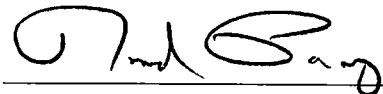


To the Graduate Council

I am submitting herewith a thesis written by Anh Hoang Ly entitled "Computer Simulation and Experimental Validation of a Ceramic Core Injection Process" I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science, with a major in Mechanical Engineering

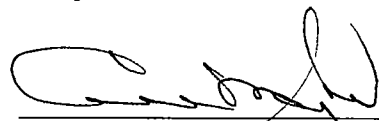


Masood Parang, Major Professor

We have read this thesis
and recommend its acceptance



Accepted for the Council



Associate Vice Chancellor and
Dean of the Graduate School

EXPERIMENTAL VALIDATION OF COMPUTER SIMULATIONS OF CERAMIC CORE INJECTION PROCESSES

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Anh Hoang Ly

December 2000

DEDICATION

This thesis is dedicated to my lovely grandmother and mother

Mrs. Võ Thị Lành

for her love and inspiration

and

Mrs. Lý Thị Dung

for her love, sacrifice, and constant support that made all thing possible in my life

also

In memory of my grandfather



Mr. Lý Văn Ngũ
(1923 - 1973)

ACKNOWLEDGEMENTS

I would like to thank my major professor, Dr. Masood Parang, for his guidance throughout my research, for his advice and assistance in preparing this thesis, and most of all for his patience and continuous support. I would like to thank my other committee members, Drs. Rao V. Arimilli and J. A. M. Boulet, for their valuable time, effort, and comments during their review of this thesis.

I am very grateful to Howmet Research Corporation for their financial support which made this research possible. In addition, I would like to thank Mr. Keith Jackson for allowing me to conduct my research experiments during my graduate co-op assignment at Howmet Morristown Casting Support facility. I would like also offer a special thanks to Dr. John Johnson at Howmet Corporation for his continuous active support of this research. Hopefully, the success of this research will enhance and strengthen the relationship between Howmet Research Corporation and The Advanced Casting Simulation and Mold Design Laboratory at the University of Tennessee, Knoxville directed by Drs. Arimilli and Parang.

Finally, I would like to thank the following people for their assistance during my study and research at the University of Tennessee:

Dr. Ke Nguyen for his advice and support throughout my undergraduate years.

Mr. Dennis Higdon for his advice and insight on data acquisition and calibration check of experimental equipment throughout the period of my research.

Mr. Eric Robbins for his modeling and simulation efforts that made this research possible.

The Mechanical and Aerospace Engineering and Engineering Science Department for supporting me financially throughout my graduate study.

ABSTRACT

In this study, a computer simulation of a three-dimensional transient ceramic injection molding (CIM) process, developed by the Advanced Casting Laboratory at the University of Tennessee for Howmet Research Corporation, was experimentally validated. Experiments were designed and conducted to measure temperature of ceramic core material as a function of time for both filling and packing stages of the injection molding process. In addition to fluid temperature, die wall temperature data were also collected for this analysis. The results were used to validate the CIM model to insure that ProCAST simulation is realistic and accurate.

The experiments were conducted under production conditions at Howmet Casting Support manufacturing facility in Morristown, Tennessee. The temperature data were taken at both 30-milliseconds and 60-milliseconds sampling rates. A total of twenty experimental runs for each sampling rate were conducted. An error band was developed from the results of the experiments. The temperature data are presented here in non-dimensionalized form so that they can be used for validation of computer modeling simulations under various initial and ambient conditions.

The results indicate that the average heat transfer coefficients (h) in the range of $1,800 \text{ W/m}^2 \text{ K}$ to $2,200 \text{ W/m}^2 \text{ K}$ best represent experimentally observed thermal characteristics of the filling and solidifying process. The flow patterns observed from short shot pictures are best approximated by flow simulation patterns using isothermal wall boundary condition. Also, the computer model accurately predicts the high shear heating observed at specific locations in the cavity during the filling process.

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LIST OF SYMBOLS AND ABBREVIATIONS

ACSMDL	Advance Casting Simulation and Mold Design Laboratory
A/D	Analog to Digital
CIM	Ceramic Injection Molding
DME	Detroit Mold & Engineering
HRC	Howmet Research Corporation
MHz	Megahertz
UTK	University of Tennessee, Knoxville
h	Convection Heat Transfer Coefficient, $\text{W/m}^2 \text{K}$
Q	Energy Transfer, W/m^2
T	Temperature

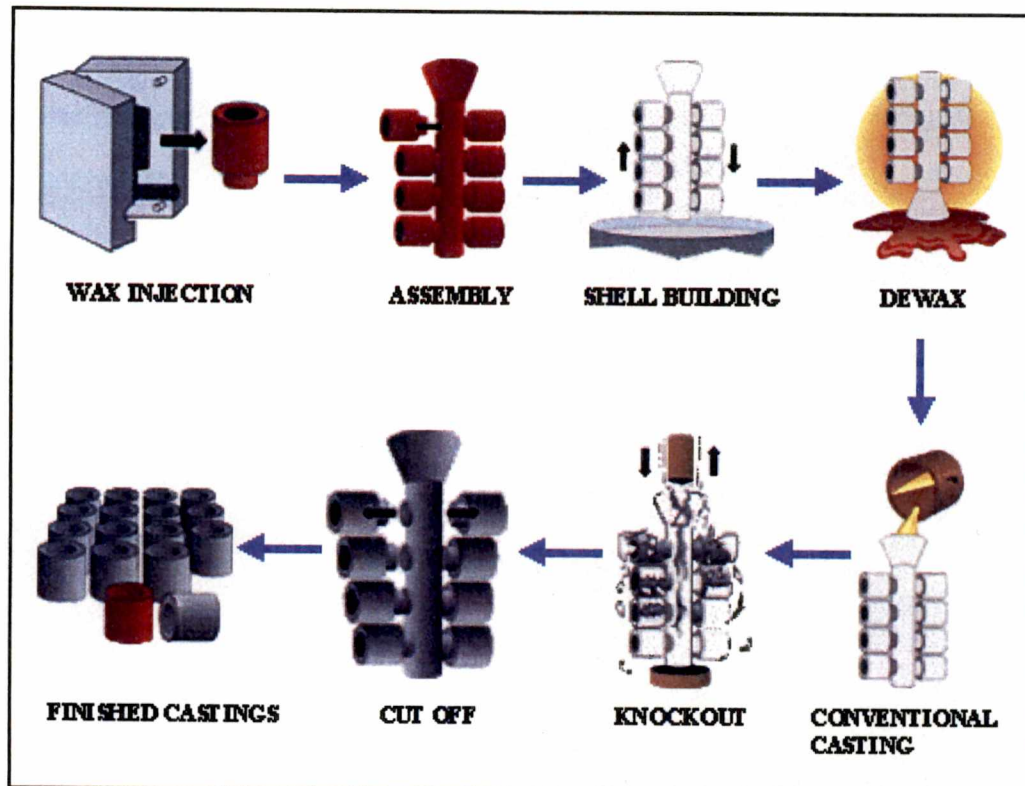
CHAPTER 1

INTRODUCTION

1.1 INVESTMENT CASTING

The modern investment casting process can be traced back to the ancient Egyptian and Chinese civilizations. The technique used was similar to what is now known as the “lost wax” process. This technique was used in the production of intricately designed ornaments and religious objects. The basic idea is almost as old as plain sand or earth mold casting. The modern process involves an injection molding to form the wax patterns of the desired casting. These patterns are attached to a sprue to form an assembly. Up to eight layers of shells are built around the assembly with combination of liquid ceramic slurry and fine sand. After the shells are dry, the wax is melted out leaving a negative impression of the assembly within the shell. The shell is then filled with molten metal in the conventional process. After the metal has solidified, vibration and water blasting are used to break-off the shell. The parts are then cut away from the central sprue with a high-speed friction saw. After a minor finishing operation, the parts are ready to be shipped to the customer.¹ The basis of the investment casting process can be viewed in Figure 1.

Today, investment casting is one of five techniques used for “precision” casting of liquid metal. The others are gravity die casting, pressure die casting, plaster mold casting, and shell sand mold casting. Of these various techniques, investment casting is the most flexible with respect to attainable intricacy, dimensional accuracy, and freedom of design in a wide range of cast alloys. Besides competing with other types of casting



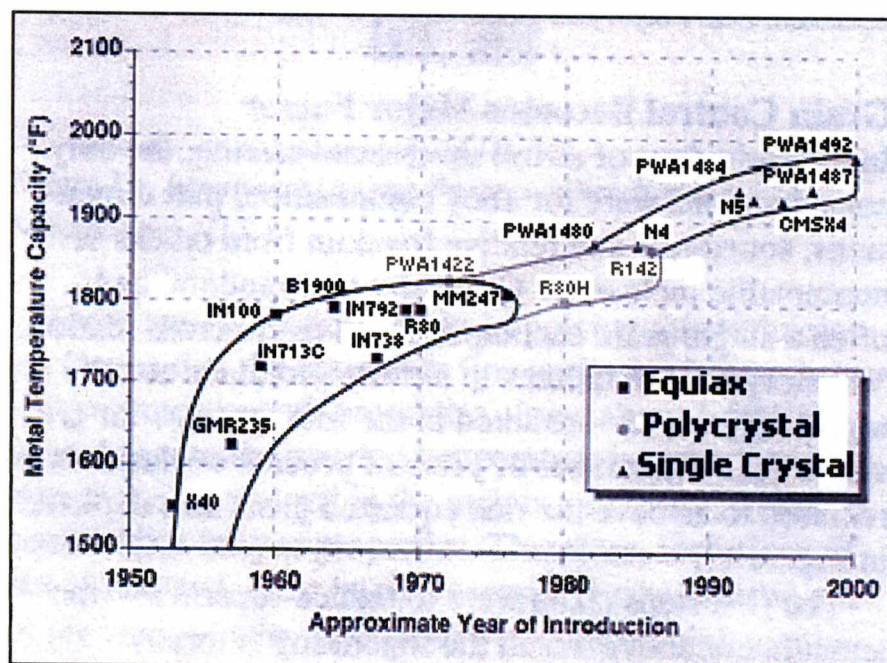
(Courtesy Hitchiner Manufacturing Company, Inc.)

Figure 1 The basics of the investment casting process

techniques, it also competes with powder metal products, forgings, stampings, spinnings, coined parts, weldments, solderments, brazements and innumerable assembled parts held together with rivets, pins, bolts or other fasteners. Investment casting popularity is due to its ability to produce near-net-shape components, which allows the manufacturer to reduce production price and stay competitive. The investment casting process makes it possible to substantially reduce or to eliminate fixturing costs, machining operation costs, and assembly operation costs. Industry did not seriously begin to utilize investment casting until the developments of the jet engine turbine bucket production program during World War II. The extreme mechanical and thermal stresses imposed on the turbine blades in the fiery combustion chambers of an aircraft engine could not have been met except for the availability of this process.^{1,2}

1.2 CERAMIC CORE INJECTION MOLDING

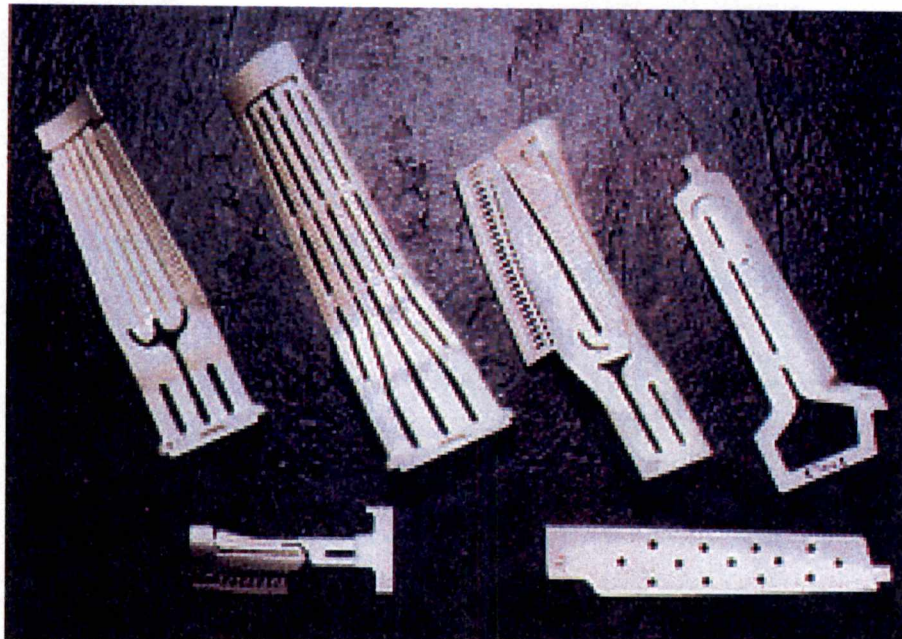
In order for the casting to be made hollow, as in air-cooled turbine blades and vanes, a ceramic core needs to be inserted in the die cavity and the liquid wax injected around it. Starting in the early 1950's, the development of superalloys and advancement in the design of internal air cooling passages have allowed gas turbines to increase their operating temperature and thereby improve performance. As illustrated in Figure 2, advancement of technology in "growing" crystals or improved grain structure have allowed metal temperature capacity to go from 1550 °F to nearly 2000 °F within a 50-year span.³ The type of solidification process will determine whether a casting is "equiax" (randomly distributed, controlled size crystal), "DS" (directionally solidified where crystals grow only in the lengthwise direction), or "Single Crystal" (one crystal makes up the whole casting). From Figure 2, one can see that metal temperature



(Courtesy of Howmet Corporation)

Figure 2 Contributions of cast alloys and processes to engine performance

capability reached a plateau by the early 1970's and engine performance improvements would have been significantly hampered were it not for internal air cooling that was made practical with the investment casting process.³ These highly detailed and geometrically complex designs of internal cooling channels are made possible by the existence of a ceramic cores (see Figure 3). Ceramic cores are manufactured through the use of a



(Courtesy of Howmet Corporation)

Figure 3 Intricate design of turbine ceramic core

ceramic injection molding (CIM) process.⁴ This process was patented as early as 1929. The principle advantage of CIM over other casting processes is the ability to form complex-shaped parts that are dimensionally accurate and have smooth surfaces. In the CIM process, important parameters for both the product and mold design are wall thickness, wall thickness transition, parting line, drafts, fillets, radii and ejector pin marks. Furthermore, size, shape, and location of the gate and runner need to be addressed. Since CIM uses conventional plastic injection machines, the maximum shot

volume, clamping pressure and the number of cavities have to be taken into account in relation to tooling costs and the unit price of the part.⁴ The process begins with a mixing of ceramic powder with a blend of polymers (wax binder) to break up the soft agglomerates in order to get a homogeneous feedstock. The main function of the wax binder is to reduce the static coefficient of friction.⁵ The flow characteristics of the mix, its subsequent moldability, and the quality of the final parts all depend on the homogeneity of the mix; so the preparation of the mix is a key factor. After granulation, the heated feedstock of ceramic slurry is injected into a cooled mold forming a green part through the use of an injection-molding machine. The green core then goes through a dewaxing process to wick out the organic binder prior to the sintering process. The dewaxing process is extremely important since it allows major binder ingredients to escape prior to sintering at high temperature without causing the part to crack and warp. In the sintering process, minimal shrinkage is permissible to achieve the required dimensional consistency while providing sufficient handling strength. Porosities are often 30% or higher for leachability. After sintering, every core is checked intensively to insure that it meets the most exacting design specifications and customer dimensional tolerance requirements. For all cores that pass gauging, both machine and hand finishing, using special diamond cutting tools and files, are done in great detail. A final quality control inspection insures that only good parts are shipped to the customer.

1.3 HOWMET – UTK CASTING RESEARCH PROJECTS

Howmet Corporation Casting Support located in Morristown, Tennessee is a leading supplier of high-volume production of complex ceramic cores used in the casting of reactive and nonreactive single crystal, directional solidification and equiax alloys.⁶ Several types of ceramic cores are manufactured by Howmet. The technology used in developing these core bodies is proprietary. The process of manufacturing a core is difficult and time consuming. Forming the cores without cracks, voids, and knit line is by itself a formidable task. In addition to making good parts and making shipment schedules, engineers also have to deal with die wear. Core dies often cost on the order of hundreds of thousands of dollars, which is a significant investment for any company.

Due to the high competitiveness of the ceramic core industry, engineers at Howmet evaluate means to improve both the design and the process of ceramic injection molding (CIM). Since 1997, Howmet Corporation Casting Support has worked with the Advanced Casting Simulation and Mold Design Laboratory (ACSMDL) at the University of Tennessee. This cooperation is focused on developing a computer model of a three-dimensional transient ceramic/wax injection molding (CIM) process including filling and solidification segments. A group of three mechanical engineering students, Christopher Strack, William Satterfield, and Roy Zeighami, participated in a Howmet project (1997 - 1998) to develop a 3-D solid model of the core, which included different combinations of fluid type, heat transfer, geometry and number of vents. In the spring of 1998, the group presented the results in a report entitled "Computer Simulation of the Ceramic Injection Molding Process" to Howmet Morristown Casting Support engineers and researchers at the University of Tennessee.⁷

The 1999 - 2000 ACSMDL – Howmet project focused on the modeling of a specific core geometry selected by Howmet Corporation. The project consisted of two parts: computer modeling and experimental validation of the developed model. The responsibility for the modeling was given to Eric Robbins,⁸ who is preparing a final report on this aspect of the project. The responsibility for conducting the experiments to validate the computer model became the primary responsibility of the author, Anh Ly. Therefore this thesis is mainly concerned with the experimental aspects and the model validation efforts in this (1999 – 2000) phase of the Howmet project.

1.4 STATEMENT OF THE PROBLEM

In order for engineers, researchers, and tool designers at Howmet Corporation to implement computer modeling and simulation in their die and core production design, the computer modeling and simulation of a three-dimensional transient ceramic/wax injection molding (CIM) process including filling and solidification must be realistic and accurate. The validation of computer models and simulation is a critically important part of this process. Therefore, the main objective of this thesis was to design an experiment to measure the material temperature variation in time during the injection molding process (CIM) and use the results to validate the three-dimensional transient model of the same process. The experiments were conducted at Howmet Casting Support manufacturing plant in Morristown, TN. The experiments included temperature measurements for both filling and packing stages of the injection process.

The motivations for this study are to use the results to improve the quality and reduce production costs of the cast products. The current ceramic injection process at

Howmet requires constant maintenance of core dies due to wear induced by the high pressure, high velocity injection needed for complete filling of the core before solidification begins. The highly viscous ceramic material requires frequent chroming of the die cavity to insure minimum core pattern erosion. The cost of repair and maintenance of core dies and the down time during maintenance contribute to the high price ceramic cores. Computer modeling makes it possible to optimize for maximum die life and minimum core die maintenance by reducing injection speed and pressure while obtaining non-defective high quality ceramic cores.

CHAPTER 2

REVIEW OF LITERATURE

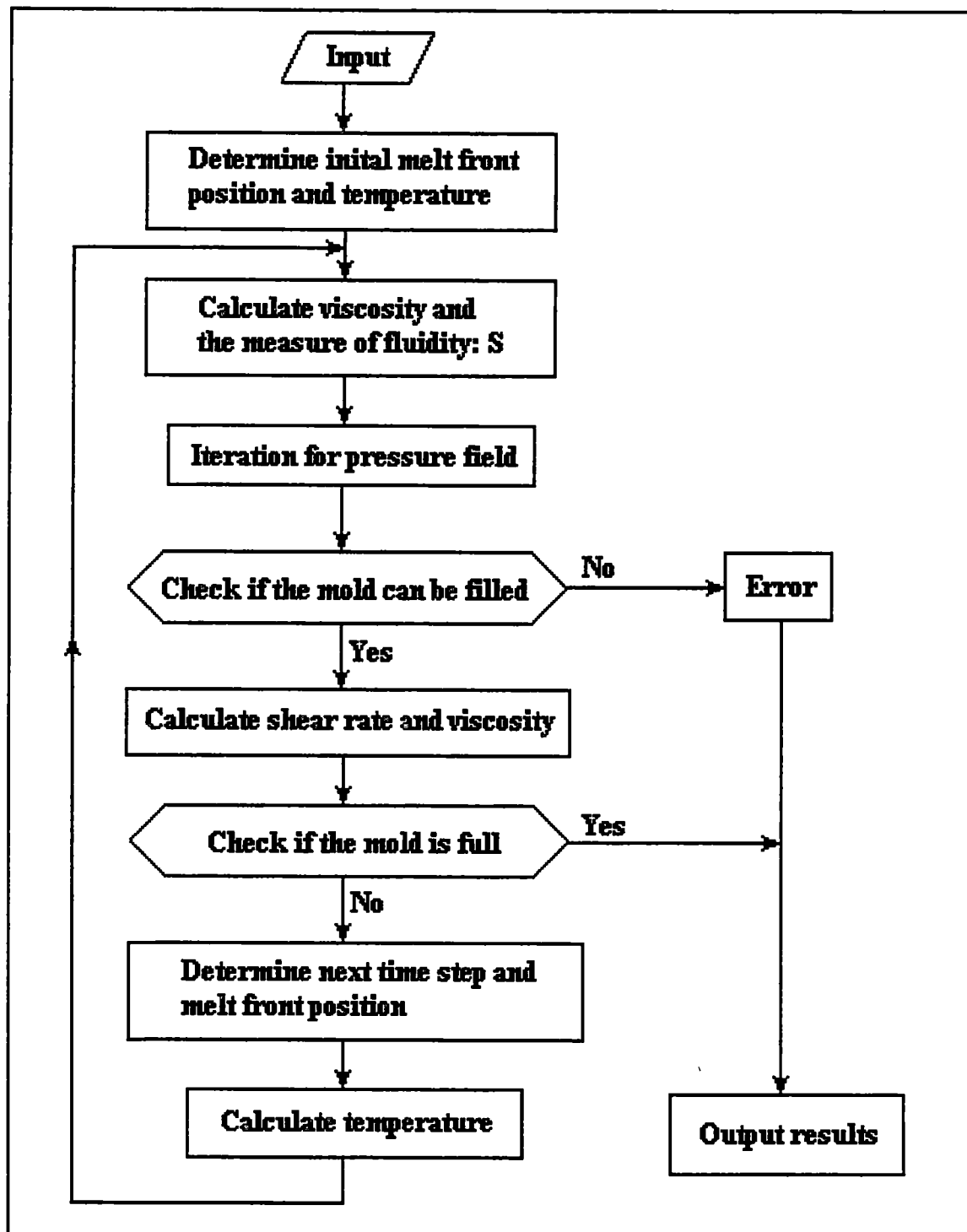
Computer simulation of the injection molding process has been in use for over a decade. It has been used extensively to design, trouble-shoot and enhance the injection molding process in the plastics industry. It is a tool aiding engineers in the development of new parts and in trouble-shooting existing parts. Computer simulation can be used to help provide information on mold filling characteristics such as pressure, velocity, temperature, total pressure drop, air trap locations, weld line integrity, maximum injection pressure, clamp force, effect of gate geometry and location, shrinkage and warpage trends. For the electronics industry which often deals with thin-walled parts that measure 1-mm or less in thickness, computer simulations have demonstrated great success in assisting design engineers to determine if the part can be filled properly.⁹ By trying various designs before making the mold, the cost of an injection molded parts can be reduced and quality enhanced. Several studies, which have focused on experimental validation of the molding process, are discussed below to illustrate previous efforts in this area.

