

In conclusion, although portions of the rib part are cured more rapidly than in an oven,
other portions are not. Thus, ribs are not a good candidate for a single-sided integrally
heated tool, strictly from a heat transfer point-of-view.
Figure 5-12: Profile of a Rib and Tool

Figure 5-13: Rib Tool Output

5.3.5 Spars

Spars are similar to ribs, but are usually oriented inboard to outboard on a wing or wing sub-assembly. They are also usually much longer and thicker. This is primarily to account
for the added strength needed to support the long moment arms of a wing. The shape studied here is a c-channel spar.

Figure 5-14: Profile of a Spar and Tool

Because spars do not have the tool thickness issue like trailing edge ribs, the part did cure better than an oven would. However, the c-channel geometry still poses a challenge for an integrally heated tool, mainly in the mechanical fitting of a heating technology to a curved surface.

In conclusion, spar tooling can perform as well or better than an oven, but the geometries can provide a challenge to fitting an integrally heated tool device to it. Further, since this study was conducted with a single thermal profile, it is obvious that a spar doesn’t need localized control, as the entire part stayed within the specification and had good thermal uniformity.

5.3.6 Skins

Skins refer to the large sheets of material that make up the profile of the outer surface of a structure. They attach to and enclose the structural parts such as the ribs, spars, stringers, etc. For composite skins, they usually have pad-ups, or thickness increases, in certain areas of the skin. This is to account for attachment points or areas where the skin needs added
strength. These thick areas of the skin pose a problem during a cure, as they have the highest risk of an exothermic reaction due to the larger volume of resin reacting during the cure.

The different heating requirements between the thick and thin portions of a skin composite laminate is a main motivation for this study. If an integrally heated tool could provide more heat to the thicker portion of the laminate without overheating the thinner portion of the laminate, then cycle times could decrease via localized temperature control.

The cure cycle performance of a skin under a single sided heating scenario was outlined in the parametric study of thermal modeling. A skin has the thinnest and thickest sections within it, and as shown in Figure 5-9, the maximum exotherm can vary a lot. This means the thinner portions would be fine under the more rapid cure cycle, but the thicker portions
would experience an exothermic reaction.

In conclusion, skins seem to be the best fit for an integrally heated tool. They need localized thermal control due to the widely different thicknesses on a single skin. They have constant tooling thicknesses, and relatively flat tooling geometries. Further, the skin cure is often the longest cure, and has the most to gain from decreasing the cure cycle time.

5.4 Conclusion

In this chapter, various heat transfer models were described and results presented. The oven analysis was conducted to prove the software capability, as well as to test assumptions on heat transfer into and out of a CFRP laminate from an oven. The model results agreed well with prior experiments.

Then, parametric studies on single-sided heating was conducted to see the effect of using 1D, 2D, and 3D analysis on an integrally heated tool set up. Conclusions were drawn as to when 1D, 2D, and 3D analysis should be used based on laminate thickness. Conclusions were also presented on how the different models predict the maximum internal temperature given different thickness and a top heat transfer coefficient.
Finally, the modeling methods were applied to real parts, and conclusions drawn that the skin part family has the best performance and utility of integrally heated tooling. Ribs lack a good tooling geometry to enable single-sided heating from below, and spars do not really benefit from or need localized control. Skins have poor thermal uniformity at faster cure rates and higher potential to deviate from the upper limit of the cure specification. They also have a roughly flat tooling geometry that enables single-sided heating and thus provides a potential improvement over an oven cure. Another reason why skin tooling benefits from the integrally heated concept is that skins are often cured as single units in the oven (not the case for autoclaves), and thus do not have the energy efficiency benefits of batch processing. This means all the energy used in an oven is allocated to that one part, while if multiple parts are loaded into an oven or autoclave, the amount of energy required is not doubled, yet the energy used can be divided by the two parts in the oven or autoclave. Therefore, integrally heated tooling benefits those parts that are large enough that they would be a one for one replacement of an oven with regards to energy usage.
Chapter 6

Scale-Up Analysis

This chapter discusses both qualitative issues of scaling up an integrally-heated tooling system in a CFRP manufacturing setting, and quantifies some hypothetical savings given numbers found in literature. It assumes that the heating technologies are indeed integral to each tool, and that there is only one tool per final part produced.

