ANALYSIS OF IN-CAVITY THERMAL AND PRESSURE CHARACTERISTICS IN ALUMINUM ALLOY DIE CASTING

A Thesis

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

By

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ABSTRACT

The lack of effective control of the die casting process is the primary reason for the occurrence of defective die cast products. A reliable process control system must be capable of measuring the process variables, comparing them to the standard or ideal values and making suitable alterations in the process to eliminate any deviation from the ideal. This study attempted to facilitate the development of such a process control system. A two pronged approach was used to achieve this objective. The experimental approach addressed some of the problems in the measurement of process variables. The analytical approach addressed some of the problems in the design of the process and subsequent identification of the ideal process variable values.

The experimental approach concentrated on the measurement of in-cavity pressure and thermal characteristics of the die casting process. Kistler direct pressure sensors were evaluated and utilized for cavity pressure measurement during the die casting campaign. Thermal probes using staggered thermocouples were developed and utilized for the simultaneous measurement of die surface temperatures and heat flow rate through the die. The measured thermal and pressure characteristics were related to the injection characteristics measured using the shot control equipment of the Buhler H-250SC die casting machine used in the campaign.

The analytical approach concentrated on the verification of the predictions of a computer numerical solidification analysis, namely BINORM, by comparison with the experimental data obtained as an output of the die casting campaign. Particular attention was paid to the predictions of thermal characteristics like freezing time and die surface temperature. A sensitivity analysis was also performed to determine the effect of changes in individual variables on the predictions of BINORM. This sensitivity analysis was restricted to the study of the effect of variations in process conditions on the freezing time and initial die surface temperature predictions.

The probes were mounted on a die insert, called the wall die insert, and the die casting campaign conducted using a Buhler H-250SC die casting machine. The thermal and pressure measurements were recorded and analyzed by relating to the injection characteristics measured by the shot control equipment of the die casting machine. Further, the measured thermal data were compared to the thermal predictions of BINORM for the experimental operating conditions. The thermal probes developed were found to be accurate but not suitable for continuous operation in die casting conditions. They require some modifications in design before further evaluation under industrial conditions. The Kistler pressure probes were found to be accurate and reliable in the die casting environment, but require further evaluation under industrial conditions. The BINORM model was found to be an effective instrument for predicting the thermal conditions in die castings with simple cross sections.

Dedicated to my parents

ACKNOWLEDGMENTS

I wish to thank my adviser, Dr. Jerald Brevick, for his patience and guidance that made this thesis possible. I also thank Dr. Carroll Mobley for his constructive role in helping structure and refine this thesis. I am also grateful to the invaluable help extended by Lloyd Barnhart, Angela Wollenburg, Xue-Heng Zhang and Yong Park, without which the die casting campaign might not have been possible. Finally, I am indebted to my friends Avinash Gandhe, Srikanth Balasubramaniam and Venkatalakshmi Balakrishnan for their continuous support through the most demanding period of my life.

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CHAPTER 1

INTRODUCTION

1.1 Process Overview

The die casting process is a high production rate casting method that can produce cost effective, primarily non-ferrous, products of complex shapes with excellent surface finish, good dimensional tolerances and high material yields. It is essentially a near net shape manufacturing method where molten alloy is forced into a metal die and allowed to solidify under pressure to take the shape of the die cavity. The basic cold-chamber die casting process (Figure 1.1) consists of the following stages:

1) die closure, where the die halves are brought together and locked with the required clamping force,
2) ladling, where the predetermined volume of melt is ladled into the shot sleeve from the holding or melt furnace,
3) cavity filling, where the superheated molten metal or alloy is injected at high velocities and under high pressure into the die cavity to ensure rapid and complete filling,
4) melt solidification, where the injected melt is solidified under pressure and under predetermined thermal conditions,