Zhongshuang, Dequen and Jingrong¹⁰ developed a mathematical model and simulation program for simulating filling of thin cavities during injection molding. They developed governing equations for flow in a cavity by extending the classical Hele-Shaw flow to an inelastic, non-Newtonian fluid under non-isothermal conditions. In order to obtain a solution to the problem, the following assumptions were made.

(a) Heat conduction in the direction of the flow is negligible compared to conduction in the gapwise direction, (b) Thermal convection in the gapwise direction is negligible. (c) Viscoelastic effects are not included. (d) Normal stresses are neglected in comparison with shear stresses. (e) Inertial effects and the gravity of the melt in the force balance are neglected due to the high viscosity characteristic of polymer melts. (f) The melt is incompressible and thermal conductivity and specific heat are assumed to be constants.

A flowchart of their filling analysis program can be seen in Figure 4. In order to examine the validity of their mathematical model and the simulation program, they designed a simple geometry (a cup, as shown in Figure 5) for their experimental verification. The comparison between the predictions and the experimental results are shown in Figure 6. The solid line in Figure 6 represents the pressure curve recorded in their experiments for locations 1, 2, and 3 as shown in Figure 5. With the maximum error of 12%, they concluded that the agreement between the simulation and the experimental results is satisfactory and the simulation program is reliable.

Hunt and Evans, and Woodthorpe¹¹ carried out extensive research to determine the origin of defects in ceramic injection molding through the use of computer modeling, simulation, and experimental validation. In phase 1 of their research, the group began developing routine laboratory procedures for obtaining thermal property data for their solidification model. Specific heat data were measured over a range of injection molding temperatures using a differential scanning calorimetry. Mercury displacement in a borosilicate glass phial was used to measure the specific volume. These experimental data were then used in obtaining a general equation of state that is capable of predicting the specific volume over the temperature and pressure ranges that occurred during the



(Courtesy of Huazhong University of Science and Technology)

Figure 4 Flowchart of filling analysis program (ref. 10)

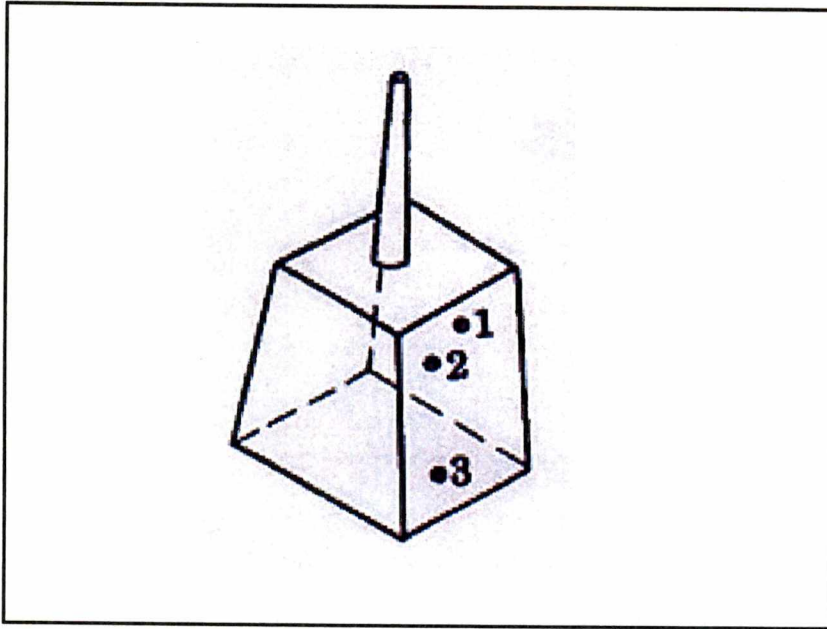


Figure 5 Experiment part geometry and location of pressure transducers (ref. 10)

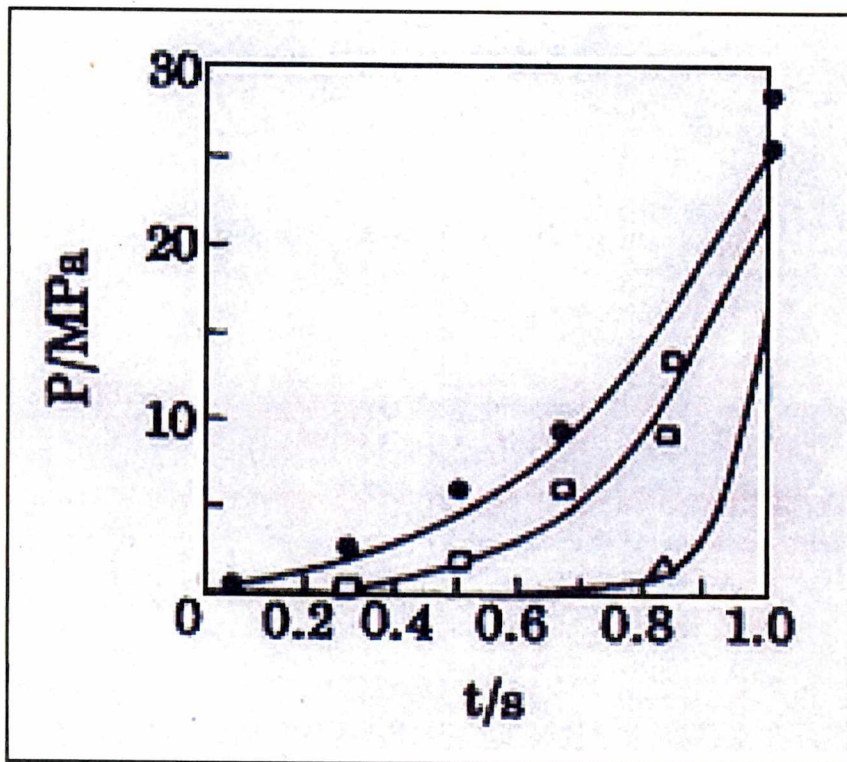


Figure 6 Experimental and predicted pressure trace (● = 1, □ = 2, and Δ = 3) (ref. 10)

injection molding process. Thermal diffusivity of the ceramic suspension was measured using a modified Hands and Horsfall method. These properties were then used in their finite difference numerical model, which used two-dimensional unsteady heat transfer assumptions to simulate the complex solidification process of the ceramic suspension inside the mold cavity. The numerical model would be able to calculate the residual pressure, which is a function of hold pressure applied by the injection-molding machine. By knowing the residual pressure right before solidification, voids can be predicted. It was known that voids are a result of zero pressure at the center of the mold just prior to solidification. In validating the model, an experiment was conducted using a simple geometry of a rectangular bar (see Figure 7). Three series of bars were injected using a Sandretto 6GV/50 reciprocating screw injection molding machine. The experimental results (Table 1) showed that computer predictions slightly underestimate the initial cavity residual pressure needed to prevent the formation of voids. The experiment did conclude that whenever wall temperature is significantly above the softening point of the material at the time when residual pressure falls to zero then "sink marks" appeared as seen in Figure 8. Because the ceramic injection molding market is much smaller relative

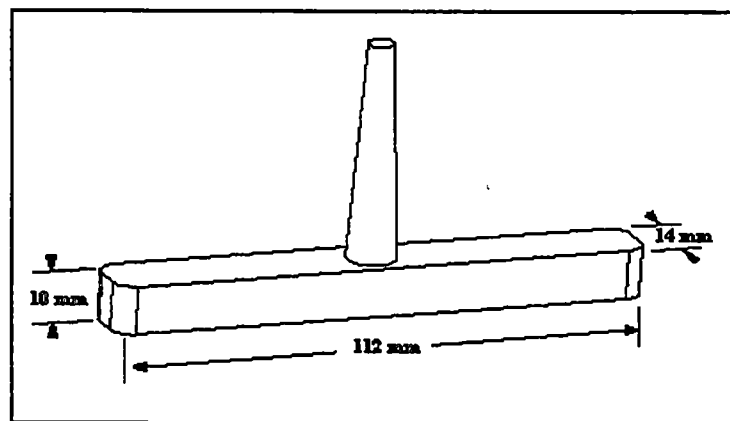


Figure 7 Dimension of the experiment rectangular bar (ref. 11)

Table 1 Comparison of calculated and experimental residual pressure for development of voids (ref. 11)

Molding Series	Sprue diameter (mm)	Mold temperature (°C)	Injection pressure for void-free molding		
			Calculated ^a (MPa)	Experimental ^b (MPa)	Calculated ^c (MPa)
1	6.9	25	45	between 57 and 80	75
2	6.9	46	41	between 35 and 56	77
3	10	25	28	between 33 and 47	57

^a Using sprue solidification time calculated by finite difference method
^b Using cavity pressure fall time obtained by experiment
^c From radiographs of two bars at each injection pressure

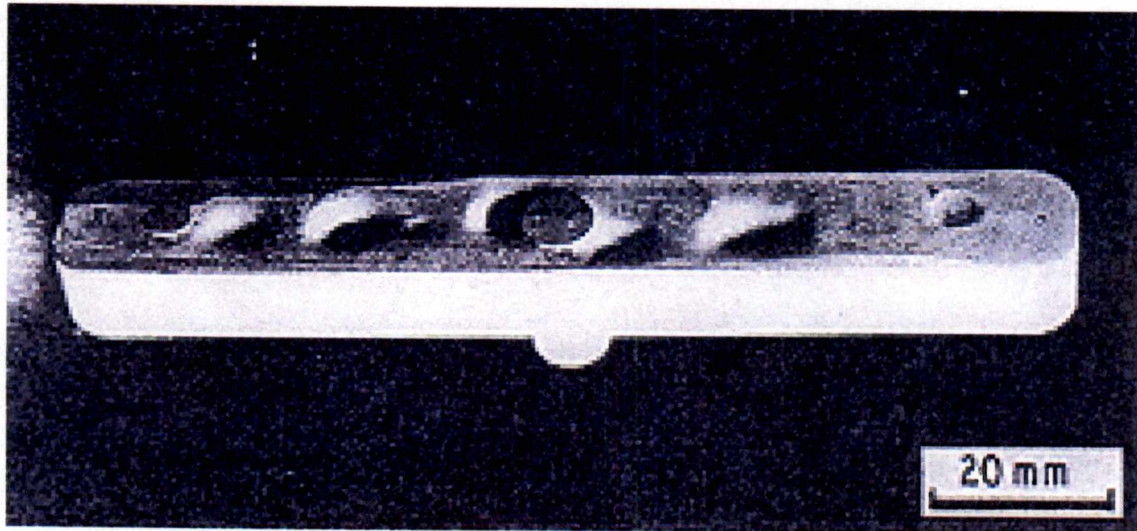


Figure 8 Sink marks in a bar prepared using Molding Series 2 conditions (ref. 11)

to the plastic injection molding market, there have not been many published technical papers that deal specifically with modeling and validation of the ceramic injection process. Almost all technical papers that deal with the process, manufacturing, and computer modeling of ceramic injection molding are proprietary and are not made public due to the intense competition between suppliers in this industry.

CHAPTER 3

EXPERIMENTAL INVESTIGATION OF CERAMIC CORE INJECTION PROCESS

3.1 COMPUTER MODELING AND SIMULATION

The Advanced Casting Simulation and Mold Design Laboratory (ACSMDL) at the University of Tennessee - Knoxville, uses ProCAST software to model the ceramic core injection process. ProCAST is commercial finite element analysis software from UES Software, which was developed to simulate casting and casting processes.¹² Howmet Research Corporation selected a particular (8602B) core to be the model for the ACSMDL – HRC project. The reasons for this selection were:

1. It is a single plane core, which makes the development of a 3-D solid model more convenient and also it has a history of problems that need to be resolved.
2. It has the geometry of a typical core with turbulator, conical, crossover slot, trailing edge slot, trailing edge exit, root passage and the variation of cross sectional area from thick root to thin trailing edge exit. (Core diagram and terminology can be found in Appendix A.)
3. Howmet has a retired production die that could be used for experimental validation of the modeling and simulation process.

The selected core is typical of a first stage high-pressure blade. Such blades are used on the world's largest and most powerful aircraft engines such as the GE90 (see Appendix B) which powers the Boeing 777 aircraft family. The following material only deals with some of the basic concepts in modeling and the reader is referred to other publications by ACSMDL.^{7,8}

3.1.1 Geometric Development

The 3-D geometry of the 8602B ceramic core was modeled in 1998 in the first phase of this project using SolidWorks®, a 3-D CAD program. The solid model was developed using measurements made by dial caliper and micrometer. Most of the part geometry such as root, leading edge, tip, trailing edge, crossovers, and conical section were built using extrusion bosses, extrusion cuts, and extrusion lofts. Details such as turbulators, trailing edge exits, and the area between root and trailing edge is created using cuts and lofts. Also, to compensate for the die to fired shrinkage, the SolidWorks® part-scaling feature was used to scale up all dimensions.¹³ The solid view of the 8602B ceramic core geometry is shown in Figure 9.

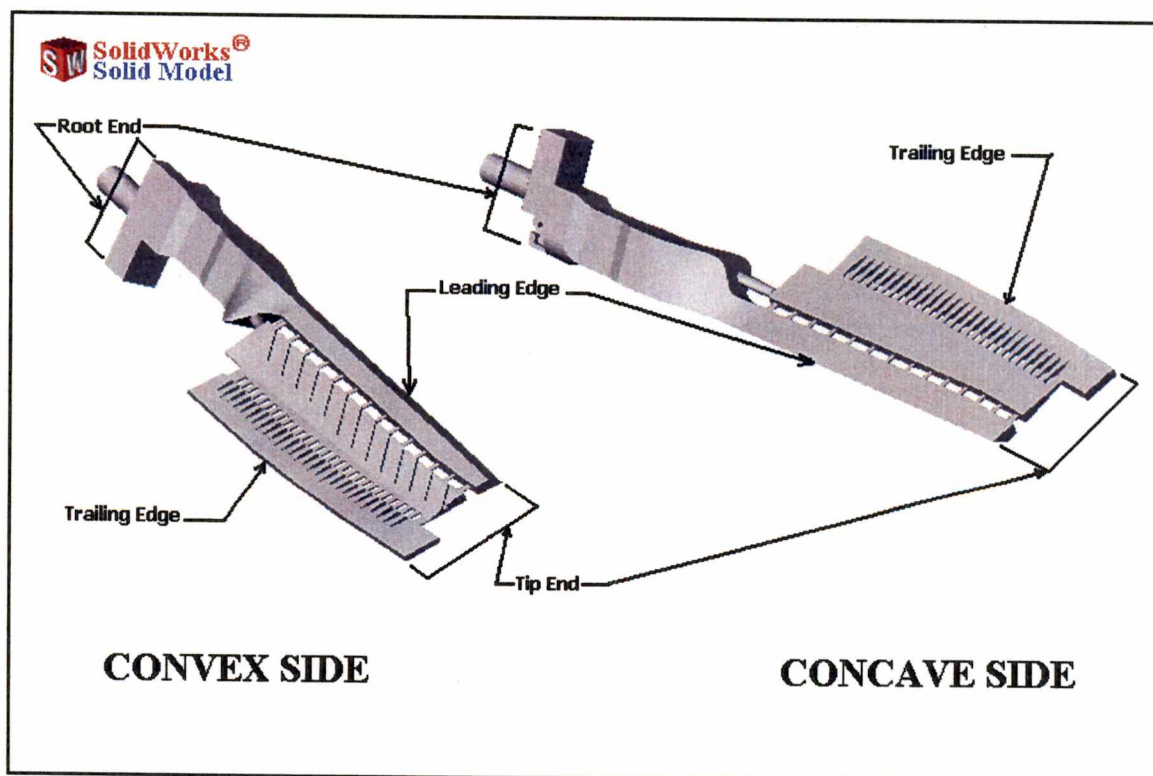


Figure 9 The 8602B ceramic core modeled by SolidWorks®

3.1.2 Model Preparation for Casting Simulations

The 3-D solid model file was transferred to PATRAN from SolidWorks in a parasolids format. The PATRAN program generates a surface mesh using a triangular node configuration as seen in Figure 10. After the surface mesh was completed, the PATRAN file format was transferred into MeshCAST. MeshCAST is a fully automatic 3-D tetrahedral mesh generator. It constructs a 3-D solid mesh by generating interior

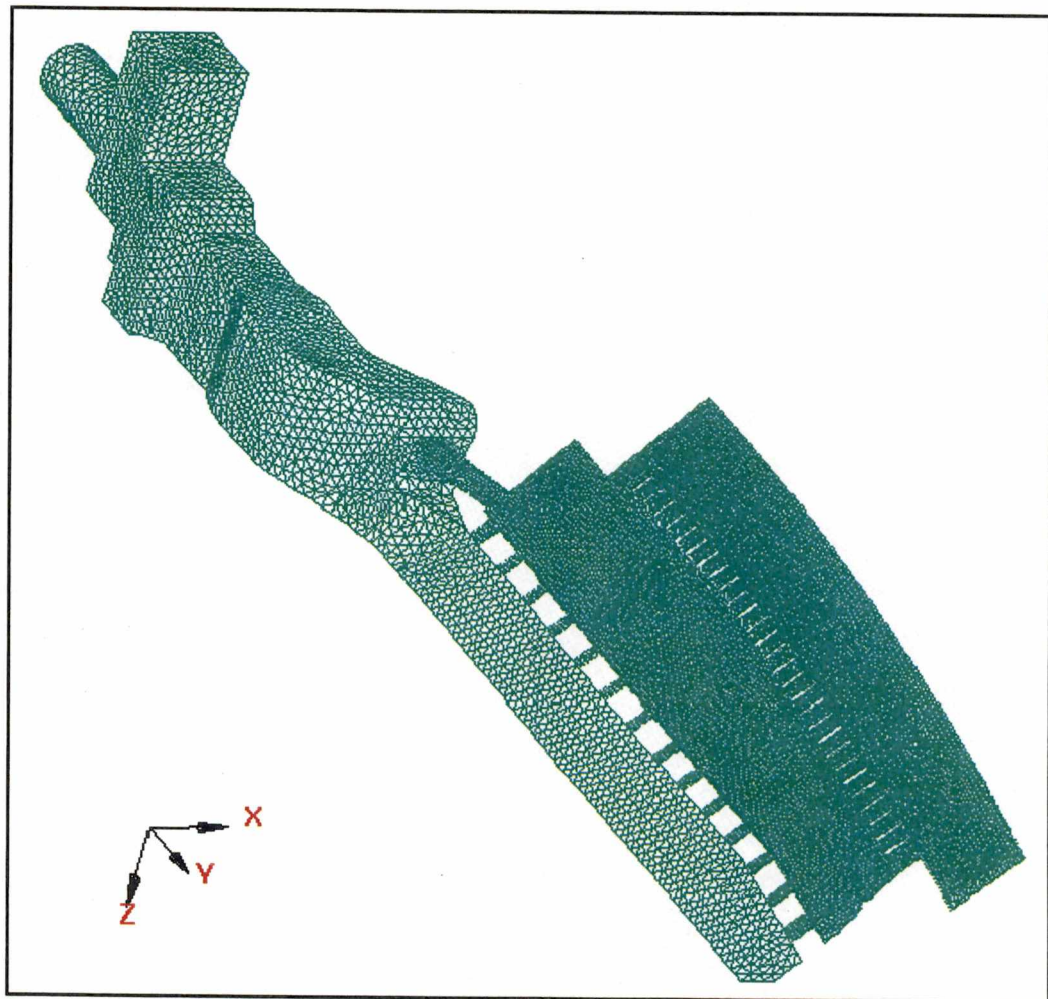


Figure 10 Surface mesh of 8602B core by PATRAN®

nodes from the surface mesh. After the meshing phase was completed, PreCAST was used to specify all the initial conditions, boundary conditions, and material properties of the 3-D solid mesh model.⁷ After all process parameters were specified, DataCAST was used to do an extensive error checking, convert all units into a standard system, and create a summary file. ProCAST was then used to perform simulation analysis by solving mass, momentum, and energy equations at each node until the filling process was completed.¹² The injection filling was performed from the root to the tip of the core. Once ProCAST completed modeling the injection process, ViewCAST was used to create contour plots of the velocity, temperature, and pressure. ViewCAST also animated the filling process by showing the contour plots at different time steps. Examples of ViewCAST thermal contour plot can be seen in Appendix C, Figure C.1 to Figure C.9. Those figures also include the short shot provided by Howmet Casting Support of the 8602B core that was modeled. For this particular case, the model ran with an isothermal boundary condition. PostCAST, another post-processor of ProCAST, was used to generate graphs of temperature, pressure, and velocity at any node as a function of time. A graphical flowchart of ProCAST analysis can be seen Figure 11.