6.1 Operational Costs

Discussion

Operational costs for these systems are made up of labor, materials, and energy. Given that the same number of parts need to be cured whether one uses an oven or an integrally heated tooling system, it is assumed that labor and material costs of the cure are roughly equivalent. One could argue that with the lower cycle time of an integrally heated tooling system, one would need fewer personnel to operate the system. This conclusion, however, is misguided in that the labor costs are incurred mostly during the set up and take-down portions of the cure. The cure itself should run fairly autonomously. This means that labor costs are more correlated with the number of tools that need to be prepared for or removed from the curing station, and not the cure duration itself. Since the number of tools does not change whether an oven or an integrally heated tool is used (assuming no rate tools, discussed in the Capital Costs section), the labor and material costs also do not change.
In fact, set up and take-down costs may actually increase with integrally heated tooling because of the larger number control channels that need to be connected, initialized, and removed post-cure. Leaving out the effect of rate tooling and going back to the assumption of one tool set per CFRP part set means that, in reality, the main benefit in operational costs to integral heating would be the decrease in energy usage because of the shorter cycle times. There is not a 1:1 linear decrease in energy usage with shorter cycle times because the power used during each step of the cure is different, as discussed in Chapter 4, Section 4.3.1. Increasing ramp rates to decrease cycle times may even increase energy usage.

**Energy Savings**

Using the energy intensity data presented at the end of Chapter 4, and assuming all the energy comes from electricity, one can coarsely calculate the maximum energy benefit per kilogram of part cured using integrally heated tooling. For this, we must also assume that integral heating does indeed use less energy than an oven (untested as of yet). The range of values in Chapter 4 equate to 15 kWh-75 kWh of energy used per kilogram of part cured (lower bound for an oven, upper bound for an autoclave). Assuming electricity rates posted by the US EIA from 2015 for industrial customers of $0.066 per kWh, this means if one assumes that 50% of the energy used for each kilogram of part cured is saved (unlikely, but this is just to get an upper bound), then the maximum savings per kilogram per cure of composite part cured is $2.50/kg relative to an autoclave, and $0.50/kg relative to an oven.

Multiplying these numbers by the total weight of parts being cured and by the yearly throughput can yield energy savings.

\[ Y_{NRC} = \nu \cdot D \cdot G \cdot Q \]  

(6.1)

Where:

- \( Y_{NRC} \) = Total yearly energy savings from Integral Heating ($)
- \( \nu \) = Percent of expected energy savings (assumed as 50% in the above example)
- \( D \) = Energy-Cost Intensity ($/kg/cure)
- \( G \) = Total mass of parts being cured per shipset (kg)
\[ Q = \text{Total number of shipsets per year (batch cures)} \]

Assuming that the structure is roughly 25% of the Maximum Allowed Takeoff Weight (MOTW) of a current aluminum 737-800 NG [6, 57], and that roughly 20% weight savings can be achieved by composite over aluminum [21], this means \( 79,000kg \cdot 25\% \cdot 80\% = 15,800 \) kg of composite material is cured for every hypothetical fully composite 737 created. This means for each 737 produced, integrally heated tooling could save between \$8,000\) (compared to oven curing) and \$40,000\) (compared to autoclave curing).

At projected production rates of 52 per month, this means a hypothetical annual energy savings of \$5 - \$25 million per year. The lower bound would be savings over an efficient oven, and the upper bound would be potential savings over an inefficient autoclave.

The relatively arbitrary numbers used in the above calculation were for academic purposes and to get a rough ballpark of the operational cost savings.

However, assuming a similar \$104 million sticker price for a 737 MAX [51], the savings are less than 0.03% of the total price of a 737. The relative arbitrariness and roughness of above assumptions cannot be understated, but are provided only for context into the overall costs of a hypothetical future fully composite 737, as discussed in Chapter 2. This also assumes that all composite parts are made in house and that the manufacturer gets the full benefit of the energy savings.