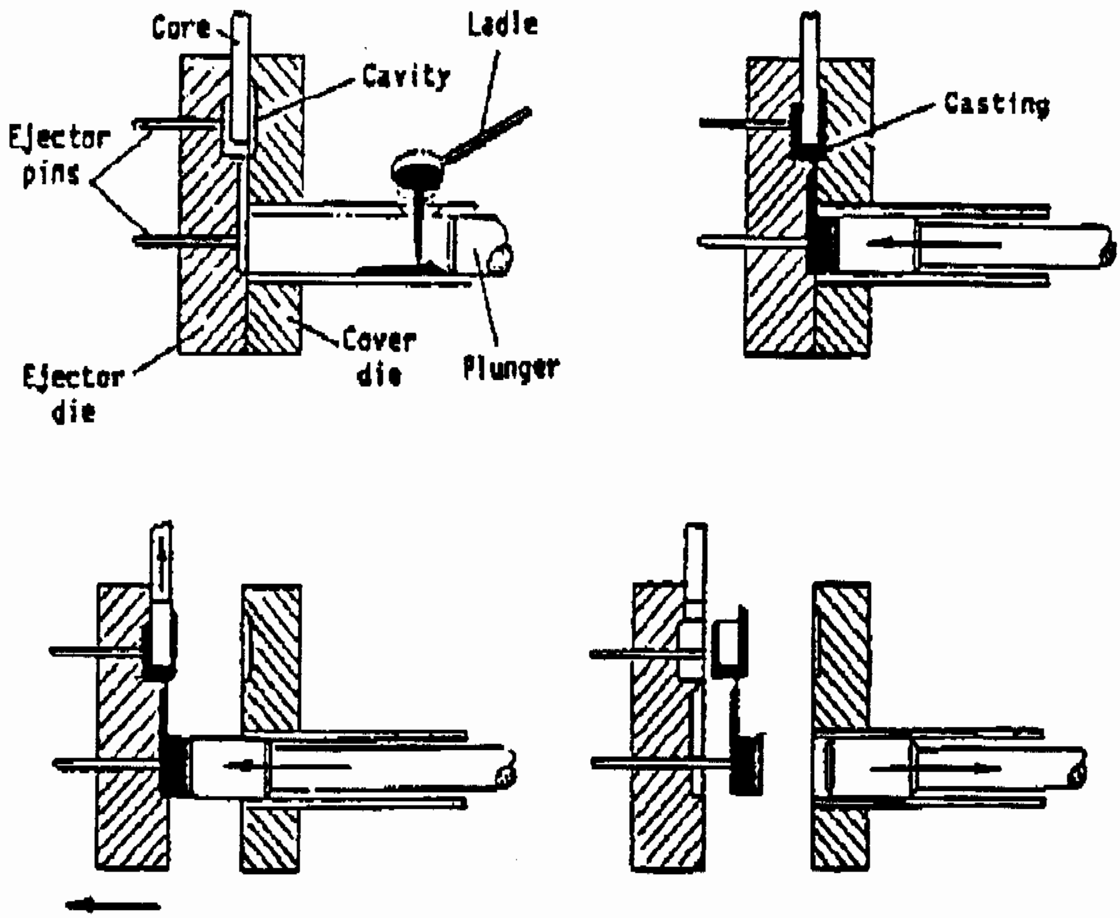


Fig. 1.1: Cold-chamber Die Casting Process Sequence [15]

5) die opening, where the die halves are separated and the solidified casting is ejected by pneumatic or mechanical force, and
6) die lubrication, where the open die halves are sprayed with lubricants and anti solder compounds.

This process cycle is repeated continuously over long periods for cost effective production of complex, primarily thin walled, parts. It is a near net shape manufacturing process in that the cast components can be used in the as-cast condition with little or no machining.

There are two basic die casting processes; hot-chamber and cold-chamber. The primary difference between the two processes is that in the hot-chamber process the melt or holding furnace is an integral part of the metal injection system while in the cold-chamber process the melt or holding furnace is a separate unit with a ladling unit as a means of transprting the molten metal to the injection unit. Another variation of die casting, namely direct injection die casting, where the aim is to extend the technology used for polymers to metals, is still in its infancy [14]. Schematics of typical hot-chamber and cold-chamber die casting systems with their major components labeled are provided in Figures 1.2 and 1.3, respectively.

1.2 Problem Statement

For the success of any process and the related industry, it must be able to reproducibly manufacture components of acceptable quality. These acceptable qualities are usually a predetermined range of properties that any component manufactured by that process must satisfy. The die casting process is no different. Characteristics of die cast components that can lead to products that are defective or of poor quality include galling,

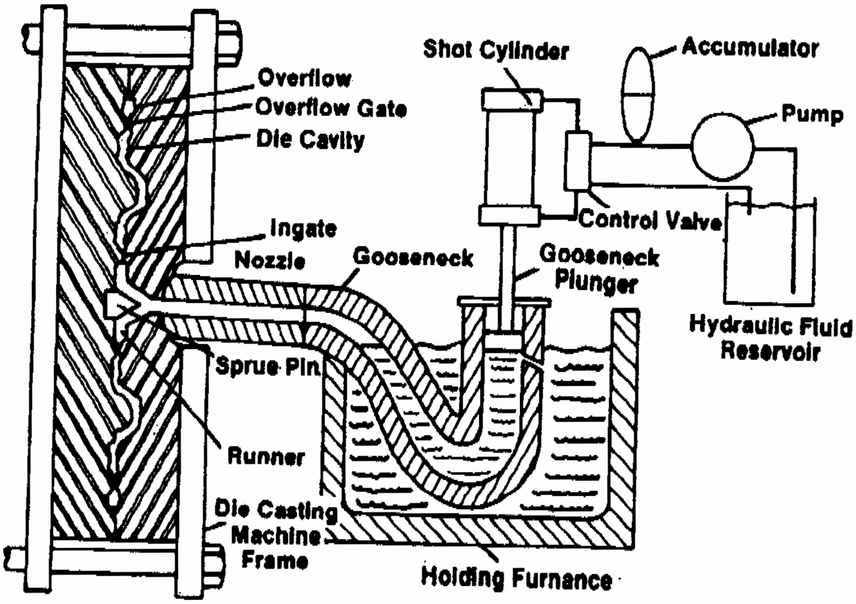


Fig. 1.2: Basic Components of a Typical Hot-chamber Die Casting Machine [15]