3.2 EXPERIMENTAL OBJECTIVE

The main objective of the experiments at the Howmet Morristown Casting Support facility was to verify the ProCAST analysis for their ceramic core injection process. The experimental data also help in refining boundary and initial conditions used in the simulation process. The use of ProCAST in the analysis will allow engineers to redesign the injection process by minimizing the injection speed and pressure which in

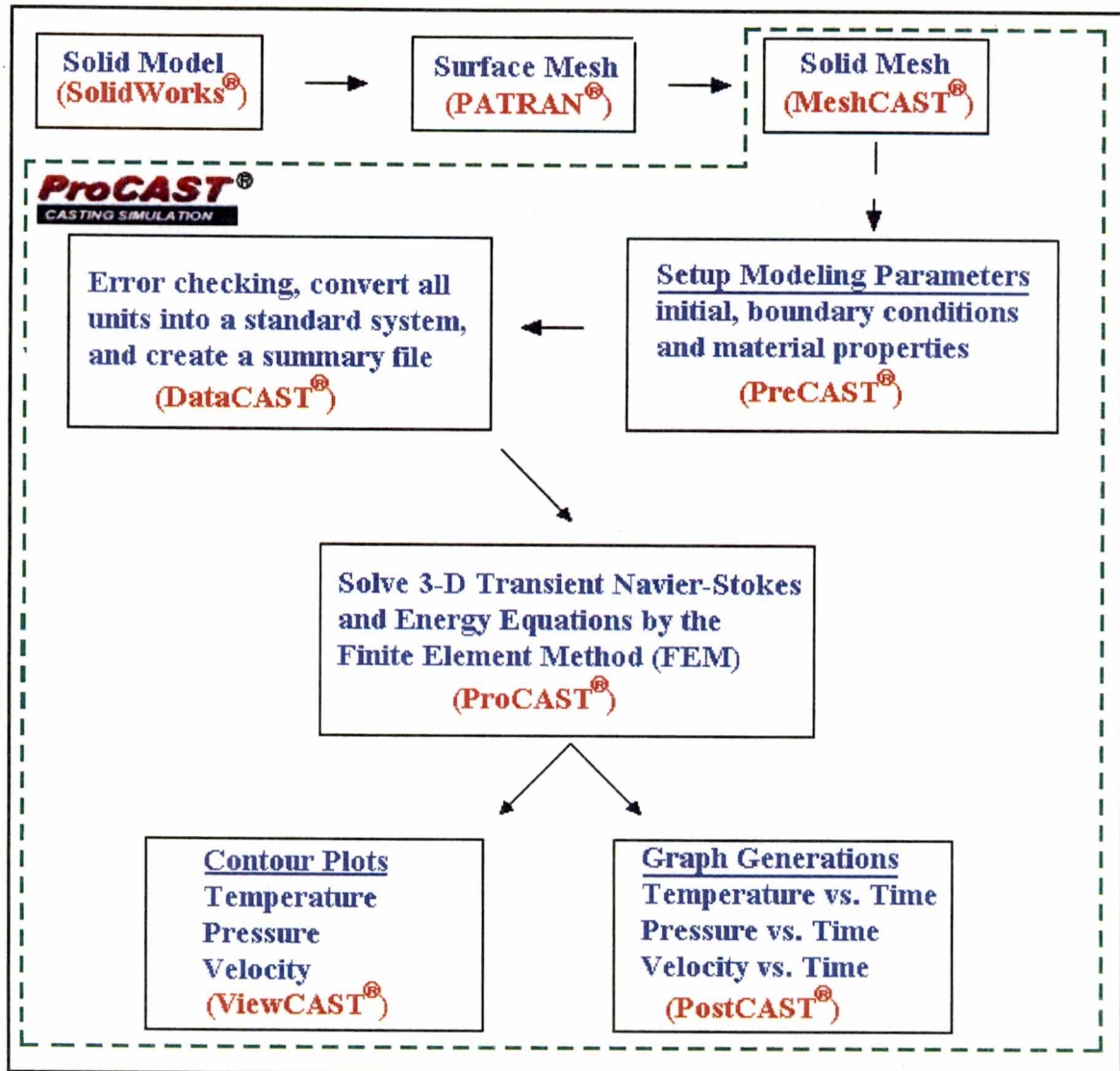
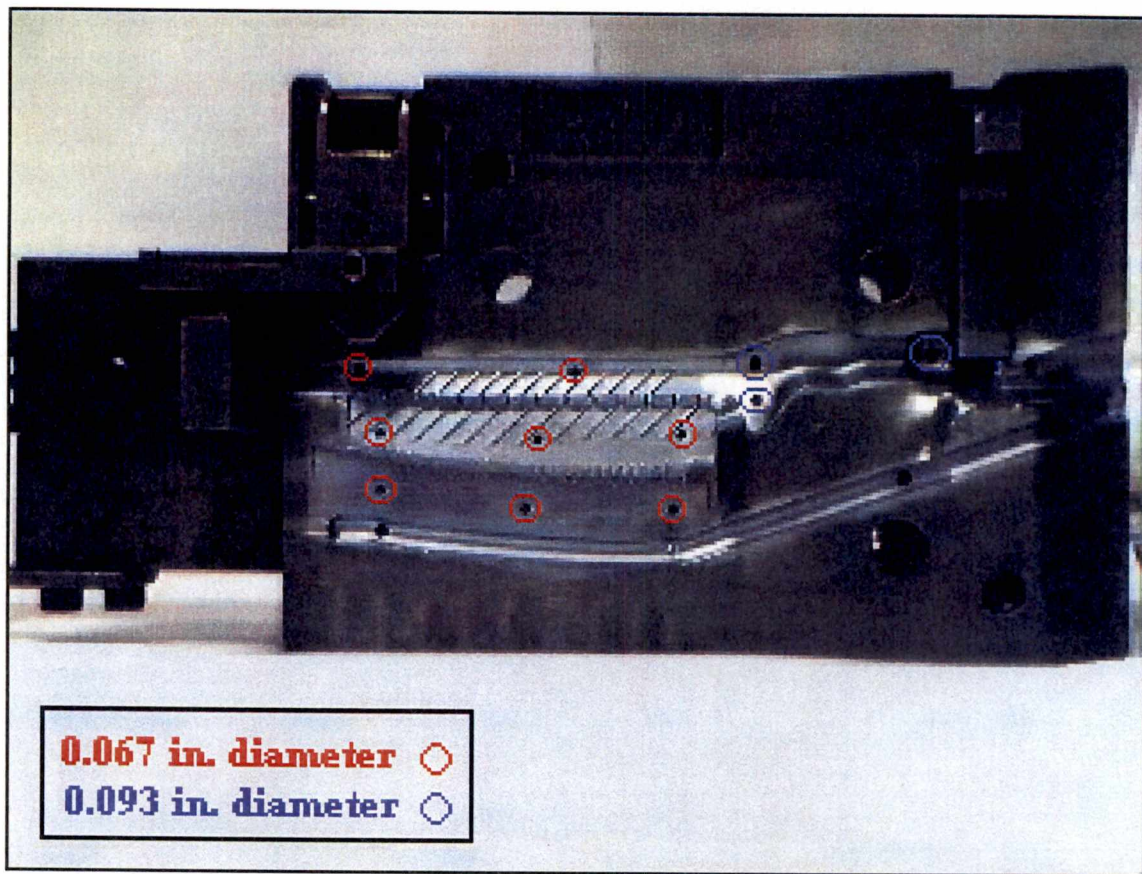


Figure 11 A flowchart of ProCAST® analysis

turn will reduce die wear and prolong the life of the core die. However, the use of ProCAST predictions in optimizing the injection process without adequate validation would not be prudent. Therefore it is important to emphasize experimental preparation and execution in the model validation problem to insure credibility of the model predictions and their reliability.

3.3 EXPERIMENTAL CRITERIA

Howmet Morristown Casting Support allowed the use of the 8602B die cavity, a retired core die, for the validation experiment. The 8602B die cavity can be seen in Figure 12. The 8602B core die configuration mainly consists of the die cavity, the ejector pin plate, and the Detroit Mold & Engineering (DME) mold base. The core



(Courtesy of Howmet Corporation)

Figure 12 A close-up view of the 8602B core die cavity 1

pattern lies inside the die cavity with its visible ejector pinholes as seen in Figure 12. The ejector pin plate houses 11 pins that help to lift the core from the die cavity surface. The DME houses both the injector pin plate and the die cavity. The 3-D SolidWorks assembly drawing of the 8602B core die is presented in Figure 13. The die cavity

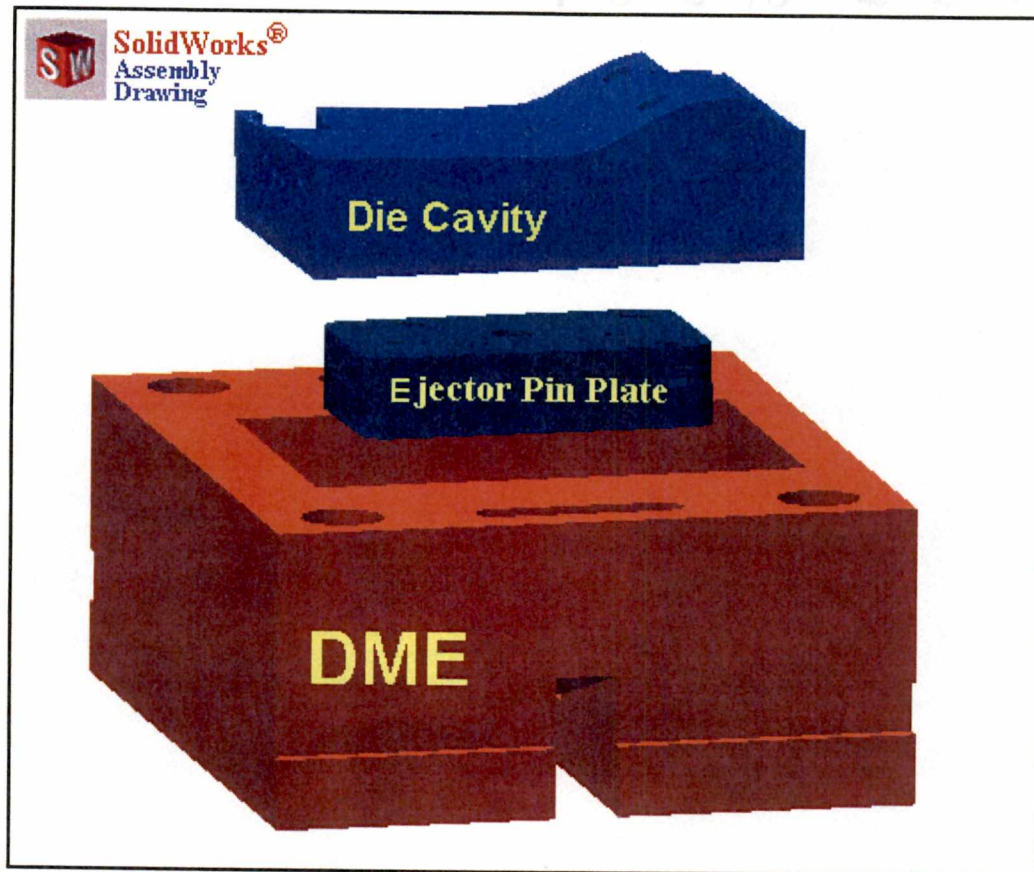


Figure 13 An assembly drawing of the 8602B core die configuration

contained eight 0.067 inch diameter and three 0.093 inch diameter ejector pin holes.

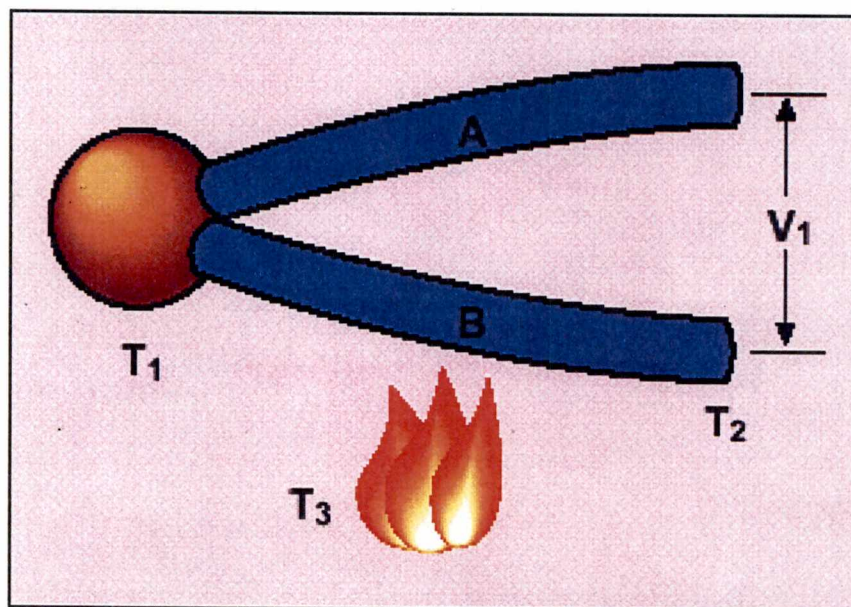
Measurement with a dial caliper gave a cross sectional thickness inside the cavity varying from 0.070 inch at the tip to a maximum of 0.325 inch at the root section. Due to the high viscosity of the core material and the high injection pressure of 2000 psi for the 8602B, the die cavity surface is chromed at Howmet to add strength to the pattern area that lies within the die cavity. The chrome used for the interior surface makes the die cavity shiny to the eye as shown in Figure 12.

3.4 PRELIMINARY EXPERIMENTAL STUDY

The proposed measurement included temperature and pressure inside the die cavity during both the filling and packing stages of the injection molding process. To minimize die modifications, the ejector pin holes were used for instrumentation. As a result, the type of measurement that could be done was constrained by the size of the ejector pinholes. Pressure and temperature sensors are the only two types of measurement device that could be instrumented using the ejector pinholes. In the past, several computer modeling validations were carried out using pressure measurements.^{10,11} In those studies, the geometry was simpler and therefore they were easier to instrument. However, pressure measurements were not considered for the present study because miniature and subminiature pressure transducers are prohibitively expensive. Also, a miniature pressure probe is an extremely delicate instrument, which may not survive even the first experimental trial due to the combination of high injection pressure and stresses in the highly viscous core material. On the other hand, temperature measurements looked promising, especially using thermocouples.

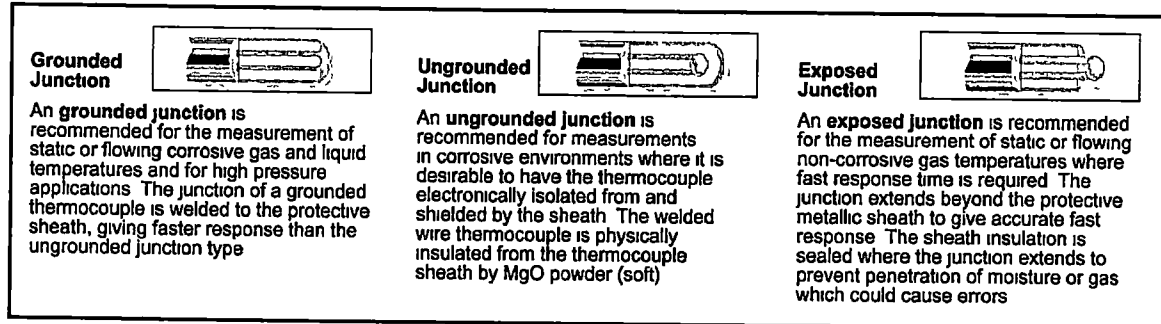
The thermocouple is one of the four common temperature transducers. The others are resistance – temperature detector's (RTD's), thermistors, and integrated circuit sensors. Of the four temperature transducers, thermocouples seemed to be the best choice for the present experiment because they have a fast response time, are self-powered, are rugged, have high accuracy, are easy to calibrate and are easy to fit within the physical constraints of the core die. A thermocouple consists of two alloys (e.g. A and B in Figure 14) joined together at one end and open at the other end. The electromotive force (emf) at the output end (V_1) is a function of the temperature (T_1) at the closed end as seen in Figure

14. As temperature increases, the output emf of the thermocouple rises. All dissimilar metals exhibit this effect, known as the Seebeck effect (discovered by Thomas Seebeck in 1821), where a continuous current in the thermoelectric circuit is established if one end of the thermocouple junction is heated. The four most common thermocouples are Iron-Constantan (type J), CHROMEGA-ALOMEGA (type K), Copper-Constantan (type T), and CHROMEGA-Constantan (type E). Each type of thermocouple has a different operating temperature range. Thermocouples also come in three different junction types: grounded, ungrounded, and exposed. The type of junction used depends on the nature of the measurement and the type of environment that the thermocouple operates. (See the illustrations in Figure 15 for a full discussion of each junction type.) Another important aspect, when choosing a thermocouple, is the time response or time constant.¹⁴



(Courtesy of Omega Engineering, Inc.)

Figure 14 Thermocouple composition



(Courtesy of Omega Engineering, Inc.)

Figure 15 Three thermocouples junction types

Time constant is defined as the time required by a sensor to reach 63.2% of a step change in temperature under a specified set of conditions. Time response is mostly a function of the probe sheath diameter. However, the type of junction also contributes to the time response. The time constant is selected based on the outside diameter of the grounded junction thermocouple (Appendix D). For a more in-depth discussion of thermocouples, the reader is referred to reference [14].

3.5 DESIGN OF EXPERIMENT

Omega Teflon insulated type-K thermocouples with 0.010-inch bead diameter and a 30-gauge wire were chosen for these experiments. Two of eleven ejector pinholes were used to house the thermocouple for the temperature measurement. One thermocouple measured the fluid (ceramic/wax slurry) temperature and the other measured the die wall temperature. The thermocouple location as seen on the die cavity and the core body is shown in Figure 16. In order to run thermocouple wires from the outside of the DME to the interior of the die cavity, the ejector pin plate was modified slightly. The ejector pin plate location relative to the die cavity and the DME can be seen in Figure 13. Howmet allowed modification to the ejector pin plate as long as its original purpose was

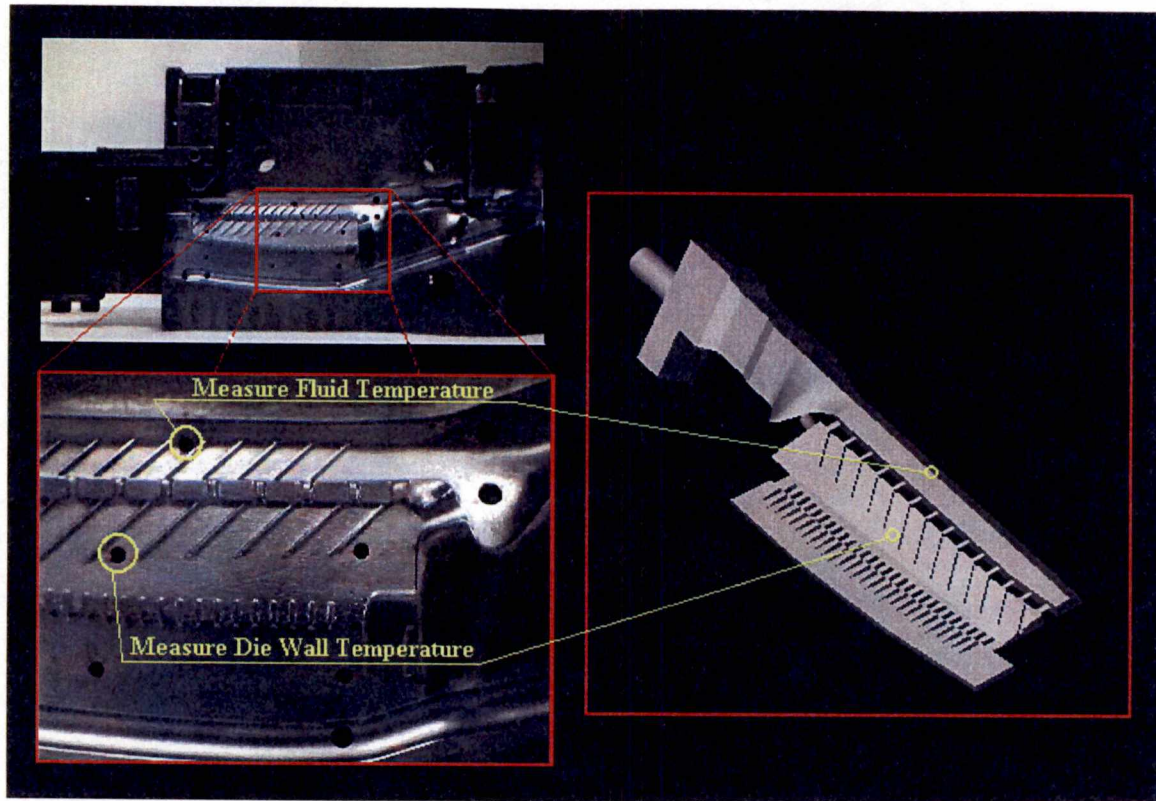


Figure 16 Thermocouples location on the die cavity and core body

not compromised. The modification was done at a Howmet machine shop. The modification made it possible to run all eleven thermocouple wires to the outside if needed. The 3-D model of the original and modified ejector pin plate were completed in SolidWorks before any material was actually removed. The ejector pin plate before and after modification can be seen in Figure 17. The next step was to find a way to secure the thermocouples inside ejector pinholes. The type of epoxy that needed to be used to hold the thermocouple in place had to withstand the injection pressure of 2000 psi and the initial material temperature of 250 °F. A suggested thermocouple epoxy was turned down due to the difficulty in preparing, cleaning, and removing it from the die.¹⁴ A better suggestion was to use red wax to hold the thermocouple in place.