### 6.2 Capital Costs

As discussed previously, capital costs of autoclaves are quite large and vary widely depending on diameter. For example, a case in the literature shows that a 3 m diameter by 9 m long autoclave was purchased in 1991 for roughly \$2 million, or roughly \$5.6 million in today's dollars [2]. Compare that with a 10 m diameter autoclave that NASA recently investigated purchasing at nearly \$100 million for the reusable launch vehicle hydrogen tanks (\$50 - \$70 million purchase + infrastructure) [31, 19]. Gruber et. al [20] did a trade study for different fabrication systems for this launch vehicle, and by backing out some of the numbers from their “Figure 2”, it is possible to compare capital costs between autoclaves and ovens. After subtracting out fiber/resin combination and placement equipment costs, and only considering
the curing (or “consolidation”) equipment costs, their assessment shows the un-amortized autoclave cost at approximately $50 million, while the technologies using an oven have capital costs between $2 - $3 million. On the low end, Verrey et al, using simple IR and Post-cure ovens for a Resin-Transfer-Moulding process cites a cost of €70 - €120,000 for rapid production of automobile floor pan quadrants with areas of roughly 1 m². For orders of magnitude, this means ovens cost from tens of thousands of dollars to a few million for the largest ovens [64, 20]. Autoclaves range from a few million USD for medium-sized autoclaves to possibly $100 million for the largest autoclaves in the world (from NASA) [31, 19, 2].

Integrally heated tooling capital costs suffer from scale issues. The cost of an autoclave is just one autoclave and it can cure any part. If an integrally heated tool is to be truly mobile and integral to a specific tool, it must be custom to that tool. This means engineering and associated unit costs do not scale down much with volume (because each one is a unique engineering challenge). In addition, where an autoclave or oven has one temperature controller, each integrally heated tool control zone would need a controller; resulting in controller costs to increase significantly.

The total capital cost of outfitting every tool for a given set of parts can be represented by making some simple assumptions on any given integral heating technology.

First, the cost of a layup tool is independent of this analysis; only costs associated with outfitting an existing tool with a given heating technology is considered. This analysis also assumes there is only 1 tool per part (no rate tools). Of the total integral heating cost for a given number of n tools, \( TCI_{HT} \), there will be material cost (the actual cost of the parts used to make an integrally heated tool), controller cost (costs of the system used for temperature, safety, cure control of the technology), engineering costs, and installation/commissioning costs.

\[
TC_{IHT} = C_{mat} + C_{cont} + C_{eng} + C_{inst}
\]  

(6.2)

where:

\( C_{mat} \) = Cost of Material
\( C_{cont} \) = Cost of Controllers
\( C_{eng} \) = Cost of Engineering
\( C_{inst} \) = Cost of Installation, Test, and Qualification
6.2.1 Material Costs

For material costs, the assumption is that cost scales with tool face area. Looking at the possible technologies presented in Chapter 3, this is not an unreasonable assumption. The materials costs for a given heating technology are:

\[
C_{\text{mat}} = C_{\text{mat,a}} \sum_{i}^{n} Q_{i} \cdot A_{i}
\]

(6.3)

where:

- \(C_{\text{mat,a}}\) = Cost of material per unit area for given heating technology
- \(Q_{i}\) = Quantity of Tool Design \(i\)
- \(A_{i}\) = Tool face area of tool design \(i\)

6.2.2 Controller Costs

For controller costs for a given number of \(n\) tools, the calculation may be less straightforward. The assumption is that the controllers will be mobile and interchangeable, and only need a local power source.

Because an integrally heated tool will have multiple temperature control zones, many input channels to a controller will be required. Based on standards for thermal control of a given zone for material processing, 3 thermocouples are required for each control zone: (1) Control Thermocouple, (1) Lagging Thermocouple, and (1) Leading Thermocouple. Three are needed to ensure that the entire thermal zone meets specifications related to lag/lead and that temperature uniformity is maintained. Controller outputs, to a control valve or a variable power supply, for example, are not considered in this study, but are an obvious and necessary part of any controller.