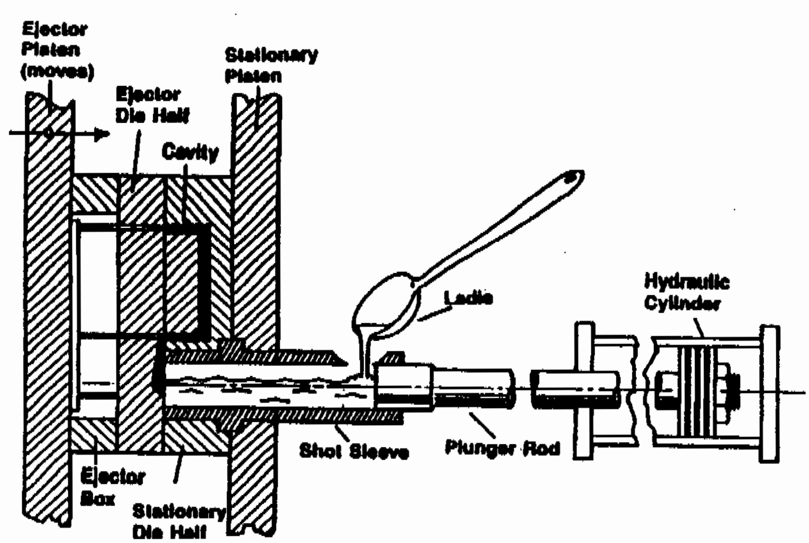


Fig. 1.3: Basic Components of a Typical Cold-chamber Die Casting Machine [16]

drag marks, die wear and erosion, cold shuts, incomplete fills, soldering, hot cracking, heat check fins and gas and shrinkage porosity. In turn, mechanical properties, like tensile strength and fatigue characteristics, of the die cast components depend on the quality of the die castings.

To eliminate or reduce these defects, the variables that affect the quality of the die castings can be addressed in two stages: product or die design and process design. The primary variables that affect the die casting quality in the process stage are:

1) alloy composition,
2) melt temperature,
3) shot profile,
4) tie bar loading,
5) die temperature,
6) casting ejection temperature,
7) release material, and
8) cycle timing. [13]

A numerical solidification analysis using these variables should, normally, suffice to predict the casting microstructure. The properties and, in turn, the quality of the die cast component are directly related to the casting microstructure. Numerical analyses, typically, predict the cavity fill and melt solidification rates and directions. Fluid flow and, hence, cavity fill modeling techniques used in die casting are, usually, either Marker and Cell (MAC), Simplified Marker and Cell (SMAC) or the Solution Algorithm - Volume of Fluid (SOLA-VOF) method. The numerical approaches used to model solidification use either front tracking or fixed domain methods. The front tracking methods solve the heat balance equation due to the latent heat effects explicitly at the phase front. Fixed domain approaches contain the moving boundary condition implicitly in the governing equation. Different fixed domain approach techniques include post iterative, apparent capacity, enthalpy, temperature recovery and hybrid schemes. The high injection pressure and fluid flow velocities in die casting and the resulting turbulence and atomization of the melt create problems in the flow simulations. The presence of solid, liquid and gas domains and the resultant mushy solidification in die casting make solidification modeling difficult [29]. The sum effect of all these difficulties is to limit the ability to accurately predict, and thereby control, the casting microstructure using computer simulations.

It can be presumed that acceptable and reproducible die castings can be obtained under controlled and reproducible operating conditions. Process control consists of essentially four elements:

1) predetermined standard (ideal) conditions,
2) measurement of actual conditions,
3) comparison of actual to ideal conditions, and
4) suitable adjustment of process to compensate for deviations. [13]

Figure 1.4 illustrates these four elements. At present, accurate knowledge of the ideal conditions required for a corresponding product quality is lacking in die casting. To this end, quantitative information relating the thermal fields of the die and casting, the pressure fields in the liquid and solidifying alloy, the gas flow through the cavity, and the injection characteristics to the quality of the resultant die cast components is required. The quality of the die cast product can be quantified by measurables such as surface finish, pressure tightness, total porosity and porosity distribution, number and location of cold shuts and laps, inclusion count, and the quantity of gas contained in the casting. However, a system capable of intelligently collecting and processing the desired quantitative process information is yet to be developed.