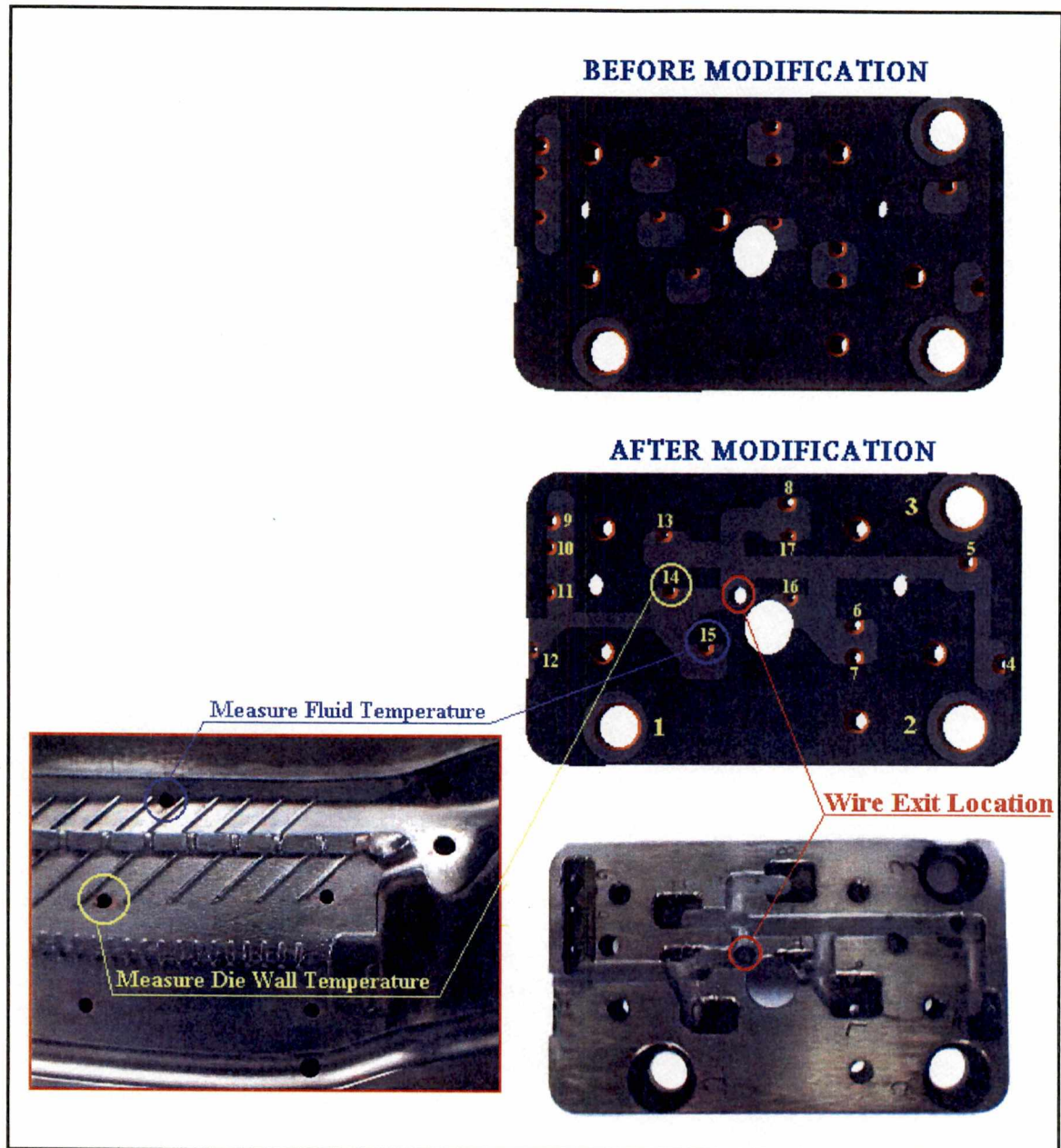


Figure 17 Ejector pins plate modification

In the past, red candle-like wax had been used to cut off flow from specific parts of the die. Red wax is easy to work with, easy to clean, and non-toxic. Even though the melting point for the red wax is low, the injection process is so quick that the wax does not have enough time to melt. At this point in the experiments it was not clear whether both the thermocouple bead and the red wax could withstand the 2000 psi injection pressure. An initial run was made to resolve this issue. A glass syringe was used to inject red wax into the ejector pinhole. Since red wax solidifies at room temperature, the glass syringe had to be constantly heated using a small portable heater. The installation of both thermocouple A and B is shown in Figure 18.

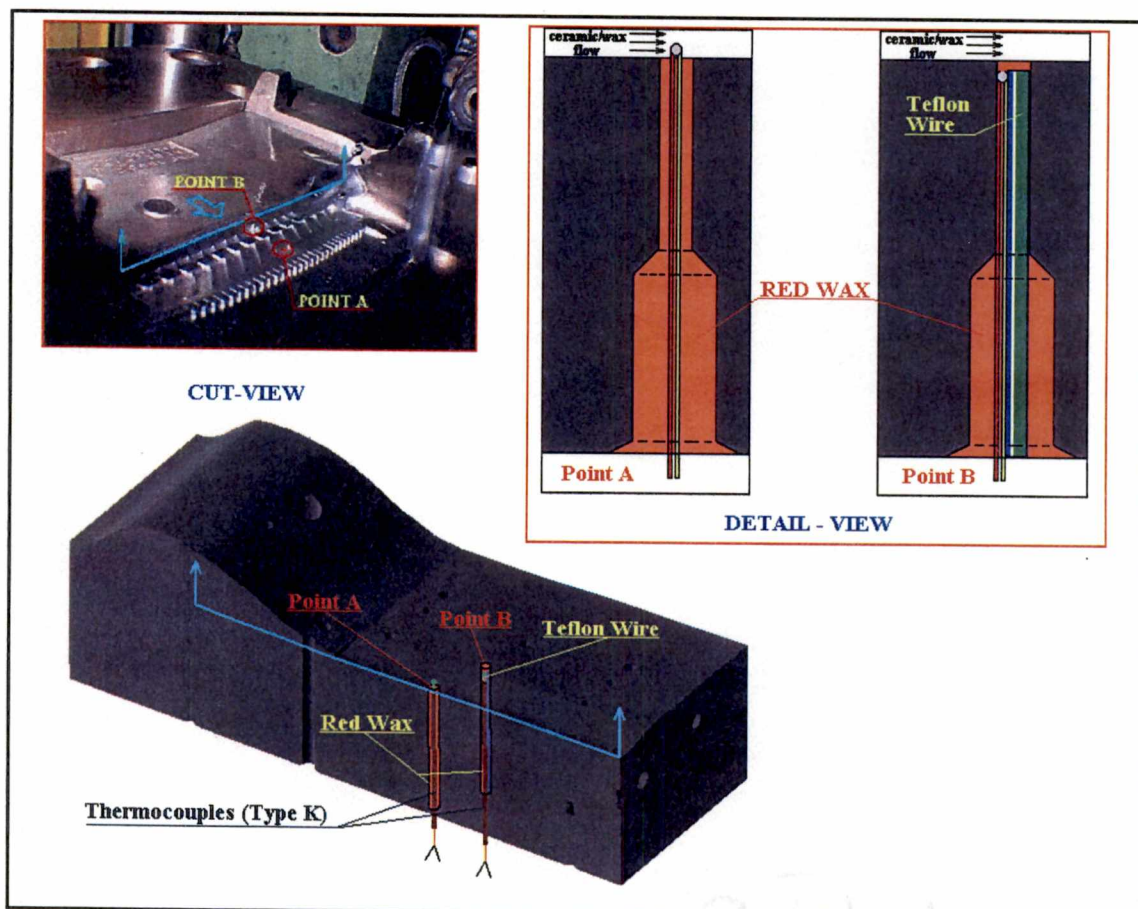


Figure 18 Installation of thermocouples for temperature measurement

Thermocouple A was used to measure the fluid temperature of the mixture and thermocouple B measured the die-wall temperature. A Teflon wire was used to press the thermocouple B bead against the die to insure accurate die-wall temperature measurement.

3.6 EXPERIMENTAL APPARATUS AND INSTRUMENTATION

The experiment was carried out on an Arburg injection molding machine very similar to the one shown in Figure 19. The mold cooling was handled by a circulating water heat exchanger. A thermocouple wire is connected to an Omega OMNI-AMP-IV thermocouple amplifier with a scale factor of 10 mV/ °F. The amplified signal then passed through a low pass filter, filtering out high frequency interference coming from

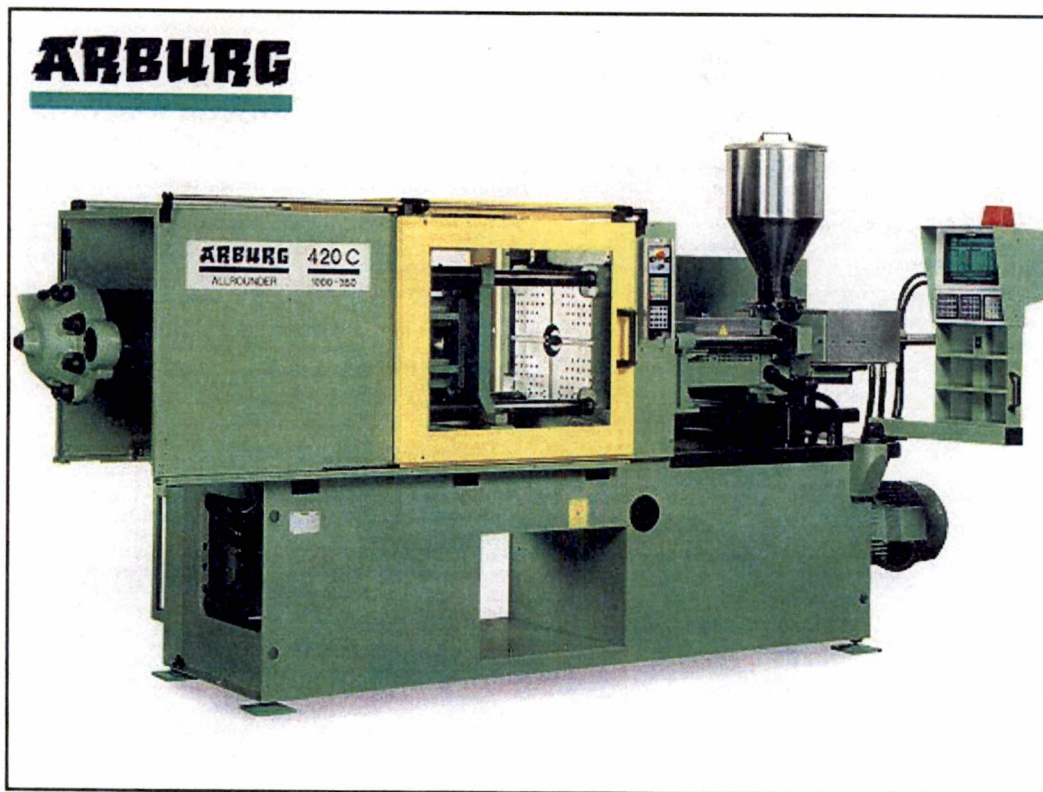


Figure 19 The Arburg injection molding machine

the 60 Hz power distribution commonly used in industrial plants.¹⁵ The low pass filter circuit diagram can be seen in Figure 20. The key term in a low pass filter circuit is the cut off frequency. The cut off frequency is that frequency above which no variation of voltage with respect to time may enter the circuit. The cut off frequency was determined experimentally using a variable capacitor switch box. The filtered signal was passed through a thermocouple panel that interfaces with the internal data acquisition board. The A/D board, a CYDAS 1420HR, converts the voltage signal into converter numbers. A LabVIEW program was written for both data collection and temperature conversion to Fahrenheit and Celsius scales. The LabVIEW program is presented in Appendix E. An Intel Celeron 333 MHz computer running the Windows 98 operating system was used to run LabVIEW 5 in collecting the temperature data during experiments. A Fluke 5500 calibrator was used to double check the calibration of both thermocouple amplifier and A/D board. The data collection schematic diagram is shown in Figure 21.

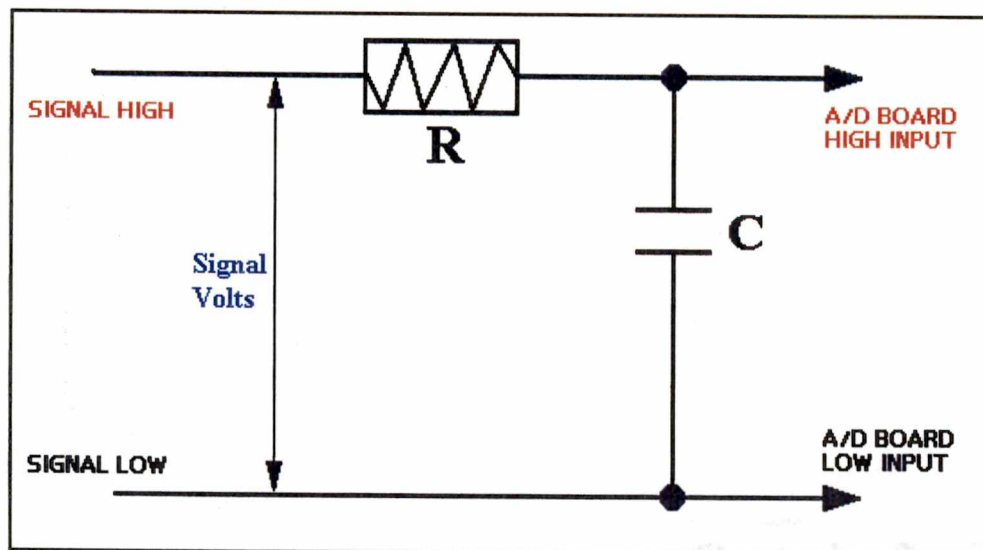


Figure 20 Low pass filter circuit diagram

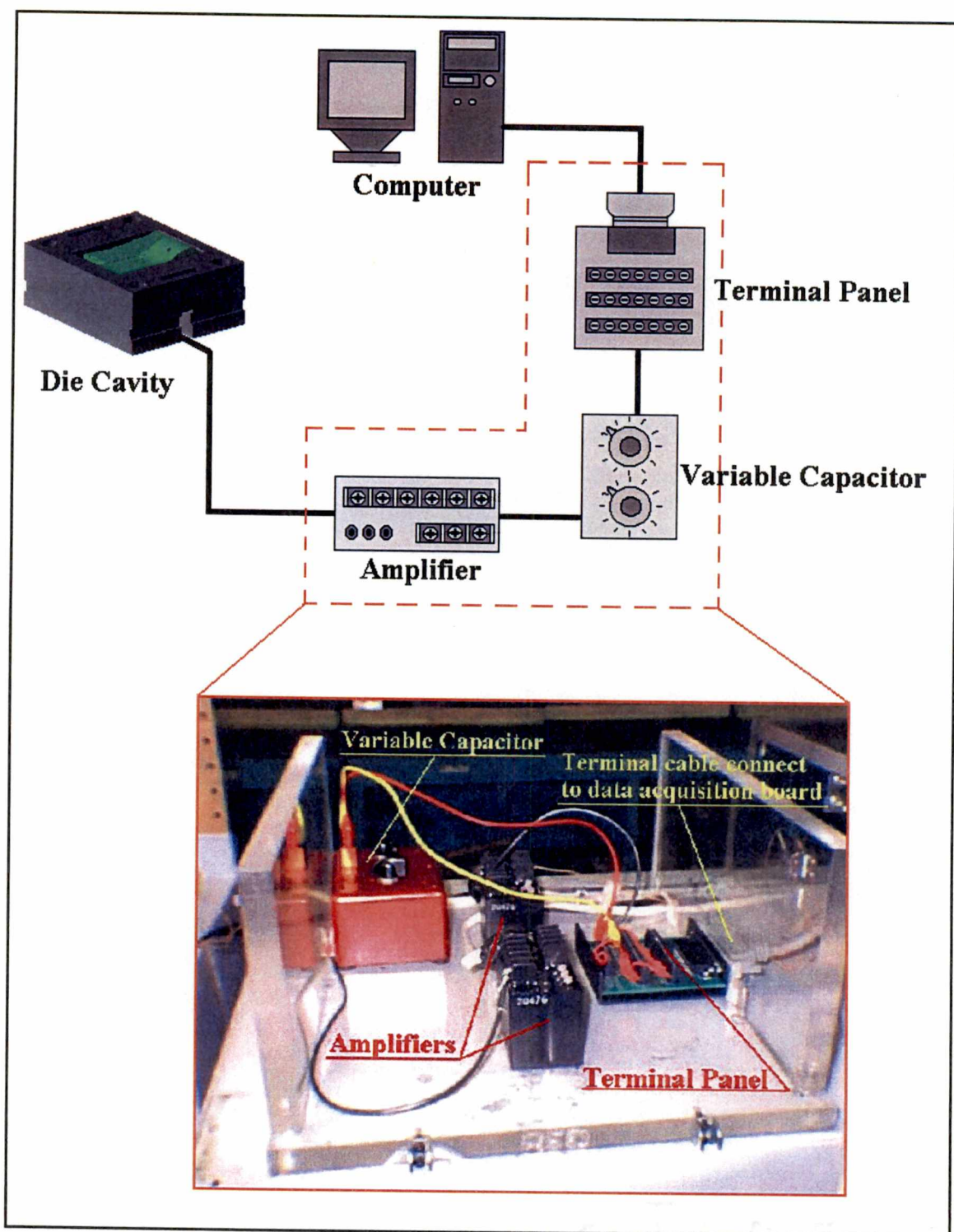


Figure 21 Data collection schematic diagram

3.7 FORMATION OF PARTS AND EXPERIMENTAL PROCEDURE

The ceramic injection molding at Howmet Morristown Casting Support is a cyclic process that is based on time, temperature, and pressure. All of the injection parameters such as screw rotation speed, nozzle temperature, nominal injection speed, total injection time and injection pressure are pre-programmed in the Arburg control system. Once the operator presses the start button, the Arburg injection machine automatically follows through the injection cycle that is specifically designed for that particular job (e.g., 8602B). The complete injection molding cycle can be broken down into the following periods.¹⁶

Dead Period – the time after the mold closes and the nozzle moves forward but before material starts to flow into the mold

Mold Filling Period – the time in which material flows into the mold and fills the cavity

Pressure Build-up Period – the time after the cavity is filled and begins to cool while the cavity pressure begins to build up to the injection pressure

Packing Period – the time during which material flows into the cavity at a relatively low rate to compensate for material shrinkage with the screw retracting at the end of this period

Cooling Period - the time during which material in the cavity solidifies and at the end of which the nozzle retracts and the mold opens.

The 8602B cavity 1 was instrumented on site at Howmet's core manufacturing plant. After the two thermocouples were placed in the die, the die cavity with the ejector pin plate was placed inside the DME. Then the DME and 8602B die cavity were installed in the Arburg injection machine as shown in Figure 22. At this stage all of the data

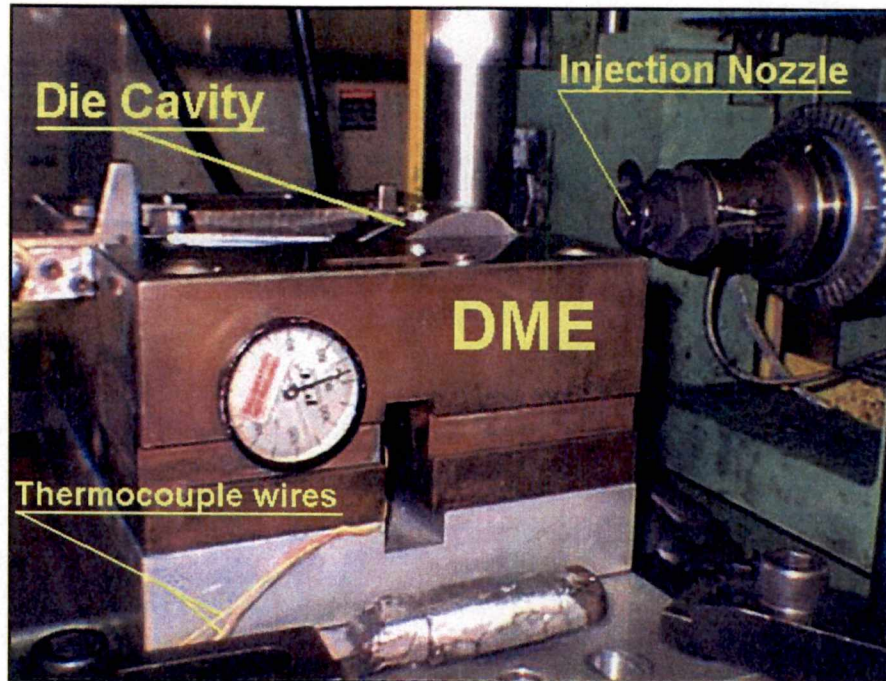


Figure 22 The 8602B die setup on the Arburg injection machine

acquisition equipment was setup and rechecked to insure that it work properly. The initial injection run showed promising results since thermocouples in both locations survived the 2000 psi injection pressure. The red wax held up very well in both cases of thermocouple A and B. Unfortunately, both thermocouples were not successful in measuring temperature simultaneously due to the high noise level even with the low pass filter in place. Therefore, only one thermocouple could be used during each run. A time response study was conducted to determine the time constant of the data acquisition system as a whole. A great deal of effort was put into determining how much the analog low pass filter affects the response time of the system. Due to the short filling time (order of 100 milliseconds), fast time response was critical in capturing the actual peak temperature of the injected material at thermocouple A location. The time response was tested using the 250 °F material at the nozzle of the injection machine. The experiment

was conducted in two sessions. The temperature data was collected at 60-millisecond and 30-millisecond intervals in the first and second sessions, respectively. The data collection began when the die closed and the nozzle began to move forward and ended when the die opened. To collect sufficient data, twenty runs were conducted in each session. For the 60-millisecond session, ten runs were conducted for thermocouple A and ten runs for the thermocouple B. The 30-millisecond session was completed in the same way. For consistency, the same batch of core material was used to run the experiment. It took approximately 30 seconds for each run to complete and another 5 minutes to save the data, remove the part, clean the die, double check the thermocouple and prepare to start the next run as shown in Figure 23. All collected data in LabVIEW are saved using ASCII text format to import into the Microsoft Excel[®] spreadsheet program for analysis.