A given controller unit on the market will have a fixed number of input channels, and usually come in multiples of 8 (as is standard for any computer I/O module). This means there may be a mismatch between the number of input channels required and those available. For example, maybe the tool only has 10 control zones (and thus needs 30 thermocouples), but the nearest sized controller is 32 channel. The remaining 2 channels can’t really be used and thus are just spares.
The number of channels required is not only dependent on the layup tool face sheet area but also the complexity of the associated layup. Both area and layup complexity increases the number of required channels. The range can go from a simple small tool, a complex small tool, a simple large tool, a complex large tool, and everything in between.

This means that without knowing the geometry and layup design of every part, it isn't possible to estimate exactly how many channels will be needed. So, as a proxy, the simple estimated area of each tool type can be used to determine how many channels are required.

The scale factor $K$ is used to determine the number of independent control zones required for a given area, in units of $\text{zones/m}^2$. This value $K$ can only be determined with some knowledge of the general capabilities of the heating technology and the complexity of the layups.

For example, maybe the heating technology can only provide enough power to control temperature over a $0.5 \ m^2$ area of tool face, but the tooling is $10 \ m^2$. In this case $K = \frac{1}{0.5} = 2 \ \text{zones/m}^2$, and the number of channels is $60 \ (3 \cdot 2 \cdot 10)$. Therefore the number of input channels needed for each tool becomes:

$$H_i = \text{Ceil}(X)[3 \cdot A_i \cdot K]$$  \hspace{1cm} (6.4)

where:

$X$ = Multiples of input channels sold in a given controller on the market  
$H_i$ = Number of channels required per tool $i$, rounded up to the nearest multiple of $X$

In Equation 6.4, the ceiling function basically says that the number of channels needed per tool must be rounded up to the nearest multiple of $X$, because I/O channels for controllers only come in groups of $X$.

To complicate things further, it may make more financial sense to buy one 128 channel controller, and split it amongst any number of tools that will fit within those 128 channels, rather than buying a bunch of smaller 16 or 32 channel controllers. Then, it makes sense to partition the controller depending on what tool/parts are required to be cured at any given time.

Therefore, to convert the required number of channels to the required number of con-
Table 6.1: Tooling Area, Complexity vs Channels Needed

<table>
<thead>
<tr>
<th>Size/Complexity</th>
<th>Simple</th>
<th>Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Large</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>

trollers, divide the number of channels by the desired controller size, $S$ (for example, a 128 channel controller).

$$L = \frac{1}{S} \sum_{i}^{n} H_i$$  \hspace{1cm} (6.5)

where:

$L=$Number of controllers required for all tools

$$C_{\text{cont}} = C_{\text{cont,unit}} \cdot L$$  \hspace{1cm} (6.6)

where:

$C_{\text{cont,unit}}=$Unit cost of a controller of size $S$

### 6.2.3 Engineering Costs

Engineering costs will vary from tool to tool based on size and complexity. Because each layup tool is completely unique (although similar to other tools), the engineering for each integral heating technology will be unique. Therefore, costs will most likely scale roughly linearly with the number of tools. Although some overhead costs will benefit from scale, for the most part, designing an integrally heated tool for completely unique tools won't benefit from economies of scale. Therefore, engineering costs will scale as per below:

$$C_{\text{eng}} = C_{\text{eng,unit}} \cdot \eta$$  \hspace{1cm} (6.7)

$C_{\text{eng,unit}}=$ Unit Engineering Cost per Tool
6.2.4 Installation and Commissioning Costs

These costs are difficult to estimate, but the largest component of these costs will be the certification of each thermal control zone. International standards on thermal control of materials processing require each thermal control zone to be independently certified. In the case of an integrally heated tool, this means multiple certifications per tool.