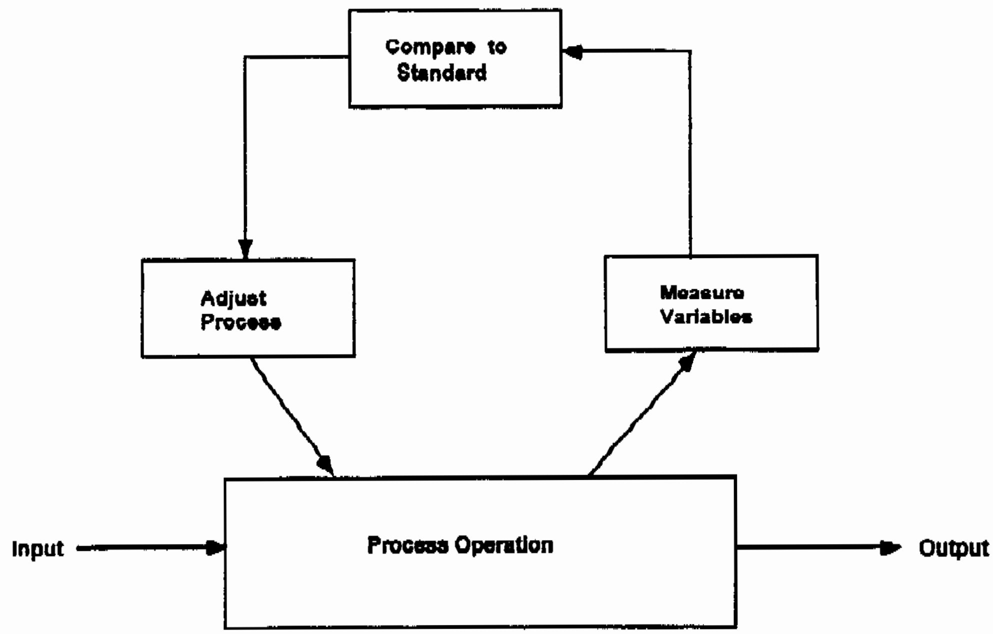


Fig. 1.4: Process Control Sequence. [13]

This study aims to address the above requirements to the extent of thermal and pressure measurements and their relation to injection characteristics. The thermal and pressure data are obtained from the thermocouple sensors developed at The Ohio State University and commercial Kistler pressure sensors, respectively, while the injection data is obtained from the plunger instrumentation of a Buhler H-250SC die casting machine. Further, it aims to verify the accuracy of a numerical solidification analysis using BINORM (formerly DIECAST) by comparison with experimental results. Such a verification will provide a reliable analytical method for designing a die casting process and determining the ideal process conditions that are a prerequisite for effective process control. It is hoped that this two pronged approach will remove obstacles to both the experimental and theoretical methods of addressing the problems faced by die casters in designing and operating under efficient and reproducible process conditions. This study is, however, restricted to the analysis of the gate area of the die. The die, and the corresponding casting, is known as the wall die casting. The study is further restricted, on an experimental basis, to aluminum alloy die castings on a horizontal cold chamber die casting machine.

1.3 Research Objectives

The primary objectives of this project are

- to develop and evaluate thermal sensors for simultaneously measuring

  (a) the die temperatures at the casting-die interface as a function of time, and

  (b) the heat flow rate through the die,

- to identify and evaluate pressure sensors for measuring gas and liquid pressure history in the cavity,

- to make measurements under base line operating conditions and to relate the thermal, pressure and injection characteristics for any given shot, and

- to verify the predictions of a computer numerical solidification analysis by comparison with the experimental data.

CHAPTER 2

PRELIMINARY REVIEW

2.1 Introduction

A comprehensive literature review, that is an essential precursor to any research, was undertaken as a part of this study. This survey aimed to cover previous work in identifying and linking casting defects to process variables and all attempts to measure and control these process variables. Additionally, a corporate survey was conducted to identify actual industrial application and usage of process variable measurement and control.

2.2 Literature Review

It is commonly accepted that the die casting process variables impact the quality of the corresponding die casting components. The primary casting defects and the operating variables that are responsible for such defects are described in Sully [14], von Takach [3] and Kaye and Street [20]. The primary variables, that need to be controlled to reduce casting defects, can be classified as depicted in a tabular form in Figure 2.1.

Furnace	Alloy Composition Melt Temperature Melt Treatment
Ladling System	Ladling Time Ladling Volume
Injection System	Shot Sleeve Dimensions Shot Sleeve Temperature Shot Delay Time Shot Profile Cavity Fill Time Intensification Pressure Degree and Timing
Die and Casting	Tie Bar Load Part Configuration Runner and Parting Line Design Gate Location(s) and Size(s) Cooling Line Location Venting Method and Vent Location Die and Casting Ejection Temperature
Ejection System	Die Open Time Ejection Timing Ejector Pin Location
Spray System	Spray Composition and Type Spray Timing and Duration Spray Volume

Figure 2.1: Process Variables in Cold Chamber Die Casting

Research by Garber and Draper [26] and Babington and Klepinger [25] further narrows the effects of critical process variables on the quality of aluminum alloy die castings. In more recent times, researchers have identified individual casting defects and the variables that cause them. Gordon, et al., [23] for example, have not only related percentage porosity in die castings to the process variables causing them, but also developed equations for predicting the percentage porosity based on prior knowledge of these particular operating variables. This study is, however, limited to the previously mentioned process variables, namely cavity pressure and thermal characteristics and their relation to the injection characteristics.

Thermal variables are primarily characterized by die and casting ejection temperatures that in turn reflect die thermal fields and heat fluxes and thereby the solidification rate and pattern. Osborne, et al., [18] concluded that poor temperature control results in greater variation in casting part dimensions. Specifically, variations were noticed in the linear dimensions between the walls of the wall die casting (Figure 2.2). These were attributed, primarily, to the effect of die cooling and dwell time on the dimensions of the die at operating temperatures and the amount of shrinkage. Papai and Mobley [17] related heat flow into the die and hence solidification rates to the initial die surface temperature that, in turn, is a function of die and casting ejection temperature. In both these studies, thermocouple probes, similar to the ones used in this research, were used. Typical die temperature values at quasi steady state over a number of cycles are depicted in Figure 2.3. According to Herman [13], control of the die temperature and thereby the heat flow through the casting-die system is essential to achieve high quality castings on a repeatable basis. Further, Herman stresses the importance of the control of casting ejection temperature in eliminating variations in casting dimensions and stabilizing casting size. Such thermal control also leads to longer die life by reducing thermal shock.