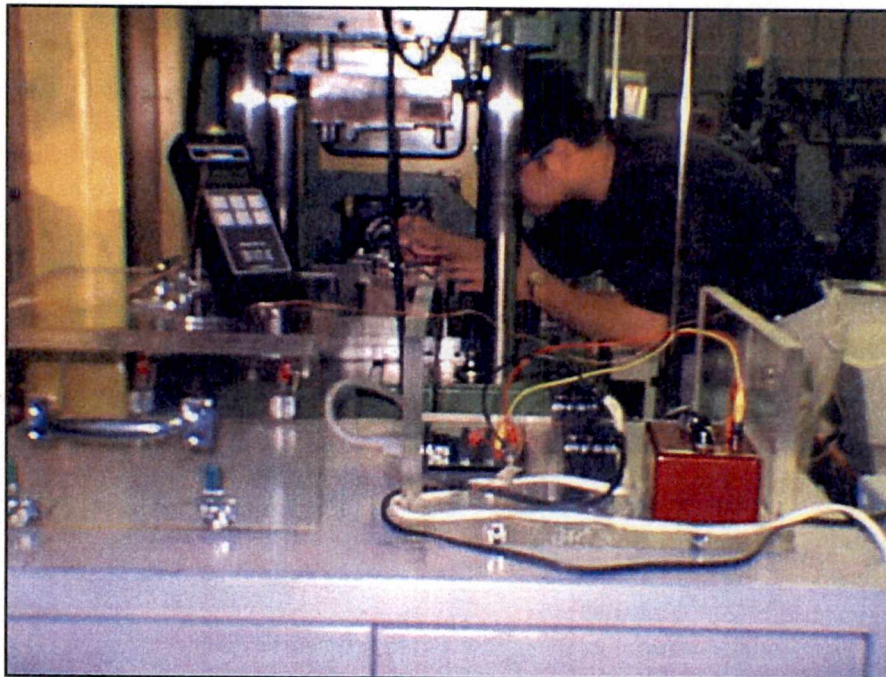


Figure 23 Cleaning and preparing core die for the next injection run

CHAPTER 4

ANALYSIS OF EXPERIMENTAL DATA

4.1 ERROR AND UNCERTAINTY ANALYSIS

The present experiments were conducted in an industrial plant environment where the collected data often contain errors due to low frequency electric fields associated with the 60 Hz power distribution lines. The error in the data was determined by observing error in a sampling of 180 data points at ambient room temperature. The results are presented in Figure 24. As one can see, the ambient temperature data have a 6 degree span. The analog RC circuit was able to successfully decrease the error due to the electrical noises to an acceptable level of 0.75 degree span. Figure 25 demonstrates the reduction of error after implementation of the RC circuit in the data acquisition system. The fluctuation error due to electrical noise was corrected in the LabVIEW temperature

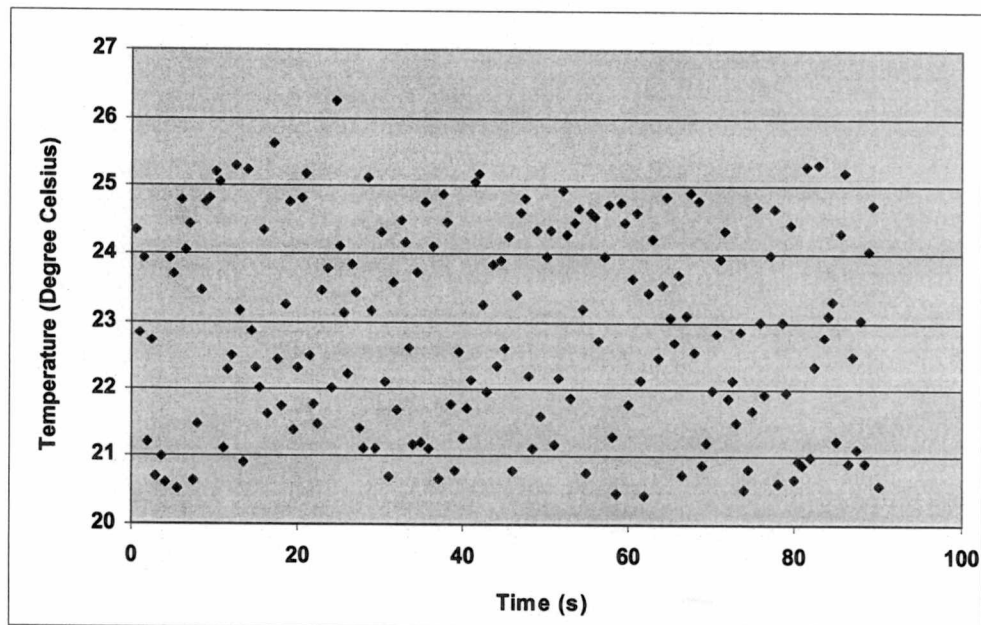


Figure 24 Fluctuation of temperature data due to electrical noises

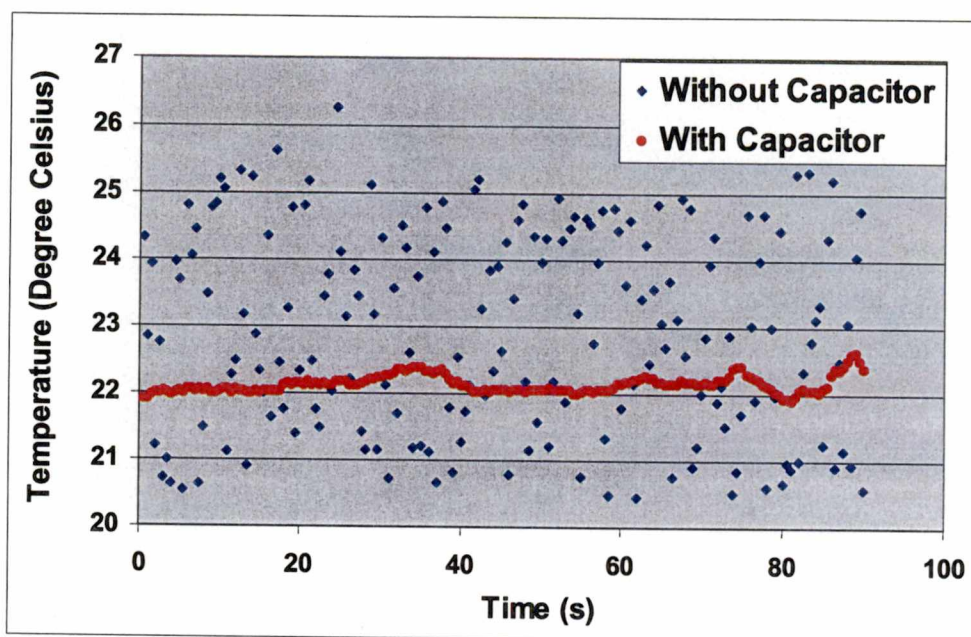


Figure 25 Fluctuation of temperature data dampened by the use of capacitor as a low pass filter.

measurement program. The use of the capacitor decreased the time response of the data acquisition system as a whole. Experimental error also occurred from the thermocouple amplifier that was used in the data acquisition system. To determine the experimental error in using the Omega OMNI-AMP-IV thermocouple amplifier, its output voltage was measured and compare with the Fluke® 5500 calibrator serving as a reference. The recorded error of the thermocouple amplifier can be seen in Table 2. The average 0.012 volt translates to an uncertainty of 1.2 °F in the temperature measurement. The largest part of the uncertainty came from the Arburg injection machine. The magnitude of total

Table 2 Error analysis for the thermocouple amplifier

Calibrator Output (°F)	Calibrator Reading (Volts)	Amplifier Reading (Volts)	Error (Volts)
250	2.500	2.515	0.015
200	2.000	2.005	0.005
150	1.500	1.491	0.009
100	1.000	0.981	0.019
		Average	0.012

uncertainty is determined through the use of an error band. Since the start time of the injection is unknown, all of the experimental runs are aligned using the peak temperature of each run. Since the peak temperature depends on the location of the thermocouple bead, any offset from its original location would cause variation of the peak temperature as seen in Figure 26. From the 10 experimental runs measuring fluid temperature at location B, the average peak temperature was found to be 218.7 °F with a 10.3 °F of standard deviation. Run #1 could be an outlier or error in the experiment probably due to nozzle temperature not reaching the operating temperature of 250 °F when injection began. If run #1 is removed from the data, the average peak temperature becomes 221.5 °F with a 5.4 °F standard deviation. Besides peak temperature uncertainty, the Arburg injection machine has its own uncertainty built in during operation. The development of an error band links directly to the repeatability of data. Figure 27 and 28 show the error band for both thermocouples locations A and B, respectively.

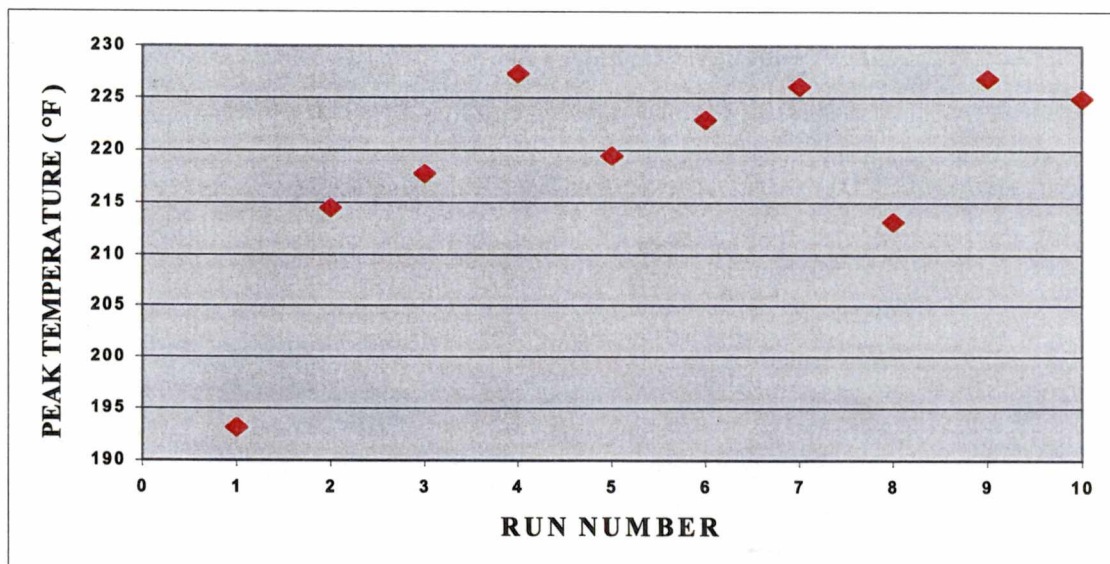


Figure 26 Peak temperature variation due to uncertainty in the height displacement of the thermocouple bead measuring fluid temperature at location B

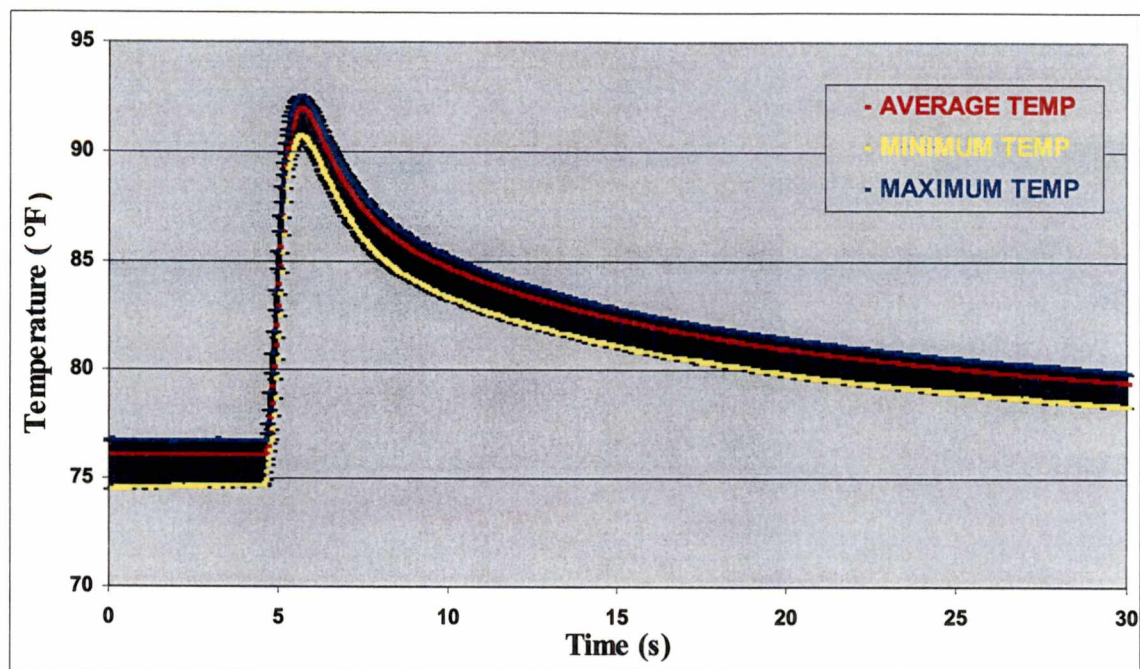


Figure 27 Error band for the die-wall temperature measurement

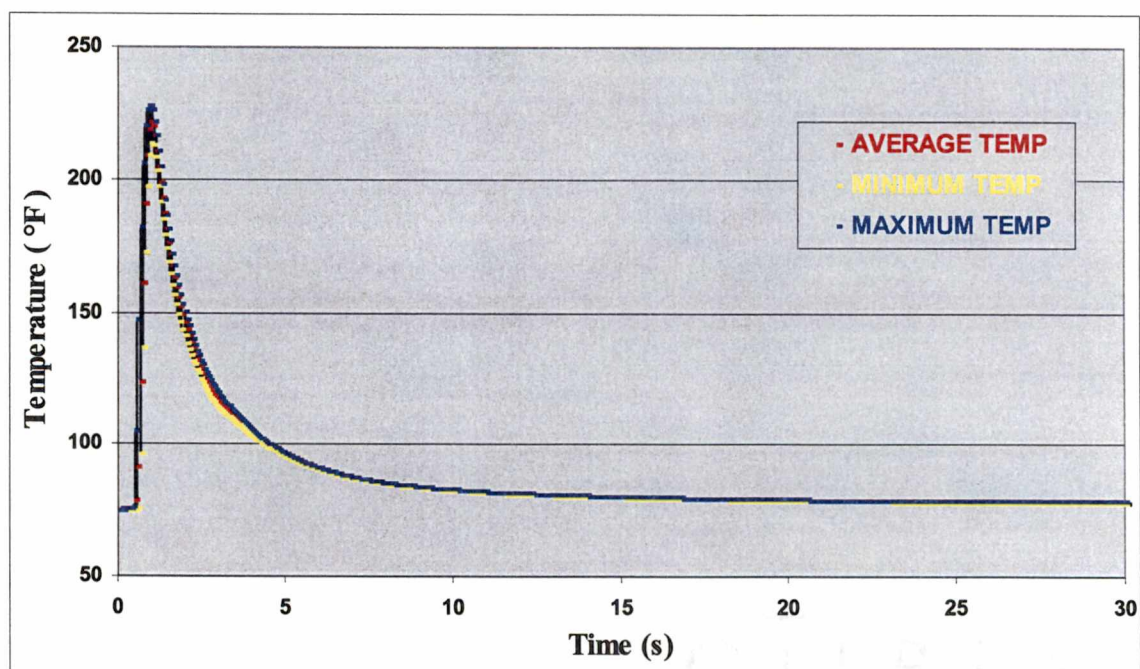


Figure 28 Error band for the fluid temperature measurement

4.2 SYSTEM TIME CONSTANT ANALYSIS

As discussed earlier, the thermocouple time response is related to the type of junction and the diameter of the thermocouple bead. However, the greatest influence on the response time of the thermocouple came from the data acquisition system itself. A fast response time was needed for the data acquisition system in order to capture the correct peak temperature during the 100-millisecond filling process. Slow response time will only bring more uncertainty to the peak temperature in every experimental run. Also by including a low pass filter in the data acquisition system, the time response of the acquisition as a whole was decreased. The time constant of the acquisition system was determined using a step change response from the ambient room temperature to the nozzle (initial) fluid temperature. The time constant was determined by measuring the time needed to reach 63.2% of the step response amplitude. The results show the acquisition system has a time constant of 0.83 second with no low pass filter and a 1.55 second with the implementation of a low pass filter. Consequently, the low pass filter that helps to damp out the electrical noise unfortunately increases the time constant of the system by 86%. The time response for type K, 0.010-inch bead diameter, thermocouple with and without the use of a low pass filter is presented in Figures 29 and 30.

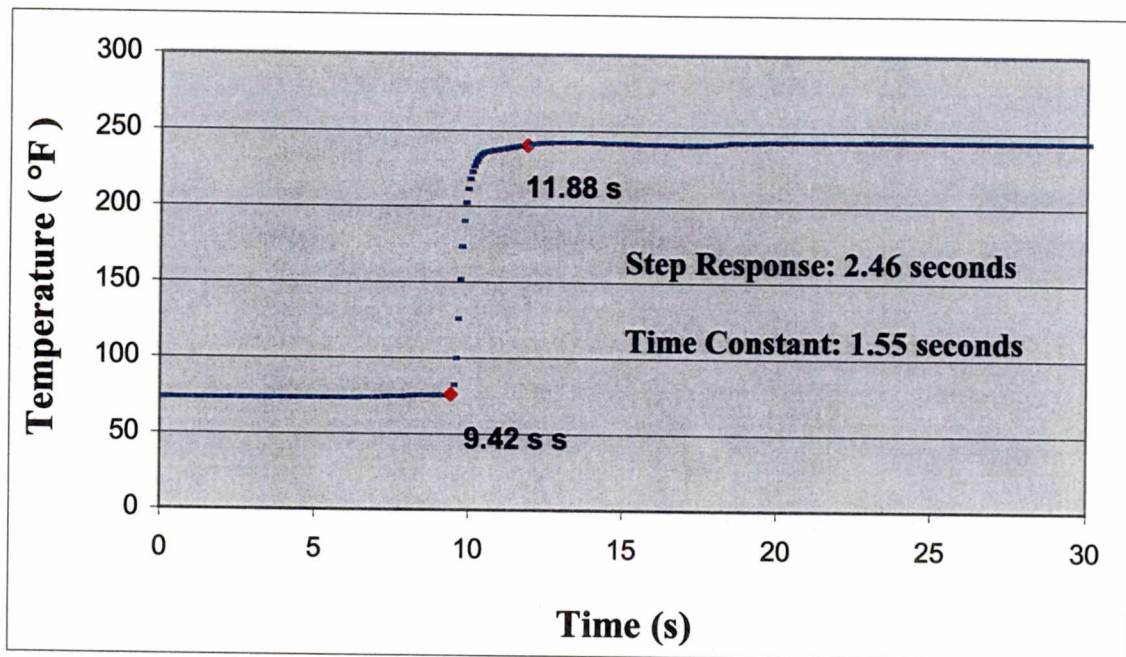


Figure 29 Time response test with the use of a low pass filter

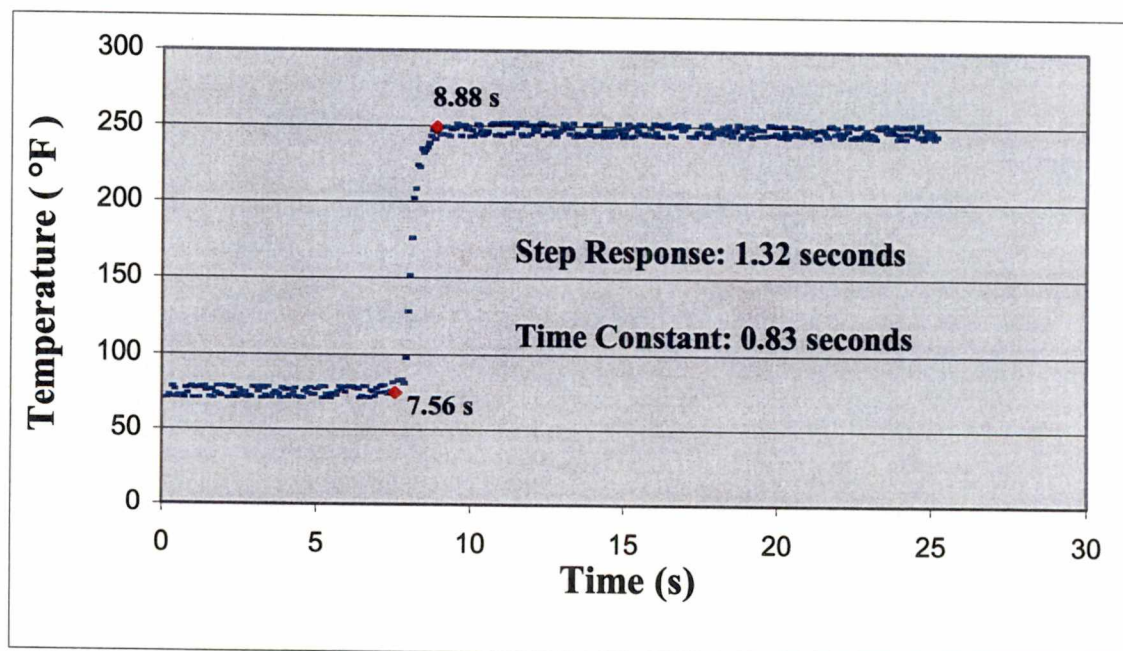


Figure 30 Time response test without the use of a low pass filter

CHAPTER 5

RESULTS AND DISCUSSION

The average experimental results from the ten experimental runs for both thermocouple locations A and B can be seen in Figure 31. As a reminder, the thermocouple at location A measures the temperature of the die wall, and the thermocouple at location B measures the temperature of the fluid. Also, all runs have the same initial conditions with injection pressures of 2000 psi and nozzle temperatures of 250 °F. The computer model was a free surface model of the injection fluid. The only possible comparison between the experimental and modeling data is expected at thermocouple location B, which measured fluid temperature. If the 8602B-die cavity was ever to be modeled, then the time-temperature data at thermocouple location A could

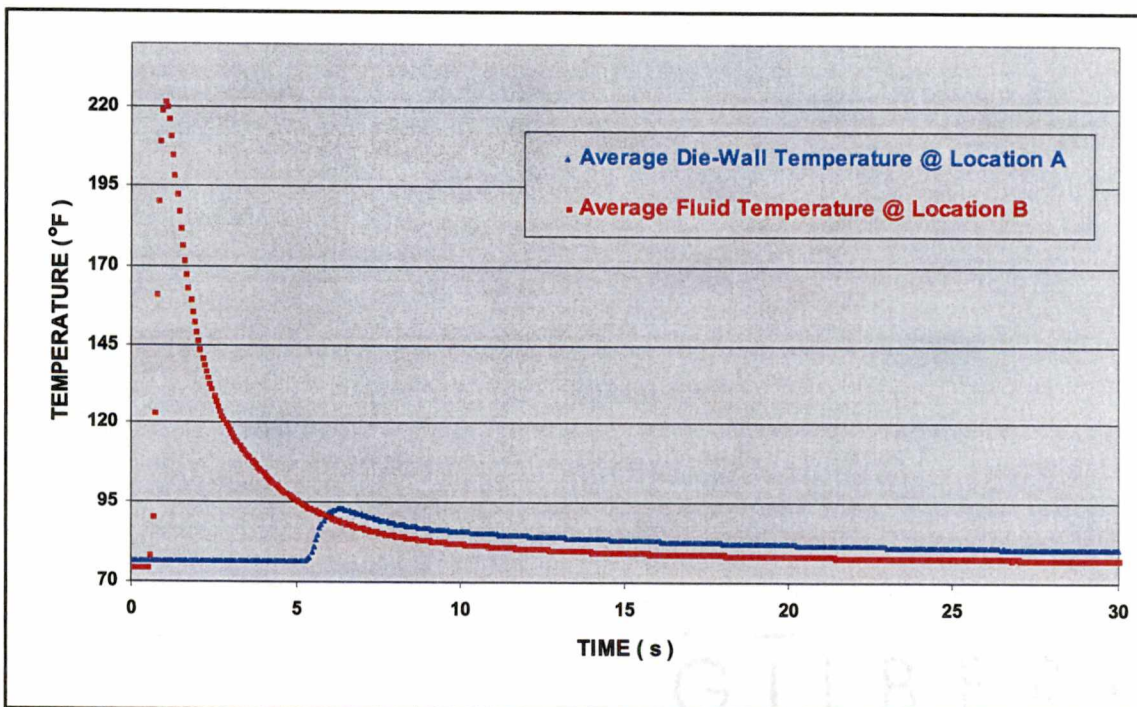


Figure 31 Experimental fluid and die-wall average temperature results

be used for comparison purposes in the future. However, in this study the time-temperature data at point B was the only data used to validate the model. Before comparing the two sets of time-temperature data, both the temperature and time were normalized. Nondimensionalization of both the experimental data and the modeling data are important in any validation process. The formula used to normalize the experimental and modeling data is the following:

$$\frac{T - T_{ambient}}{T_{initial} - T_{ambient}}$$

The exact time of injection in the experiment was unknown. It could not be determined exactly when the injection process started. So in order to compare the time-temperature data of the experiment and the computer model, the time was normalized. The time was shifted using the time at which the maximum temperature occurred in the experimental and modeling data. In other words, the time was shifted to compensate for the unknown starting time of injection in the experiment. The formula used to shift the time in the experimental and modeling data was the following:

$$Time - Time_{@Maximum_Temperature}$$

A graph showing the comparison between the experimental and modeling data is shown in Figure 32. The experimental data are bounded between the two extreme boundary conditions of the modeling data. These two extreme boundary conditions were the heat flux $q'' = 0.001 \text{ W/m}^2$ (adiabatic) and the $h=20,000 \text{ W/m}^2 \text{ K}$ (isothermal boundary).