In an oven or autoclave, with only one thermal zone of control (the entire internal volume), these costs are much smaller. This is one of the major downsides of integral heating with multiple thermal control zones. These costs are not trivial and often make up a significant portion of commissioning costs.

Further, these thermal control zones need to be re-certified after a fixed period of time, adding to the operational costs (and possible downtime for testing/re-certification).

In any case, the cost of commissioning can be estimated solely based on the number of control zones, stated previously.

\[ C_{\text{inst}} = C_{\text{inst,unit}} \cdot K \sum_{i} A_{i} \]  

(6.8)

where:

\[ C_{\text{inst,unit}} = \text{Certification costs per control zone} \]

6.2.5 Incumbent Costs

For a greenfield site, comparing the total capital costs of the integrally heated tooling versus the total capital costs of new ovens or autoclaves can help determine, in conjunction with operational cost differences, which technology is a better financial choice. Actual costs of autoclaves and ovens was discussed in 6.2.

Because autoclaves and ovens offer more flexibility, fewer are needed than the total number of tools. Grouping part families together and designing ovens to be the proper size for these part families is a common choice by manufacturers. For example, an oven dedicated to skins, and oven dedicated to spars, and an oven dedicated to ribs may be chosen for the system design.
Another advantage for ovens and autoclaves is that they can be copied to scale up a process. This means the second, third, or fourth unit, can be acquired at a cheaper price than the first because they are exact copies. Integrally heated tooling does not benefit from this, as each tool is unique.

First, take into account the quantity of ovens required for a given throughput, cycle time and number of tools for the manufacturing process. Then compare this with of the cost of acquiring $Y$ number of ovens for the $n$ number of tools to match the throughput that an integrally heated tooling system design could achieve.

The detail in these calculations will not be discussed, but an assumed cost of $C_Y$ for the total capital cost of using incumbent technologies can be used for comparison.

### 6.2.6 Incumbent vs Integral Heating

Setting $C_Y$ equal to a scaled $TC_{IHT}$ from Equation 6.2 can determine how much cheaper an integral heating system design would need to be to be competitive on a capital cost basis. This is expressed per below:

$$C_Y = \alpha \cdot C_{mat} + \beta \cdot C_{cont} + \gamma \cdot C_{eng} + \kappa \cdot C_{inst}$$

Where:

- $\alpha$ = Material Cost Scale Factor
- $\beta$ = Controller Cost Scale Factor
- $\gamma$ = Engineering Cost Scale Factor
- $\kappa$ = Installation/Commissioning Cost Scale Factor

The individual scale factors in Equation 6.9 can be used with Solver to make the two sides equal. Following this, it is possible to determine what fraction each cost component needs to be in order to compete with an oven or an autoclave in capital costs. This equation is useful in determining how much known R&D costs for a given technology would need to scale down on a per unit basis in order to be competitive.

For example, if it is determined that 25 ovens are needed to cure 100 tools/parts at the desired throughput, this cost of 25 ovens can be compared to the quoted costs for outfitting
100 tools with a given heating technology. In this example, the per unit costs of designing and installing a heating technology on a tool would need to be 25% of the cost of an oven to be competitive.

Using individual scale factors for the cost components of an integral heating technology allows the user to selectively decrease costs that may be more likely to scale down (like material purchased in bulk) and determine the sensitivity of the total unit price to individual cost components (materials, engineering, controllers, commissioning) via the scale factors.

Finally, if one were to include the hypothetical energy savings of 50% over an oven or autoclave discussed in the previous section, then one could add the NPV of the annualized energy savings over the life of the system (say 15 years) to the $C_V$ value, which would allow for a more expensive upfront cost of the integral heating, as long as the energy savings are real and accurate throughout production.

It should be noted that this 50% energy savings is an arbitrary value and is assumed to be an upper bound.

6.2.7 Rate Tools and High-Rate Production

If a system has rate tools (more than one tool per part) to achieve a high rate, then the integral-heating technology would need to be installed on all tools, thus increasing the costs of a roll-out even greater. However, if the cure cycle is the rate-limiting step (the longest step in the entire process), then the reduction in cure cycle time could reduce the overall fabrication time and in turn decrease the number of tools required over the number required for an oven or autoclave curing scenario.