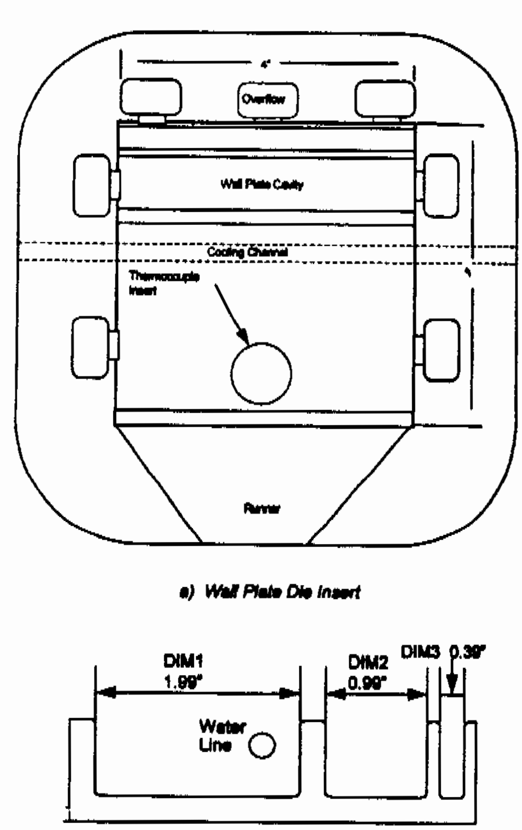


Fig. 2.2: Wall Plate Die and Measurement Locations [18]

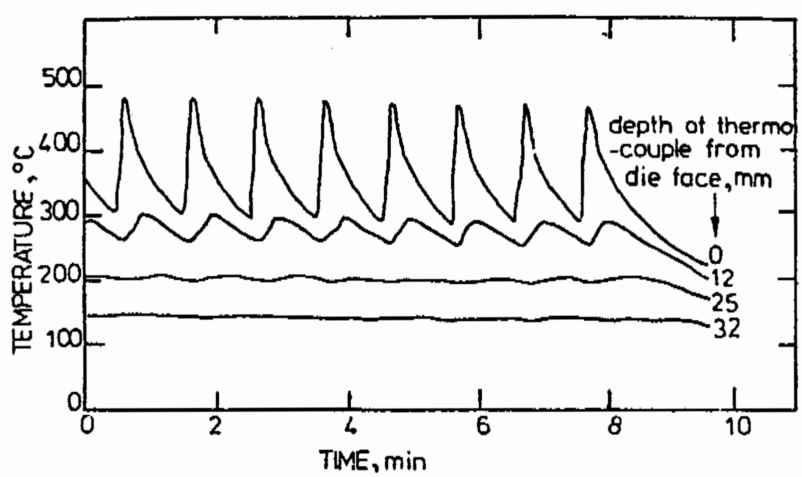


Fig. 2.3: Typical thermocouple traces from varying depths in the die [5]

Cavity pressure is an important process variable in terms of casting quality. Nishi, et al., [1] found a direct relation between the molten metal pressure in the cavity and the tensile strength, and hence the quality, of the casting. The molten metal pressure was measured in the die cavity insitu during the casting of an aluminum alloy (JIS ADC 10) in a 90 ton cold-chamber die casting machine. The mechanical properties of the castings were measured by tensile and charpy impact tests. The tensile strengths of castings made at molten metal pressures of less than 600 kgf/cm^2 (8516 psi) were found to be reduced. Tokui et al., during an analysis of the vertical pressure die casting system, also describe the effect of casting pressure on the quality of the cast components through mechanical properties. Figure 2.4 illustrates the effect of casting pressure on the tensile strength and specific gravity of the corresponding casting of Al 380. Babington and Klepinger [25] found that internal soundness improved with increasing levels of pressure up to 15,000 psi (1000 bar) and remained with further increases. Phlipot, et al., [10] conclude that theoretical cavity pressure has a significant effect on internal casting quality and, further, is responsible, along with the gate velocity, for one half of the density variations in die cast components. The pressure was measured, in this research, using pressure transducers at both the rod and head ends of the shot cylinder. Yamamoto, et al., [12] relate, in their research, cavity gas pressure with the location and extent of inner defects of castings. The gas pressure was measured using a gas pressure gauge (Figure 2.5) with a range of 1.0 kgf./cm^2.