These were the first two-computer models that were run. Since the adiabatic model did

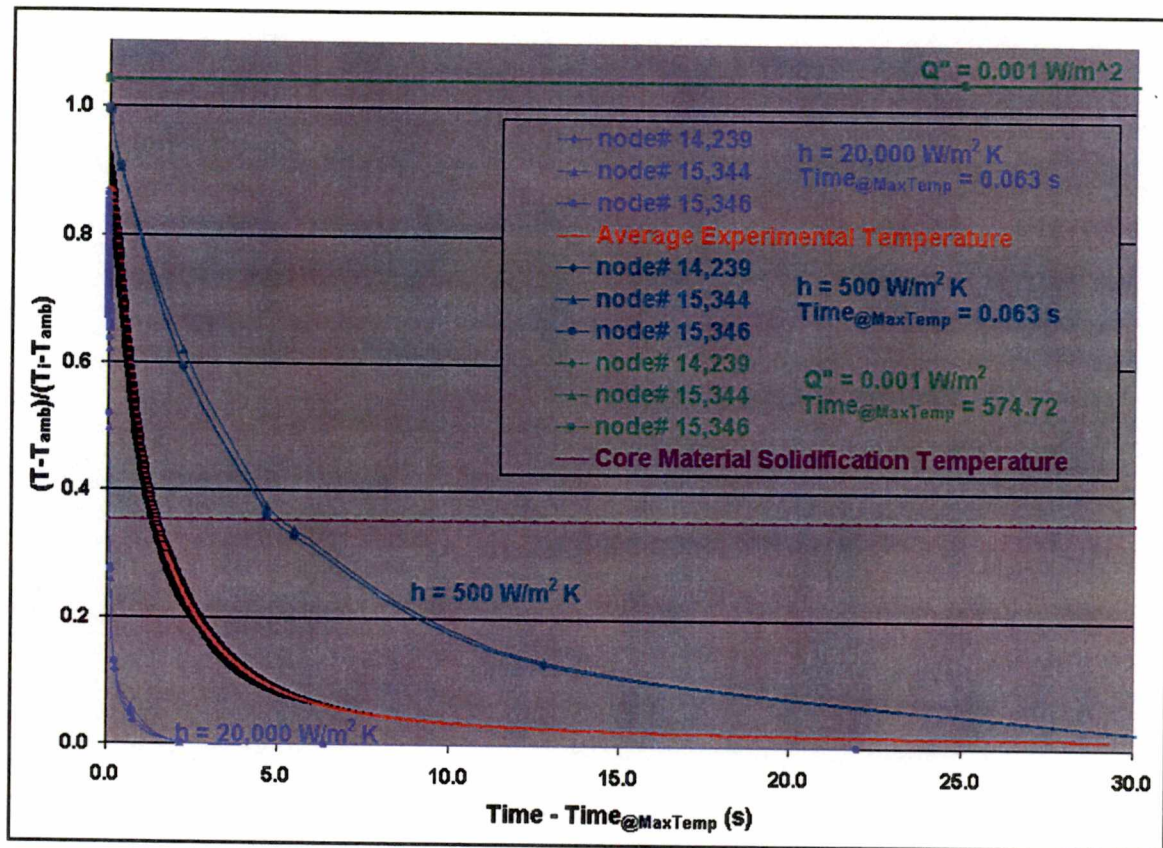


Figure 32 Material temperature variation with time – comparison of measured and model predictions looking at extreme boundary conditions.

not represent the trend in the experimental data, a third computer model was run with $h=500\text{ W/m}^2\text{ K}$. The $h=500\text{ W/m}^2\text{ K}$ data yielded a better representation of the trend in the experimental data than the adiabatic results. The experimental data fell between the isothermal or high heat flux ($h=20,000\text{ W/m}^2\text{ K}$) curve and the $h=500\text{ W/m}^2\text{ K}$ curve as shown in Figure 32. By using the lumped capacitance method,²⁰ a heat transfer coefficient could be determined that yielded results similar to the experimental data. A new heat transfer coefficient of $h=1,800\text{ W/m}^2\text{ K}$ was calculated through the lumped capacitance method. The results of the $h=1,800\text{ W/m}^2\text{ K}$ model compared to the experimental data can be seen in Figure 33. In Figure 33, the model lies within the error

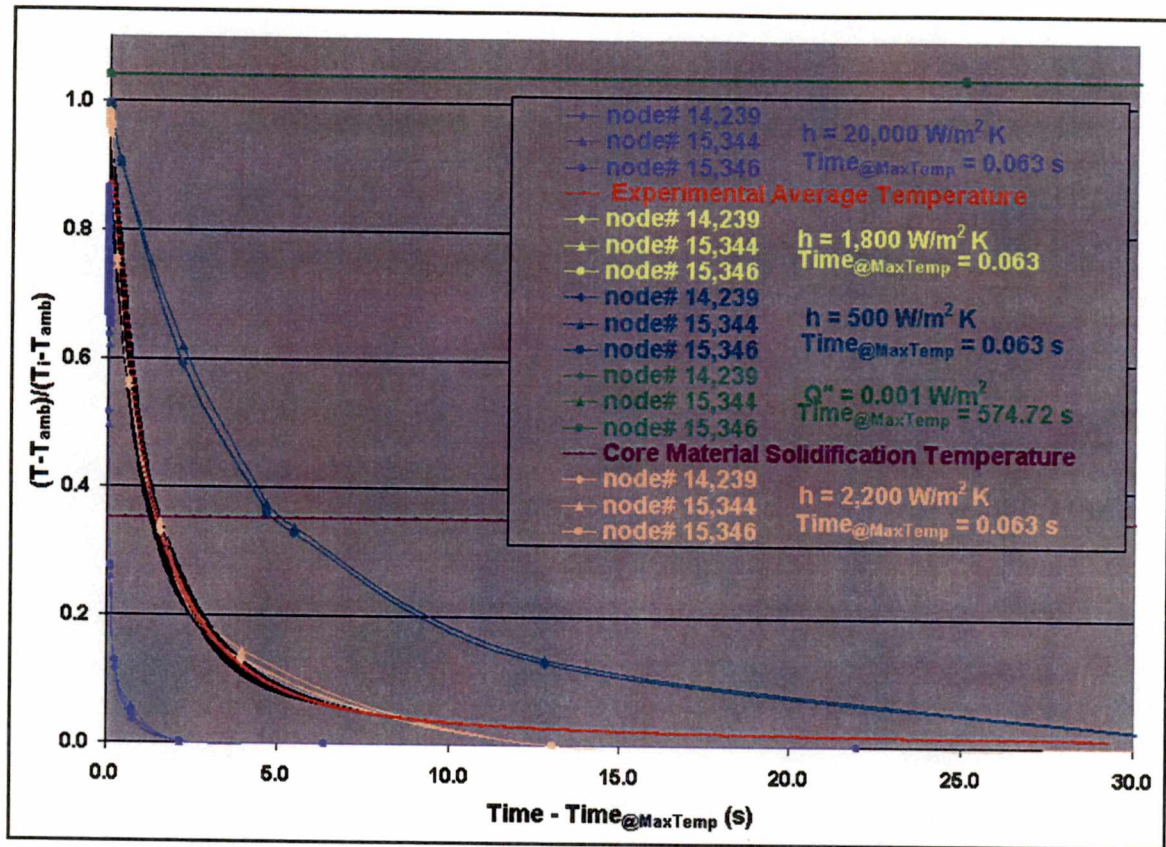


Figure 33 Material temperature variation with time-comparison of measured and model predictions include $h = 1,800 \text{ W/m}^2 \text{ K}$.

band of the experiment from 0 to 4 seconds. Greater detail in the results can be seen in Figure 34. This shows the modeling results staying within the experimental error band for the first 5 seconds. Figure 34, the maximum temperatures of the model and the experiment do not match because the experimental discrete data were sampled at every 30 milliseconds and the injection process is completed at 100 milliseconds. The only way to obtain the true maximum temperature would be to have a data acquisition system that has a much faster response time. This would provide a faster data collection sampling rate. The $h=1800 \text{ W/m}^2 \text{ K}$ data yielded slightly better results in approximating the experimental data than the $h=2,200 \text{ W/m}^2 \text{ K}$ data. However, both sets of data were

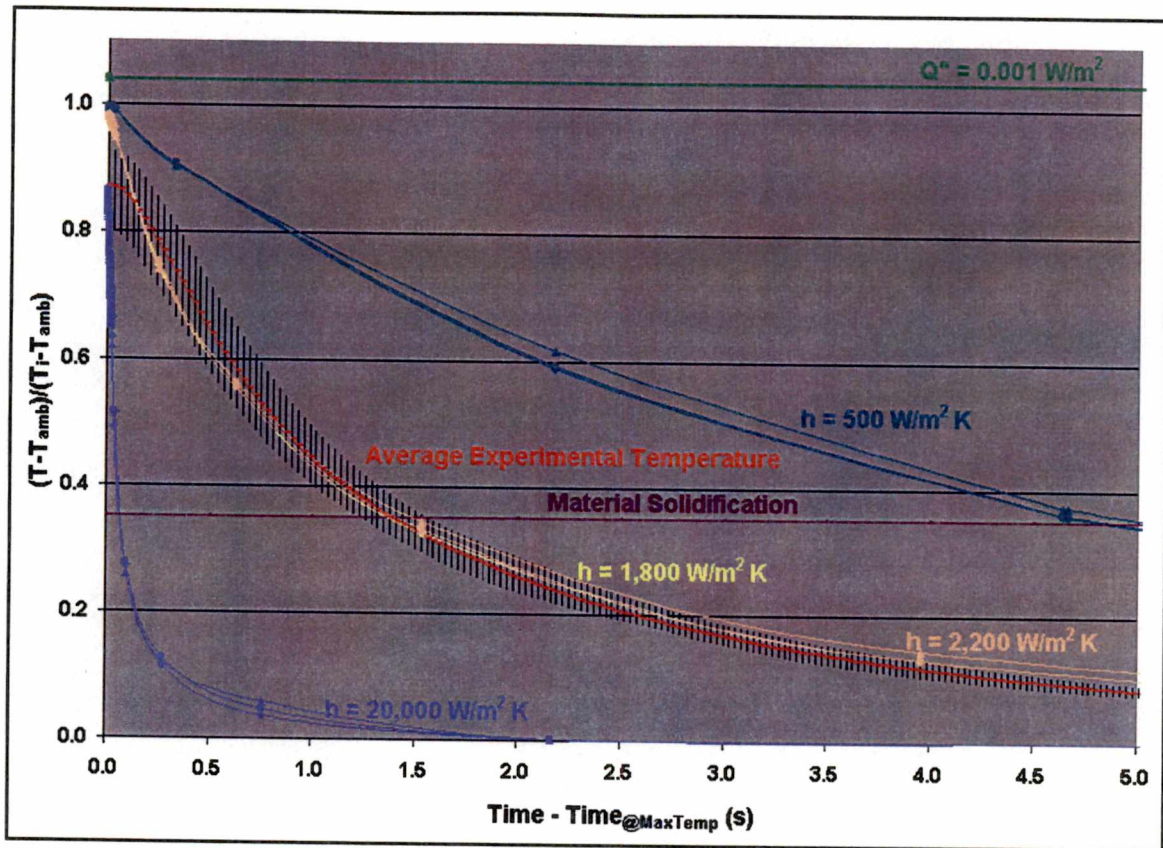


Figure 34 Material temperature variation with time-comparison of measured and model predictions looking at the first 5 seconds of normalized time.

very similar. In conclusion, the most accurate average heat transfer coefficients for the filling and solidifying process were around $1,800 \text{ W/m}^2 \text{ K}$ or $2,200 \text{ W/m}^2 \text{ K}$ with the assumption that the heat transfer coefficient was uniform throughout the die and that it was independent of time.

Comparing experimental data with modeling data was not the only way to validate the computer model. The filling pattern could be obtained experimentally through the use of short shots. A short shot is a molded part (ceramic core) that is incompletely filled because insufficient material is injected into the mold. It is a method by which the injection process is prematurely stopped at a certain time during injection to

view the filling pattern at that point in time in the injection process. The nine frames that were captured from the isothermal computer model (see Appendix C) demonstrate the same filling pattern as the short shot frames. Also, knowledge of the history of problems of the 8602B die cavity could be used to validate the computer model. This could be done by looking at the five modeling cases that were run from the adiabatic condition to the high heat flux condition. A single frame would be captured at the same injection time for each case. As shown in Appendix F, throughout the five modeling cases the last crossover from the root end of the core shows high heating in that area. This high heating is due to the high shear rate that results from forcing a highly viscous material to flow from a large cross-sectional area of the leading edge through a much smaller cross-sectional area of the crossover. This is also due to an increase in velocity at the 90-degree turn from the leading edge to the crossover. The history of the 8602B die cavity shows a problem in that area with erosion in the last crossover which increases the crossover diameter beyond the maximum allowable tolerance.

In conclusion, the ProCAST modeling software was quite capable of modeling the ceramic injection process. The modeling results are reasonably accurate and validated with confidence that it would be realistic within the uncertainty of the experimental results performed on the actual injection process. The validation of the ProCAST software insures that the injection process can now be optimized by experimenting with a variety of modifications (e.g. vent location, die pressure, temperature profile, and sprue diameter). This would allow the die-cavity to operate at lower injection pressures while obtaining defect-free cores. This scenario would result in prolonging the life of the die and greatly increasing the productivity of the manufacturing of ceramic cores.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The goals of this study were successfully accomplished. The experimental data were successfully collected from the ceramic injection process, and the ProCAST simulation software was successfully validated through the comparison of experimental and modeling data. The validation of the ProCAST software would allow the ceramic core injection process to be optimized by evaluating the different modifications (e.g. vent location, die pressure, temperature profile, and sprue diameter). This would allow the injection speed to be lowered while defect-free cores were produced. Lowering the injection speed would lower the injection pressure. This would greatly increase the life of the die through less wear. It is important to understand that experimental results collected during this project can be used as a means of comparison for future computer predictions.

For modeling studies, it is recommended that temperature dependence of the heat transfer coefficient should be explored for both the filling and cooling phases of the injection process. On the other hand, future experiments should explore similar temperature measurements at several locations using smaller thermocouples with faster time responses. Pressure measurements at the fluid boundary could also be explored and the process data could be used to validate future simulation models.

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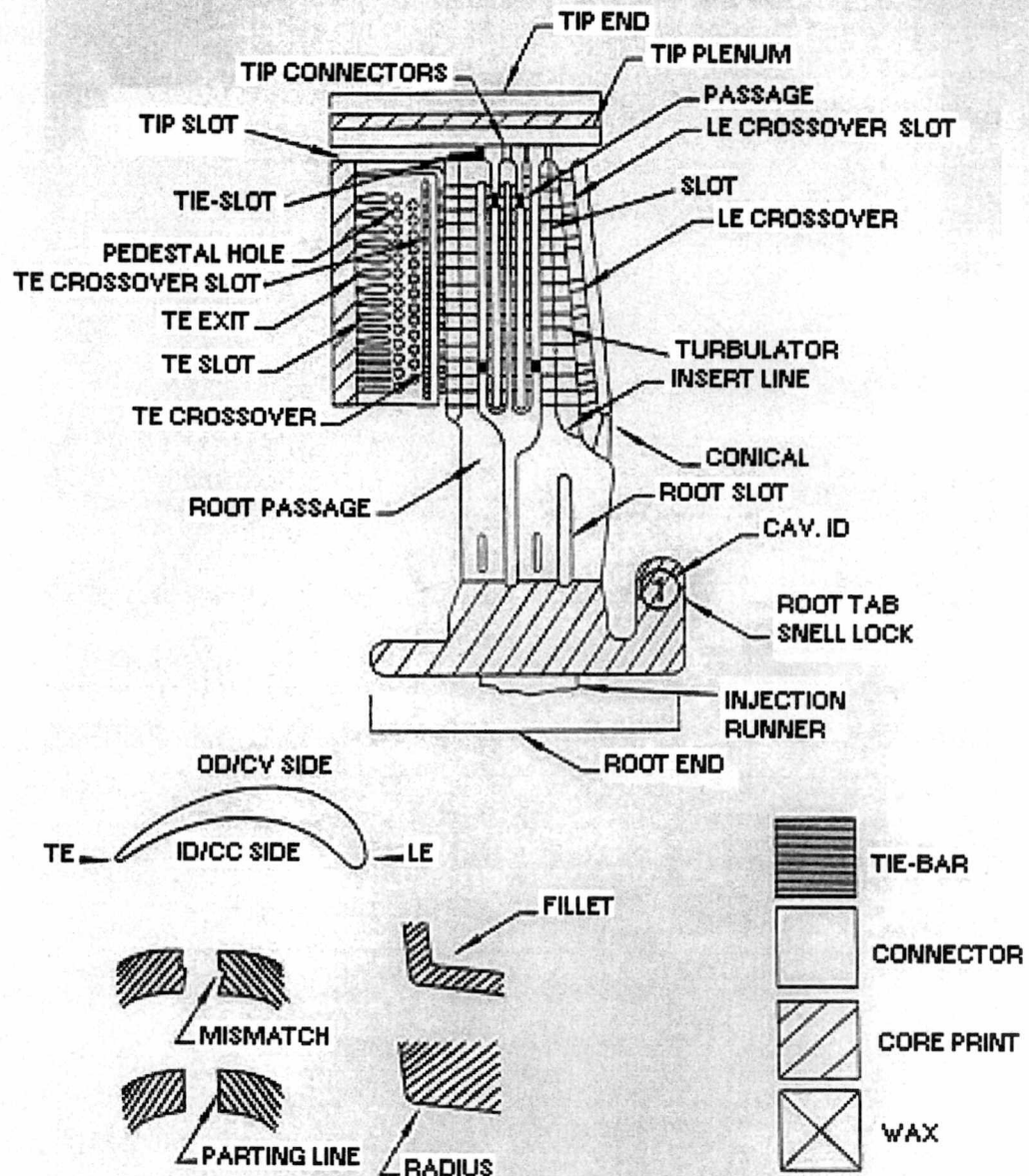
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APPENDICES

APPENDIX A

Core Terminology



(Courtesy of Howmet Corporation)