It is very important to note that if the cure cycle is not the rate-limiting step, then reduction in cure cycle times do not reduce overall fabrication times. However, going with this assumption, some simple calculations can be done. For example, in Chapter 4 a theoretical reduction of 25% to 33% in cycle time was mentioned. If this translates into overall cycle time reduction, and assuming there are a $n$ sets of rate tools (copies of each tool to make rate), then the reduction on tooling requirements (all else being equal) could theoretically be $0.66n-0.75n$ sets of tools required. This directly reduces tooling costs by the same percentage (25% to 33%) and also decreases associated variability with having rate tools that aren’t
exactly geometrically equivalent. It should be noted that in many CFRP manufacturing applications there is only one set of tooling per set of parts required.

The obvious downside of integrally heated rate tooling is that now every set of tooling needs to be outfitted with the heating technology. This may not increase costs linearly due to economies of scale gained from copying designs for each set of tooling, but the cost will still increase with the number of tools. This makes it that much more difficult to be competitive with incumbent technologies like ovens.

Therefore, integrally heated tooling as a solution for making rate needs to be looked at critically from two angles. One, is the cure step the rate-limiting step of the overall fabrication cycle? Two, is the cost of outfitting $n(1 - x\%)$ (where $x$ is the percent cycle time reduction) fewer tools with integral heating cheaper than having $n$ set of tools with incumbent technologies?

### 6.3 Reliability

Reliability of an integrally heated tool can have both positive or negative effects. Compared to an autoclave with many parts in it, a failure of an integrally heated tool mid-cure will lead to the loss of only one part; and not all the parts in an autoclave if it were to fail. However, autoclaves and ovens also often have redundant heating systems and circulation fans, so they are less likely to fail than an integrally heated tool. This means the reliability of an integrally heated tool must match the reliability of an oven or autoclave without these redundant systems. The reliability of thermocouples and associated wiring curing a cure is the same in both cases (i.e. one thermocouple can be lost in an autoclave and result in only one lost part, and this is the same for an integrally heated tool).

One could do calculations matching the likelihood of failure times the cost of a failed oven or autoclave cure versus the (likelihood*cost) of a failed integrally heated tool cure. This is an overly simplified example, but can be applied to any system when comparing a new technology to an incumbent.

\[
P(F)_{oven} \cdot (F)_{oven} = P(F)_{IHT} \cdot (F)_{IHT}
\] (6.10)

95
Where:

\[
P(F)_{\text{oven}} = \text{Probability of failure of an oven} \\
C(F)_{\text{oven}} = \text{Cost of failure of an oven} \\
P(F)_{IHT} = \text{Probability of failure of an integrally heated tool} \\
C(F)_{IHT} = \text{Cost of failure of an integrally heated tool}
\]

For example, if an oven was 99.9% reliable, and the average part loading in an oven was 4 parts valued at $1,000 each, then the weighted cost of failure is $4,000 * 0.001 = $4. Given that an integrally heated tool would only lose one part if it failed, then the cost of failure is just the $1,000 of the single failed part. Solving for the required reliability of the integrally heated tool, \(1 - \frac{4}{1,000} = P(F)_{IHT} = 99.6\%\) reliability.

This does not take into account the cost of rework because it is only the ratio that is important. Rework would theoretically have the same ratio between the two options; only the magnitude of the cost of failure would change.

However, in order for the new technology to be superior to the incumbent, the integrally heated tooling system must also have the same availability as an oven or autoclave. This means not only does it have to be as, or more, reliable (as calculated above), it must also be available for use for as much time as possible (with limited scheduled downtime and quick repairs).

With the large increase in thermal control zones, this means that re-certification all zones will require much more down time than re-certifying an oven or autoclave with one thermal control zone. This could potentially increase costs even further if the layup tooling isn't available for use due to re-certification. This would put the entire system out of service without tool duplication (a very expensive option). Even if one were to stagger the re-certifications, having one tool out of service holds up the whole process, because every part is required to make the final assembly. If one part cannot be made, the final assembly cannot be made.