Many researchers have attempted to develop an intelligent system to collect the necessary quantitative process variable information and apply it to the control of the die casting process. The ultimate aim of such research is to make the die casting process efficient and reproducible and thereby capable of producing reproducible high quality castings. Peterson [2] developed a system for the effective thermocycling control of die casting machines. Van Huis [4] applied the advantages of programmable controllers to the design of efficient systems for die casting process control. Booth and Allsop [5] describe the various methods available to the die caster for thermal control of the dies. These methods include control of cooling water flow, thermal fluid die heater/cooler units and die temperature control of the casting cycle. Mickowski [6] describes a comprehensive system designed specifically to monitor and control critical die casting machine parameters, while providing the plant personnel with current information on process performance. Meyer and Walkington [7] describe a control system in use at an industrial site. Phlipot, et al., [10] evaluated a micro processor based process monitoring system and concluded that it was sufficient for controlled experiments as well as for quality control activities. An intelligent process control system that can be universally applied in industry is, however, yet to be perfected. A schematic of an intelligent die casting system is provided in Figure 2.6.

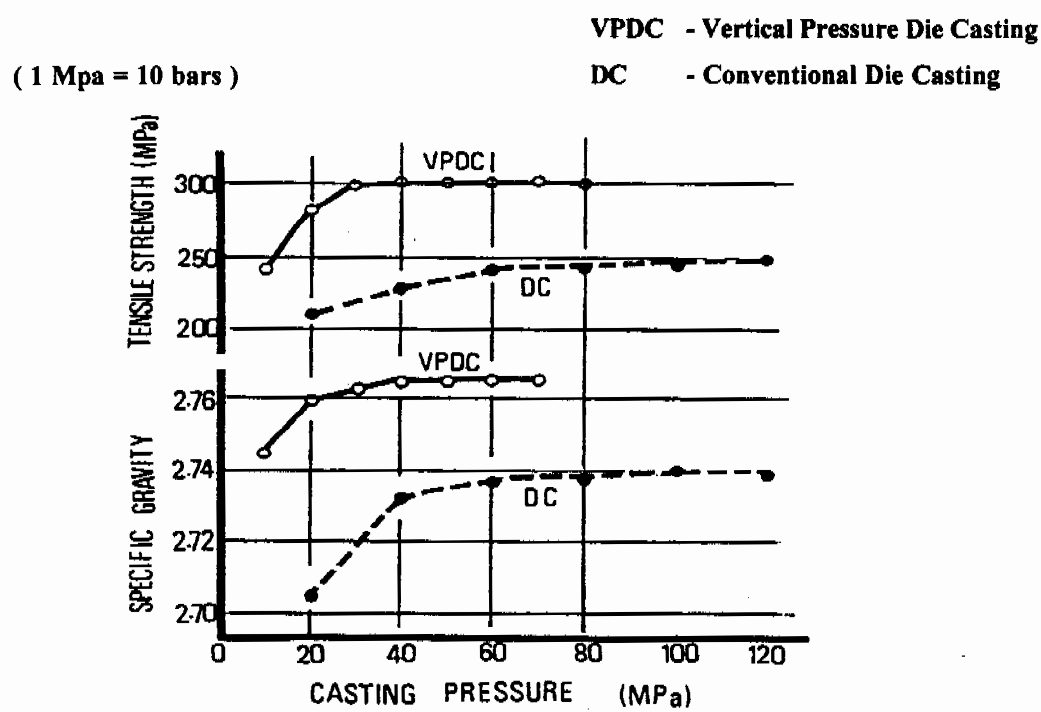


Fig. 2.4: Effect of casting pressure on tensile strength and specific gravity of Al 380 castings [8]

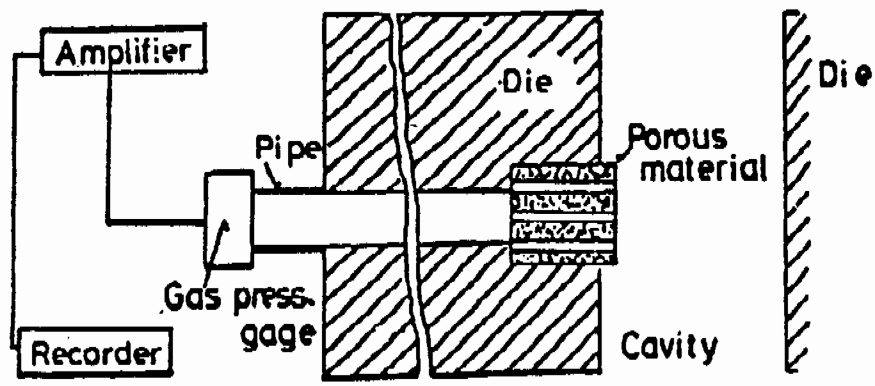


Fig. 2.5: Gas Pressure Gauge [12]

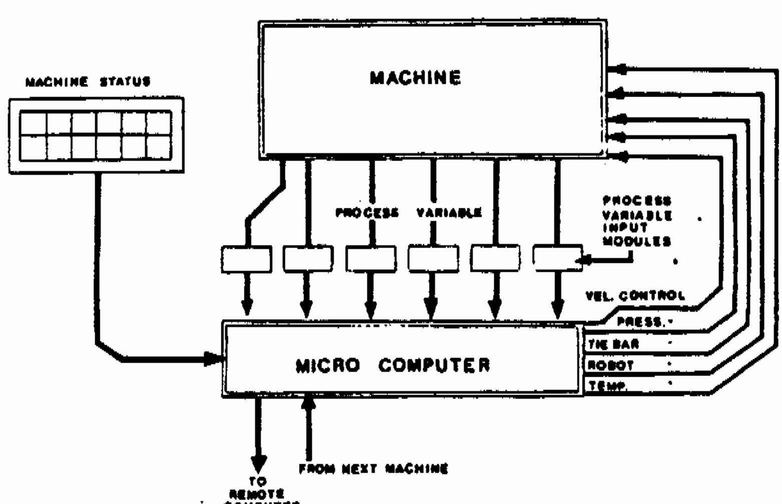


Fig. 2.6: Process Control System [6]