APPENDIX B



Figure B.1 Boeing 777 with twin GE90 engines

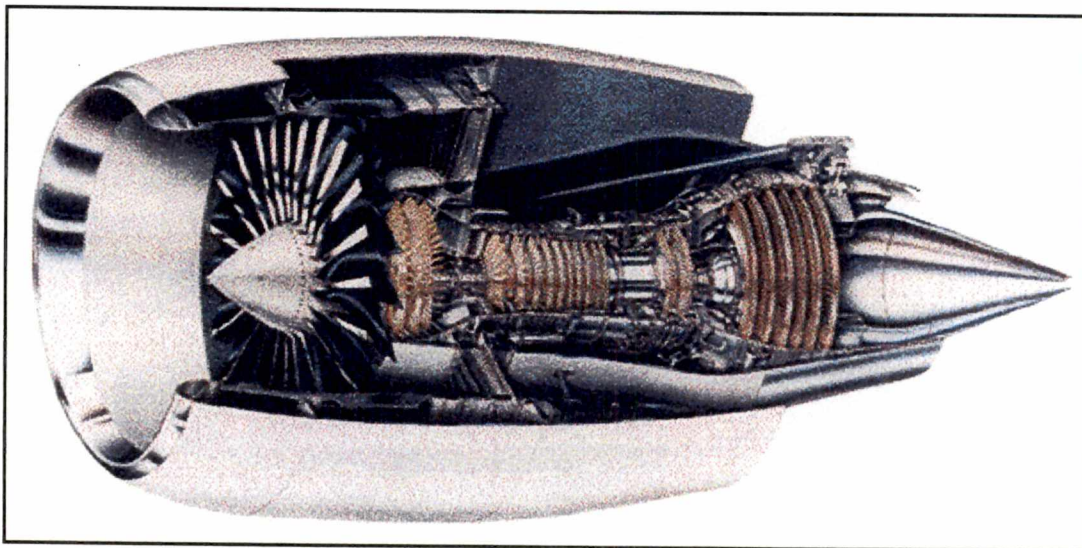


Figure B.2 GE90 – General Electric – aircraft engine

APPENDIX C

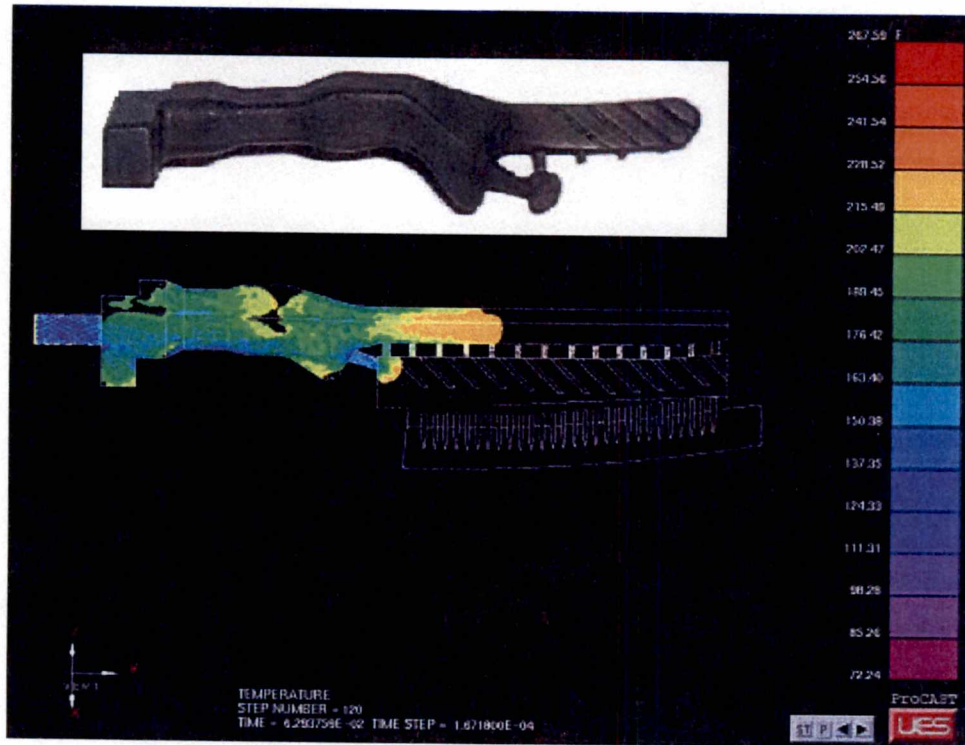


Figure C.1 Thermal contour plot @ step number 120

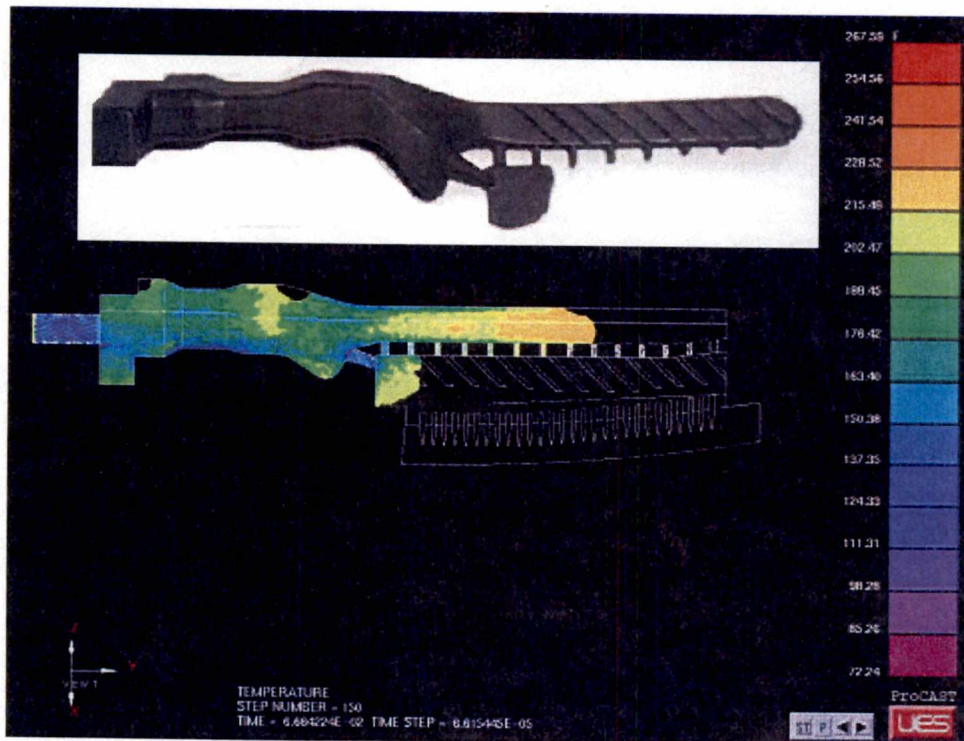


Figure C.2 Thermal contour plot @ step number 150

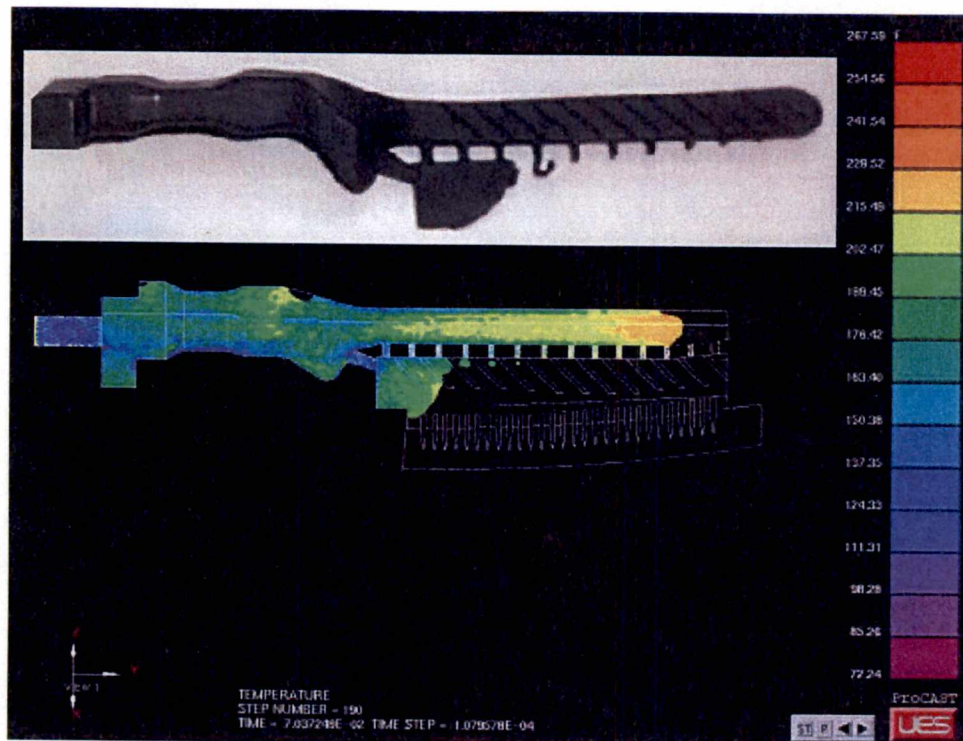


Figure C.3 Thermal contour plot @ step number 190

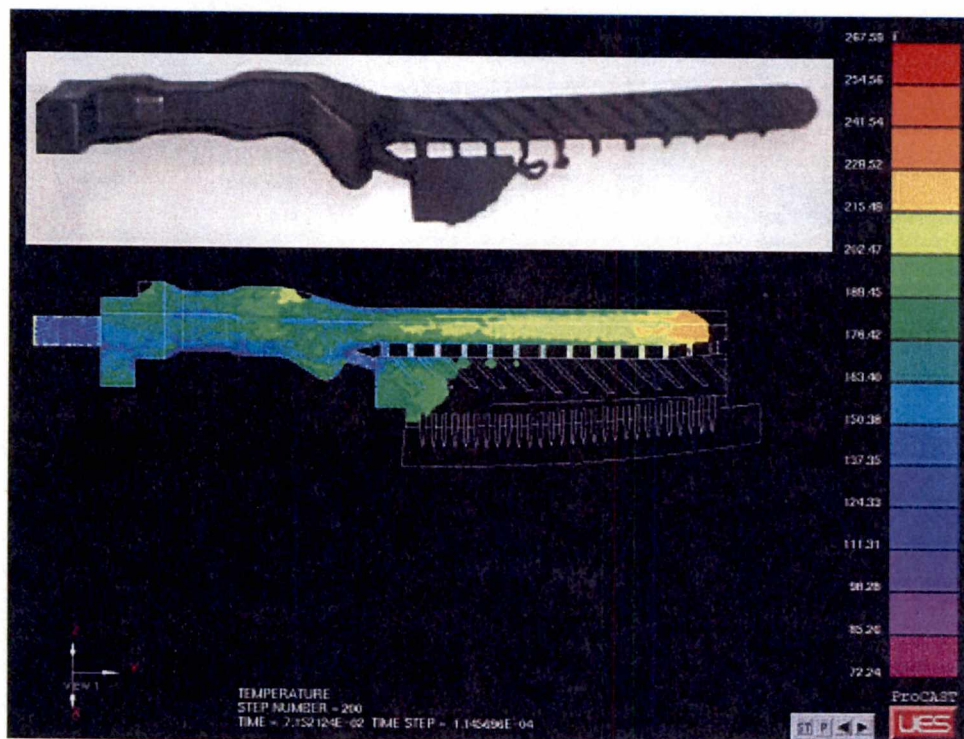


Figure C.4 Thermal contour plot @ step number 200

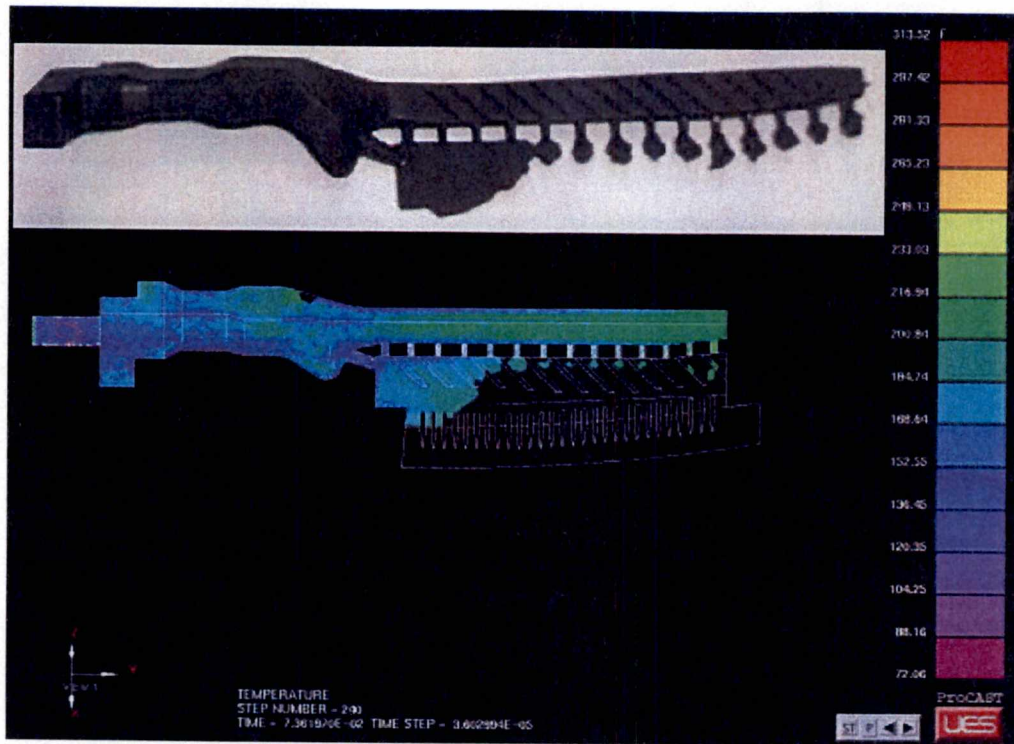


Figure C.5 Thermal contour plot @ step number 240

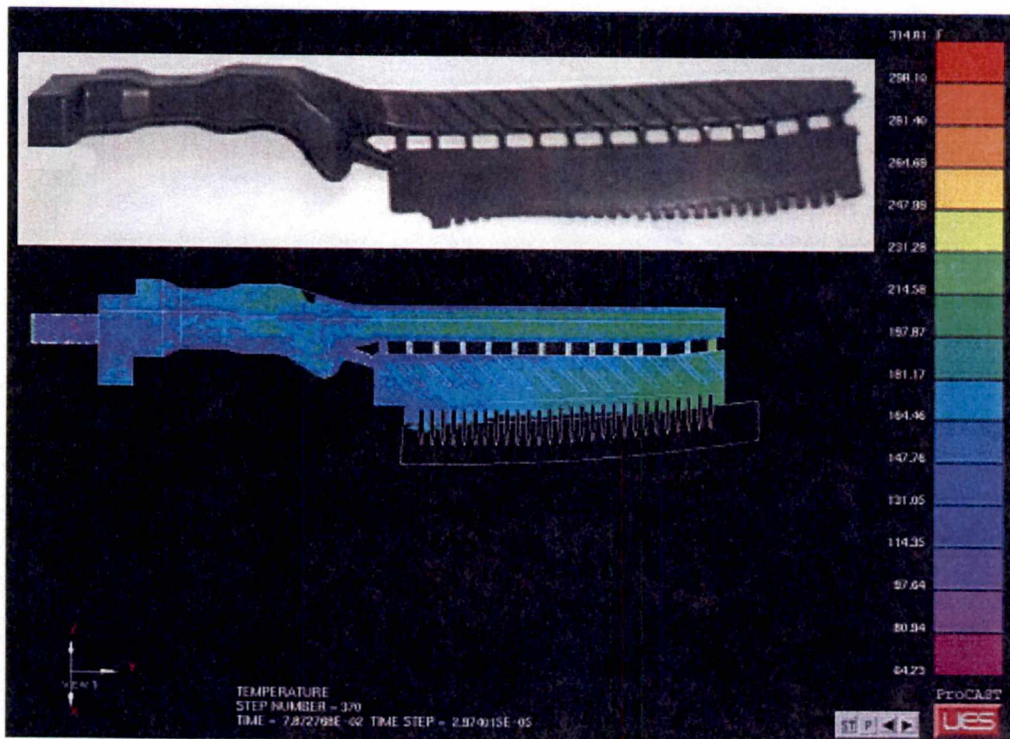


Figure C.6 Thermal contour plot @ step number 370

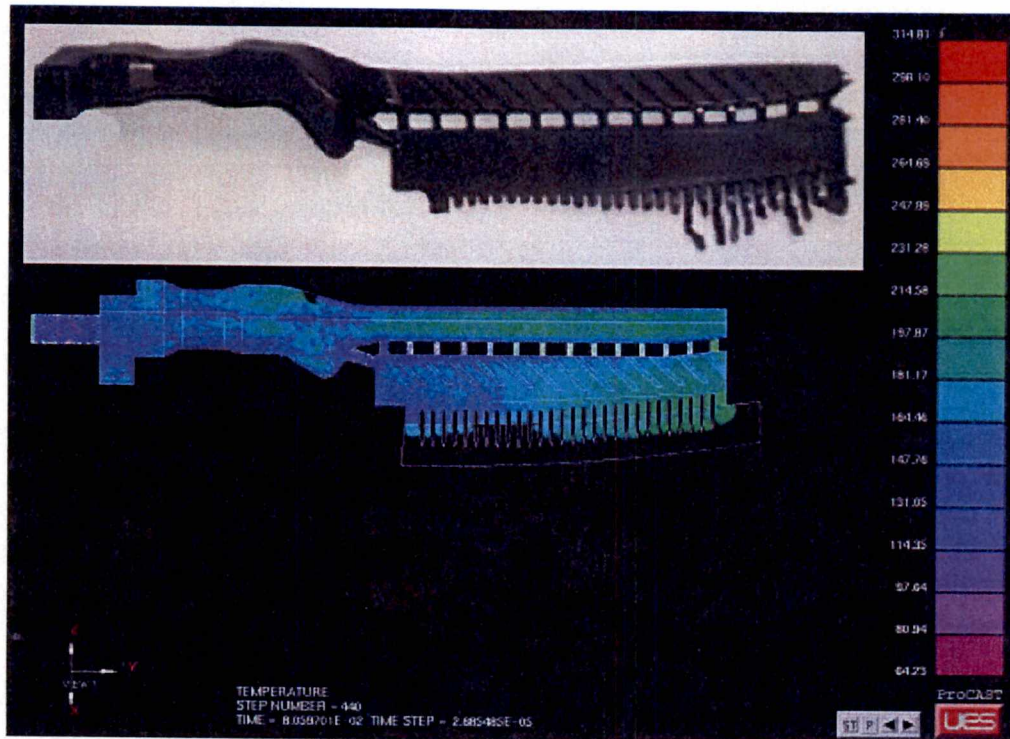


Figure C.7 Thermal contour plot @ step number 440

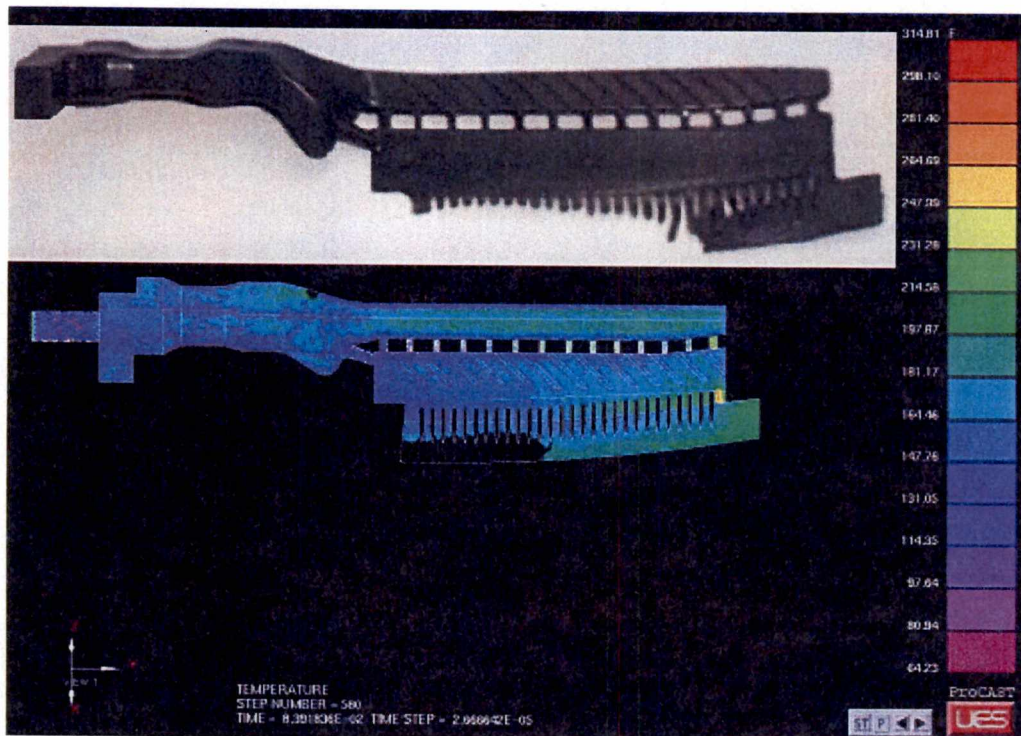


Figure C.8 Thermal contour plot @ step number 580

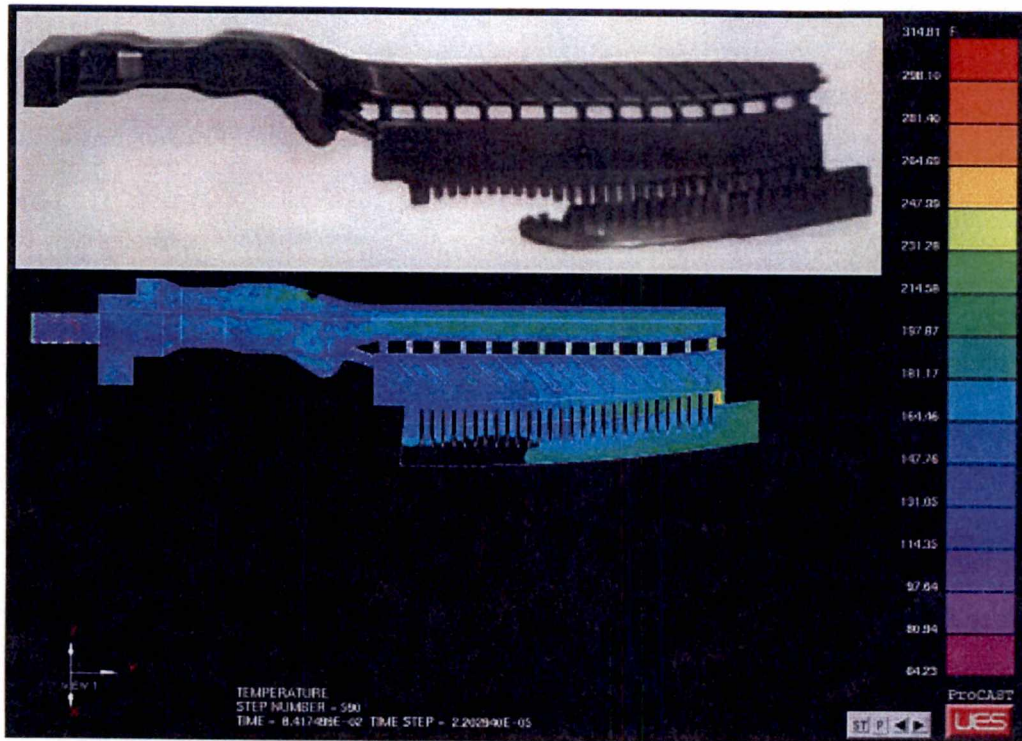


Figure C.9 Thermal contour plot @ step number 590

APPENDIX D

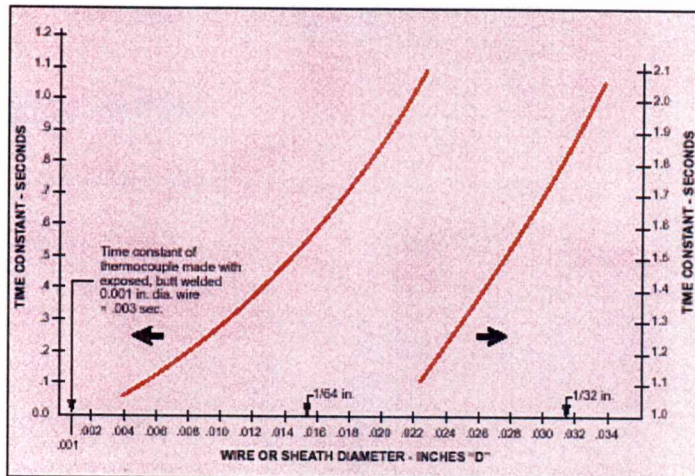
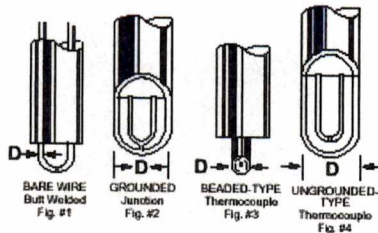
Comparison of Time Constant* vs. Overall Outside Diameter of Bare Thermocouple Wires or Grounded Junction Thermocouple In Air

Time constants calculated for air at room temperature and atmospheric pressure moving with velocity of 65 feet per second for thermocouples shown in Figures #1 and #2.