Further, looking at the technologies in Chapter 3, they appear to be fairly specialized technologies. This means that any failure would require special components that need to be kept on hand for a quick repair. If there is any lead time for a repair, this essentially puts the entire operation on hold. Ovens benefit in this regard in that most of the components
are readily available in the market (fans, electric heater banks, etc). If an oven fails, one can just redo the layup and put the tool into a different oven and the system can continue until the oven is repaired.

6.3.1 Conclusion

Reliability (probability of failure on demand) and total availability (low scheduled maintenance time or downtime in addition to reliability) must be similar to what an oven or autoclave can offer in order to be adopted in industry. Although the individual cost of failure of an integrally heated tool may be less than an oven, on a system level, a tool failure is much more dangerous than an oven failure. This is because a single integrally heated tool failure can hold up the entire assembly until it is fixed because the final assembly will be waiting on that part.

The added complexity (more and more complex parts) of an integrally heated tool would imply a less reliable system. The reliability and availability of a new and complex technology would need to be carefully considered before adoption.

6.4 Support and Safety Systems

For any integrally heated tool, support and safety systems will be required. Many of the support systems in an oven would still be needed, such as vacuum pumps, temperature controllers, thermocouple connections, and electrical connections (if electrically heated). Further, if a tool is not enclosed in a large oven or autoclave, barriers must be put in place to prevent people from touching tools or connectors that may be in excess of 180°C. If insulation is used, then a space to store the insulation between cures will also be required. This alone can take significant floor space, especially for large skin tools. The added space for storing insulation may counteract the benefit from removing an oven or autoclave. This is especially true if the insulation is custom to each tool.

Systems to remove air from an area should a runaway exothermic reaction take place (producing harmful smoke) would still need to be present. The tool would not be enclosed like in an oven or autoclave, so there is increased risk of this smoke escaping and reaching
many people.

Other concerns surrounding support systems are the electrical connections. If a large skin tool is electrically heated (such as QPoint), then the power required for such a large tool may be so large that a plug-and-play type set up would not be feasible. For safety, a hardwired connection would be required. This negates some of the mobility benefits of integrally heated tooling.

A technology-specific concern for an integrally heated tool that uses compressed air and local heaters to provide heating to the tool is the energy cost of the compressed air system. A compressed air system for a large scale roll out of integrally heated tooling would be large, and the operational costs would also be large. Using compressed air instead of recirculating air (as in an oven) means more air usage and the costs of operating a compressed air system for an entire production process would be large.

6.5 Conclusion

Integrally heated tooling still needs many of the support systems that ovens require. To get the full benefit of a mobile, integrally heated tool, the support systems would need to be mobile, shared among many tools, or adaptable to any tool at any time. The benefits of the mobility, however, come with many drawbacks.

Operational cost savings can be boiled down to energy savings alone; and as calculated in this chapter, these energy savings are fairly small relative to the total cost of the plane. The indirect monetary risks (such as reliability concerns of a complex technology) need to be taken into account if integral heating is to be used.

The capital cost of outfitting every tool can be large, and determining what the required costs are to be competitive can be useful in early analysis of a technology. The capital and operational cost comparisons discussed above can help steer decisions early in the process. Anecdotal evidence has shown that ovens are relatively cheap capital expenditures, and thus integral heating has a high bar to clear to be cost competitive with ovens.

These concerns do not, however, fully detract from the benefit of integrally heated tooling, and are only items that need to be addressed as research continues.
Chapter 7

Conclusions and Recommendations

In this paper, integrally heated tooling for the cure of a resin infused CFRP aerospace composites was investigated. The “more for less” context facing aircraft manufacturers was presented in Chapter 1, showing the pressure to produce more aircraft for less cost and in less time.

In Chapter 2, the background of composite manufacturing was presented, describing the differences between an autoclave and an oven curing process.