The primary limitation in perfecting such an intelligent process control system is the lack of reliable process variable measuring devices. Most of the high pressure die casting systems currently in commercial usage are instrumented to monitor and control the gas or hydraulic pressure applied to the plunger and the plunger position-time history in the shot sleeve. Thermocouples have also been selectively placed in dies to record the thermal history of the dies during the die casting cycle at those selected locations. To a more limited extent, pins instrumented with strain gauges or transducers have been used to measure the pressure history at selected locations in the die cavity. Also, to a limited extent, attempts have been made to measure the gas pressure level in the die casting cavity before and during filling and the amount of gas that exits the die cavity through vents or vacuum assist systems. Herman [13] and Kaye and Street [20] describe some of the state-of-the-art for instrumentation of die casting systems. Mochiku, et al., [21] describe in detail some of the practical variable measuring devices that can be applied in such a system. Hatamura, et al., [11] have used some of these sensors, namely, pressure sensors using strain gauges and temperature sensors using chromel-alumel thermocouples (Figure 2.7), to directly measure cavity pressure and die surface temperature, respectively. Peterson [2] successfully used an infra red sensor, rather than the commonly used thermocouples, for temperature measurement.

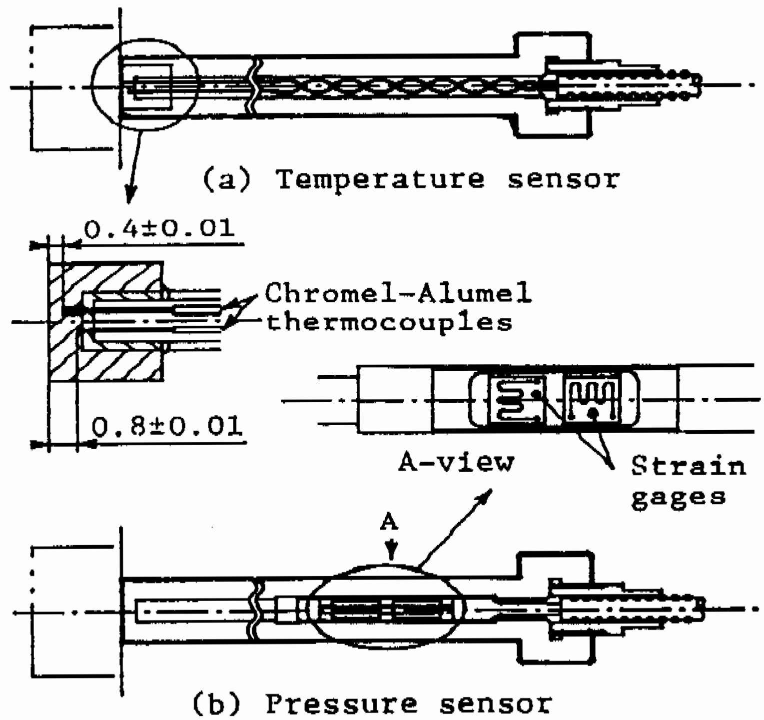


Fig. 2.7: Sensors used by Hatamura et al. [11]

2.3 Industrial Survey

It was deemed necessary to obtain a credible estimate of the extent of the current usage, in process control systems by the industry, of sensors to measure the thermal and pressure fields in the die cavity. To this end, a survey questionnaire was prepared and submitted by Dr. Mobley to a number of die casting companies. A sample questionnaire is included as Appendix A. The responses of the returned questionnaires were tabulated. Of the 63 survey questionnaires that were returned, 60 were completed by U.S. die casting companies, 1 by a non-U.S. die casting company and 2 by U.S. die casting equipment manufacturers. The die casting companies that responded operate 937 cold chamber die casting machines and 343 hot chamber die casting machines. The 1249 die casting machines of the U.S. die casting companies that responded represent 15.6% of the available U.S. die casting machines, based on the 1994 estimate of 8000 die casting machines in the U.S. More than 90% of the die casting companies that responded indicated that they possess the equipment to monitor the position and velocity of the plunger as a function of time during the filling process. However, less than half the die casting companies indicated that use or they have used temperature and pressure measuring devices in or near the die cavity as a part of the process monitoring or control practices.