For beaded-type and ungrounded junctions (Figures #3 or #4), multiply time constants by 1.5.

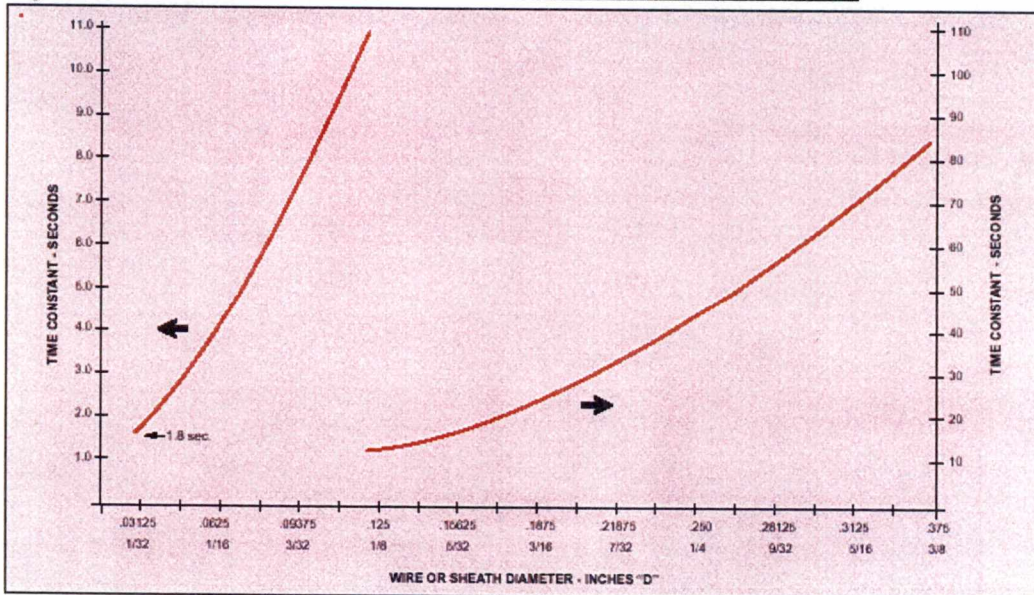
Time constant of thermocouple made with exposed butt welded 0.001 inch dia. wire = .003 sec.

* The "Time Constant" or "Response Time" is defined as the time required to reach 63.2% of an instantaneous temperature change.



Because of space limitations, time constant curve is divided into 4 separate curves.

Figure M Sheath Diameter 1/32" to 3/8"



Note:

These comparisons apply to either bare "butt-welded" or "grounded" junction thermocouples. If the thermocouples are the "beaded" type or "ungrounded," the time constant is longer. These times are only approximate and are provided for comparison purposes only. Multiply values from Time Constants by 1.5 for junctions shown in Fig. #3 and Fig. #4.

APPENDIX E

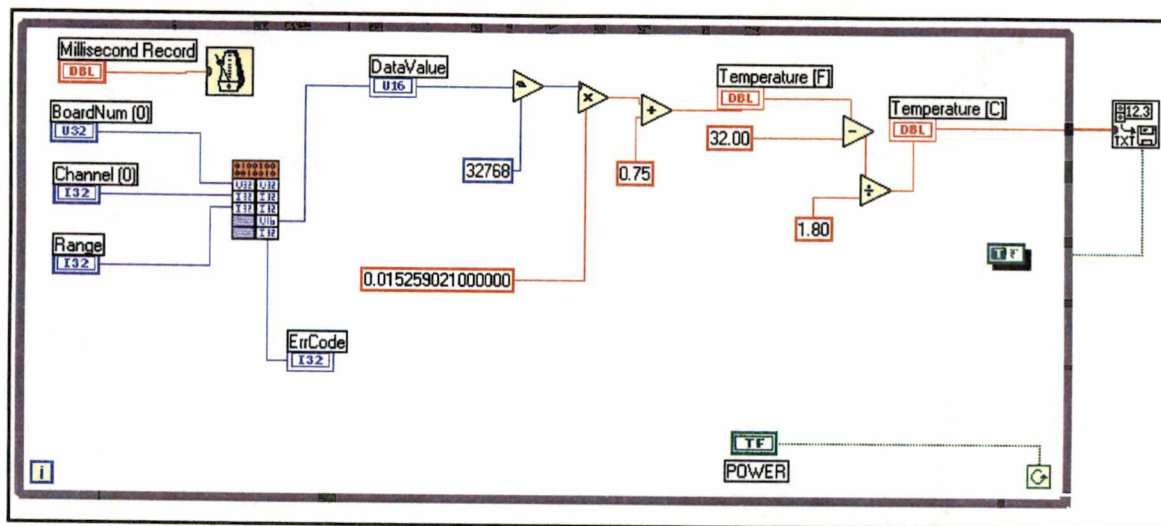


Figure E.1 Diagram view of LabVIEW program in collecting temperature data

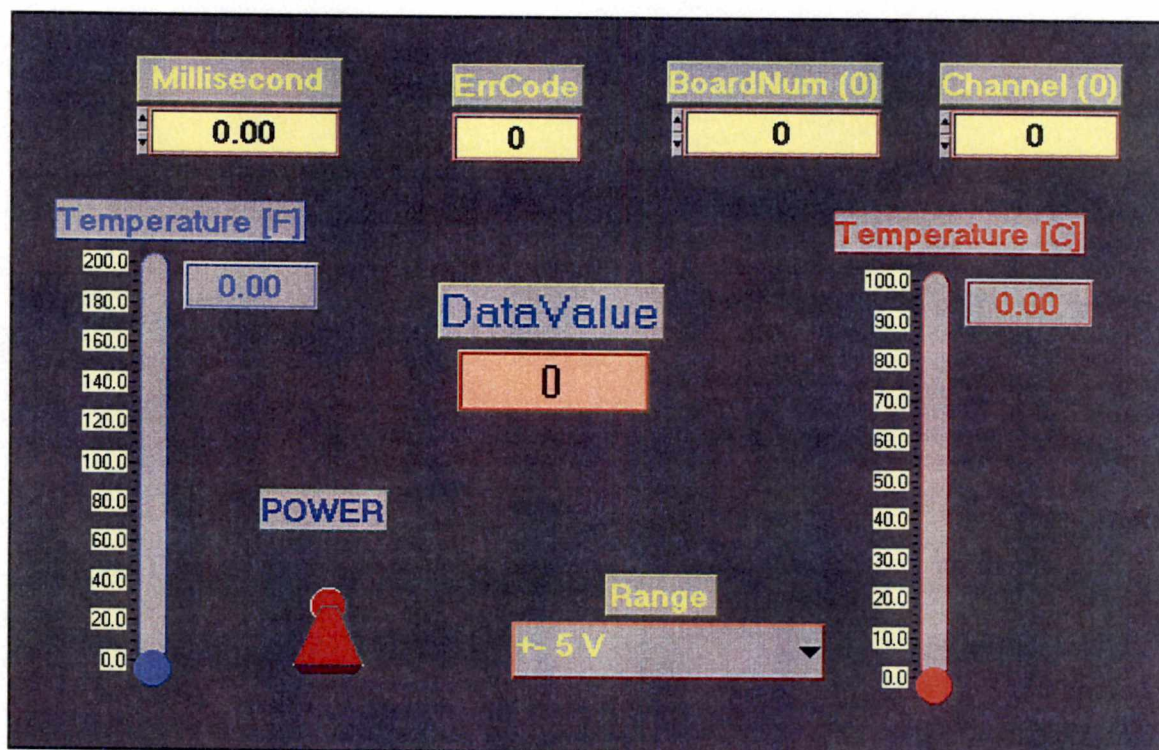


Figure E.2 Panel view of LabVIEW program in collecting temperature data

APPENDIX F

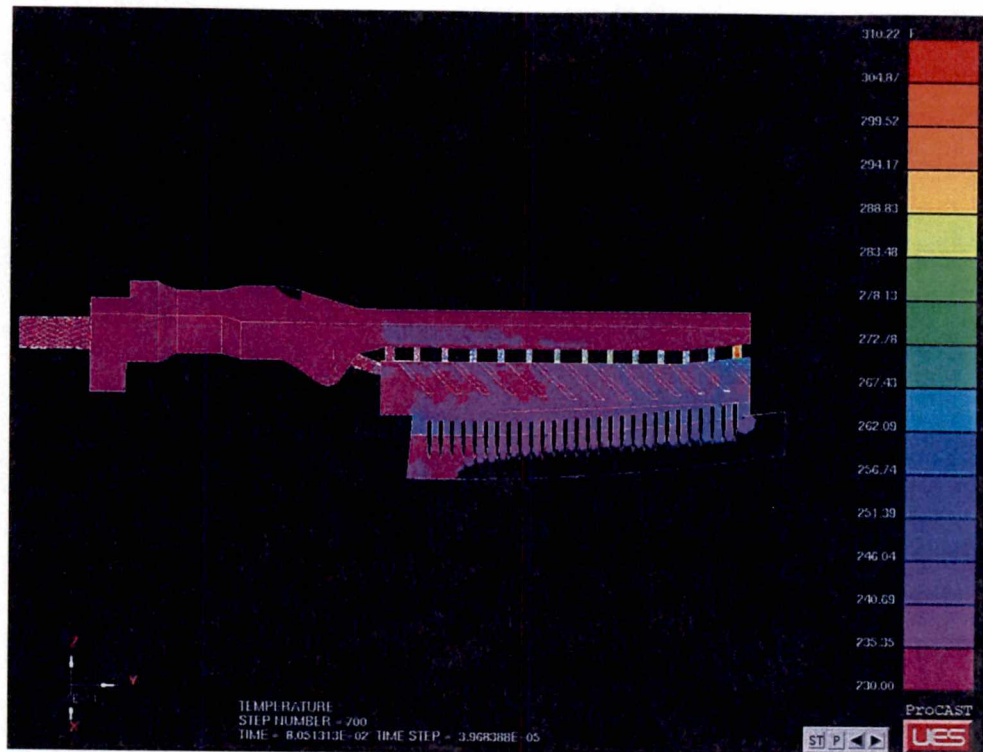


Figure F.1 Adiabatic filling condition

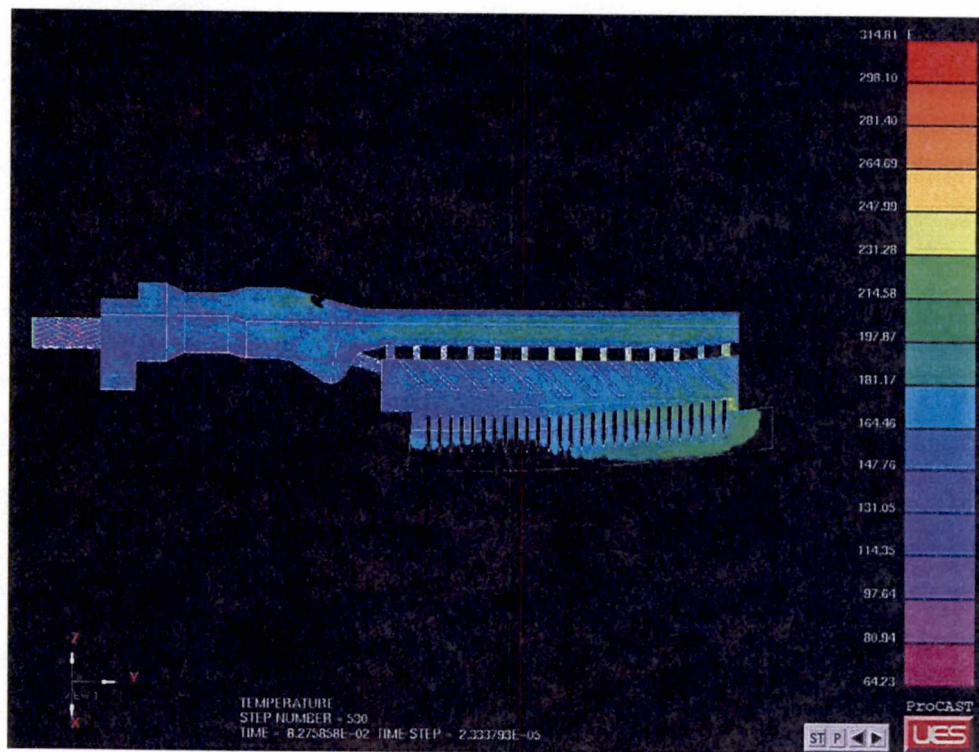


Figure F.2 Isothermal filling condition

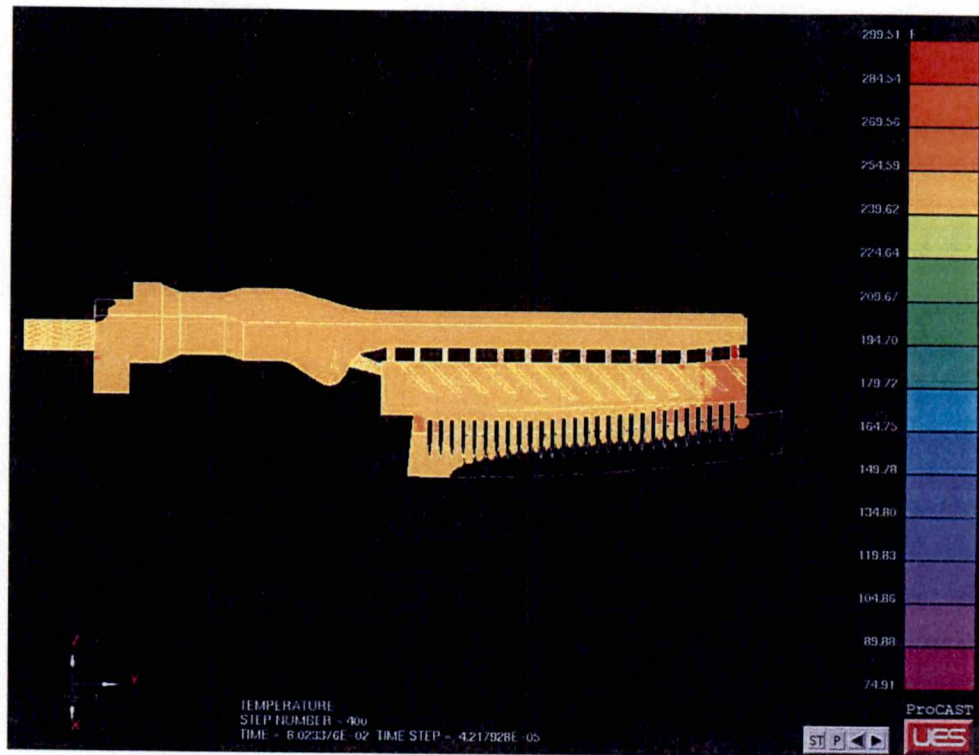


Figure F.3 $h = 500 \text{ W/m}^2 \text{ K}$ filling condition

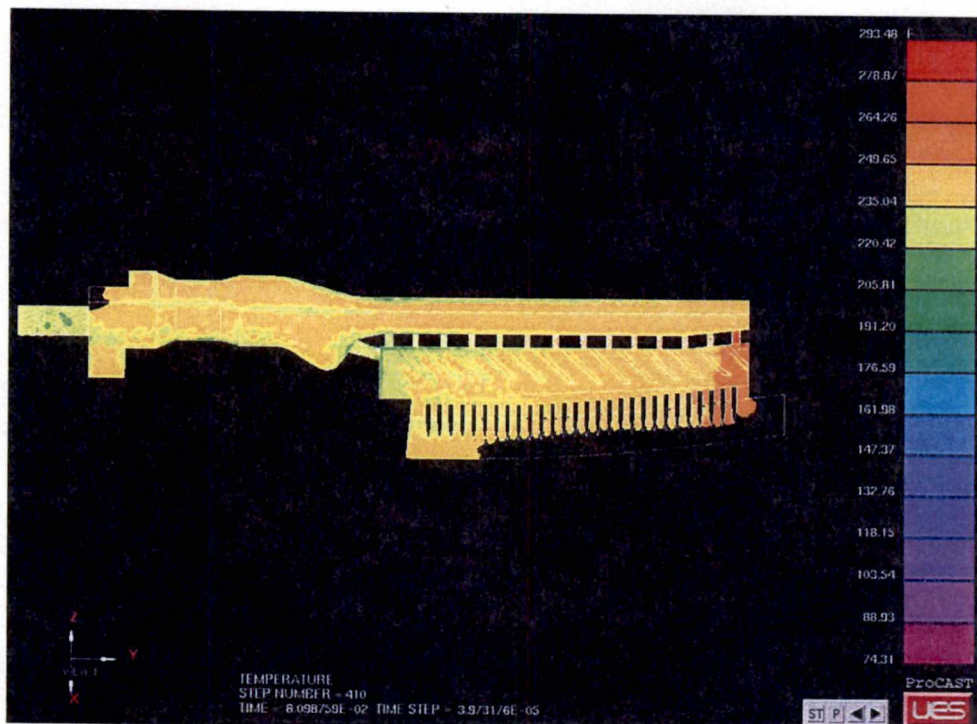


Figure F.4 $h = 1,800 \text{ W/m}^2 \text{ K}$ filling condition

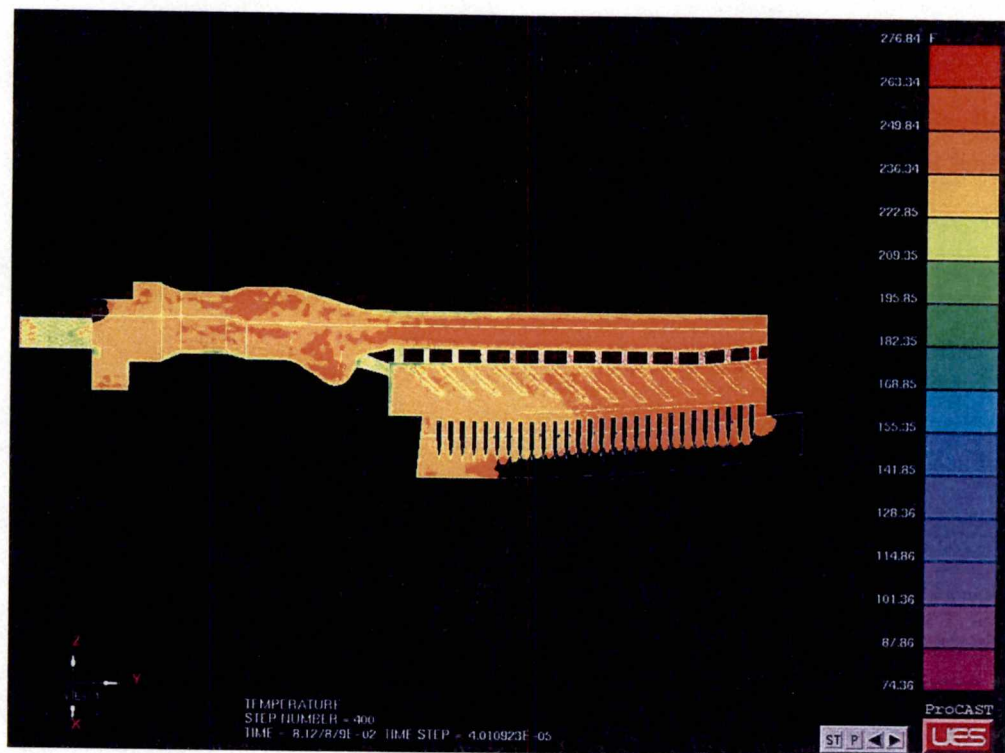


Figure F.5 $h = 2,200 \text{ W/m}^2 \text{ K}$ filling condition

VITA

Anh Hoang Ly was born in Saigon, Vietnam on March 20, 1972. He spent the first eleven years of his life growing up in Hoa Hung District where he attended the first through fifth grades at Le Thi Rieng Elementary School. In the summer of 1983, he immigrated with his mother to the United States under the Amerasian Resettlement Program. They settled in Knoxville, Tennessee starting a new life with the help from their sponsors Dr. George Brown and Mrs. Hieu Bishop from the Calvary Baptist Church. He then attended Inskip Elementary School starting in the third grade and spent a large part of his time studying the English language and adapting to the new culture. He then attended Gresham Junior High and finally graduated from Central High School in May of 1992. He began his undergraduate studies at the University of Tennessee in Knoxville, Tennessee in August of 1992. He graduated and received his Bachelor of Science in Mechanical Engineering in December of 1997. After graduation, he continued to pursue a Master of Science degree in Mechanical Engineering at University of Tennessee, Knoxville. He took the opportunity to participate in a new graduate co-operative program in Mechanical and Aerospace Engineering and Engineering Science Department working for the Howmet Corporation as a Product Engineer in Morristown, Tennessee. He finished his one-year co-operative assignments in May of 1998. Working at Howmet Corporation allowed him to gain valuable manufacturing experience while providing opportunity to conduct experimental research under Dr. Masood Parang. He will receive his Master of Science degree in Mechanical Engineering in December of 2000.