In Chapter 3, a literature review provided descriptions of CFRP manufacturing and the energy usage thereof. CFRP materials and properties were also discussed in this Chapter, and the progress of modeling the CFRP cure process was presented.

In Chapter 4, An energy analysis of ovens and autoclaves in an industrial setting was undertaken. This was done by matching many different parameters of usage over long time frames with monthly bills to find the energy usage per run of the autoclave. Ovens energy usage was directly measured. Results showed fair agreement with the literature and provided context for what an integrally heated tool would need to compete with as far as energy intensity.

Following this, in Chapter 5 a full heat transfer analysis was conducted on an oven cure to prove the methodology against prior experimental data. Then parametric studies on laminate thickness and top HTC were undertaken to get an idea on what issues and integrally heated tool would face with single sided heating. This exercise also showed when a 1D, 2D, and 3D analysis was suitable.
After this, Chapter 5 also provided thermal models of actual aircraft parts and the results presented. It was concluded that the skin part family was the best suited for an integrally heated tool technology. It was determined that ribs and spars were unsuitable for integral heating. Spars do not need the added temperature control, as they already have a fairly uniform thermal profile. Ribs suffer from complex geometries in the tooling, and thus are unsuited for single-sided integral heating. Skins are most suited because they have both a suitable tooling geometry (relatively flat and constant thickness), and a complex layup (large difference in part thickness).

Finally, a scale-up analysis related to costs and auxiliary considerations of a full integrally heated tool roll-out to a production scenario were discussed in Chapter 6. In this section, the operational cost savings were determined to solely come from energy savings, and those energy savings were put into perspective, showing very low overall savings relative to the total cost of a theoretical all-composite 737 sized aircraft.

7.1 Conclusions and Recommendations for Future Initiatives

It is recommended to continue research on integrally heated tooling, focusing on large skins as a potential candidate. Chapter 5 showed that the rib part family struggled to maintain thermal uniformity, and that although the spar part family had great thermal uniformity, the c-channel shape can cause problems for installing integral heating. Chapter 4 showed us that the energy intensity of incumbent ovens is fairly low, and so the benefit of an integrally heated tool will be more on cycle time reduction than on energy savings. This means that only the part families that struggle with exotherm potential (skins) would benefit from the local thermal control that integrally heated tooling provides. Spars showed a minor exotherm when exposed to the fastest cure rates allowed by the specification, but it still fell within the upper temperature allowed by the specification.

With regards to the physical roll out of integral heating, it is recommended to do a ‘spotty’ approach. It is recommended to use a reliable oven for the large majority of the
part that does not need the active temperature control provided by integrally heated tooling and only use the localized heating control for the thickest portions of the laminate. A thermoelectric device would be a good candidate for localized heating/cooling control while still utilizing the reliability and cost-competitiveness of an oven. Thermoelectrics can both provide auxiliary heating and auxiliary cooling with the same device just by changing the direction of current flow. These devices are solid-state, have no moving parts, are relatively simple and are readily available. They are also very scalable and can have thin profiles. The thin profiles are advantageous if being applied to the underside of a tool face.

Finally, full 3D modeling, although interesting, does not need to be utilized for all laminate thicknesses. Thinner laminates can utilize simpler 1D and 2D models even though they may introduce error. This can save the company significant time in performing thermal models of a cure, while still allowing for a robust design informed by quality thermal performance data.

In conclusion, heating a part from the underside of the tool face while utilizing an insulation blanket over the top does appear to provide benefits over oven curing for certain part families, and can lead to faster cure times. The energy usage difference, although theoretically less, is not as great as anticipated, due to ovens being more efficient than previously thought.

Although integrally heated tooling has faced, and will face, many challenges to be widely utilized in industry, this investigation proves its effectiveness in single-sided heating and provides recommendations and thoughts on where to go with future investigations.

Cost and delivery pressures do not appear to be going away any time soon, so if manufacturers are to stay ahead of competition, they must continue to investigate technologies like integrally heated tooling for the curing of advanced aerospace composites.
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