2.4 Summary

It was concluded from the literature review and the industrial survey that process variable measurement and hence their control is a long way from perfection. Even those sensors that are in wide use are surrogate measures, in that they measure the plunger hydraulic pressure and bulk die temperature rather than cavity pressure and die surface temperature. The plunger hydraulic pressure and the bulk die temperature give, at best, approximate measures of the cavity pressure and the die surface temperature respectively and are certainly insufficient for effective process control. Even the 'direct' pressure measuring instruments are usually strain gauges mounted behind pins and are inaccurate to the extent that the friction between the sliding pin and the die is not generally known. This study aims to develop and evaluate sensors that can measure directly the cavity pressure and the thermal characteristics at the gate. Furthermore, most sensors are useful only in an experimental situation and are not rugged enough for continuous industrial usage. This study aims to evaluate the developed in-cavity sensors under industrial operating conditions. Also, most researchers tend to compare, in isolation, either the temperature, pressure or some other process variable with the quality of the casting. This is not advisable as these variables are mutually inter-related and cannot be viewed in isolation. Such isolation will lead to misinterpretation of data and a wrongful attribution of cause of defect to one or the other variable. This study, on the other hand, aims to simultaneously relate the measured cavity pressure and thermal fields with other process injection variables. This study takes both the experimental and analytical approaches to determining the effect of process variables.

CHAPTER 3

EXPERIMENTAL APPROACH

3.1 Introduction

The primary objective of this study is to analyse the in-cavity pressure and thermal characteristics of the die casting process. The first step to such an experimental analysis is the development of effective and reliable sensors and the corresponding instrumentation to record and process the data. The literature review and the industrial survey revealed the commercial availability of such sensors and the extent to which they were being used by the die casting industry.

3.2 Sensor Development

3.2.1 Pressure Sensors

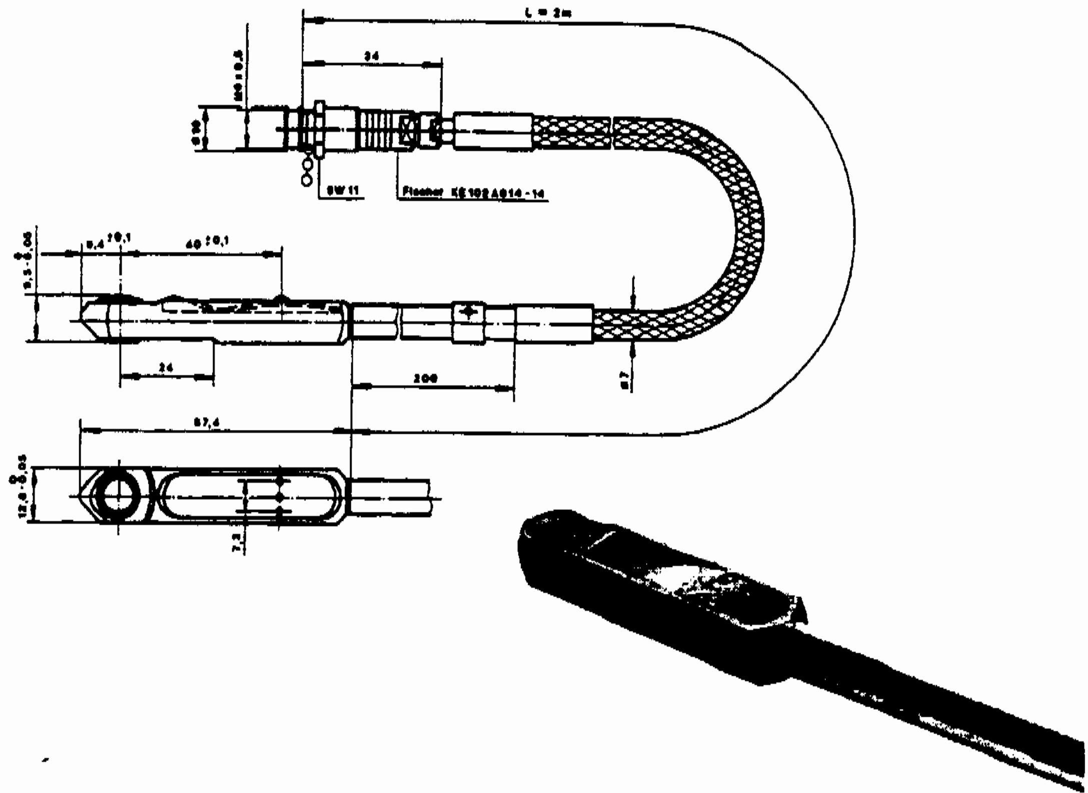
There are basically two types of pressure sensors that are commercially available for the measurement of the liquid alloy pressure in the die cavity. They can be classified as:

- indirect pressure sensors, which are usually load cells or transducers that are placed behind ejector or specially located pressure pins, and

- direct pressure sensors, which are quartz pressure sensors that are located such that they are in direct contact with the alloy in the die cavity.

The indirect pressure sensors have been widely used by the aluminum die casting industry for many years. However, there have been many problems associated with their use, the primary problem being the reliability of the measured output. Since the cavity pressure is translated to the sensor via a sliding pin, the friction existing between the pin and the die affects the measured pressure value. This deviation in measured pressure is not known, as the friction varies from shot to shot due to inconsistencies like the die temperature and the amount of lubrication applied to the die. Comparatively, the direct measurement pressure sensor is a new introduction to the die casting industry. At the initiation of this project, it was estimated that four European die casting companies had incorporated such direct pressure sensors in their process monitoring systems.

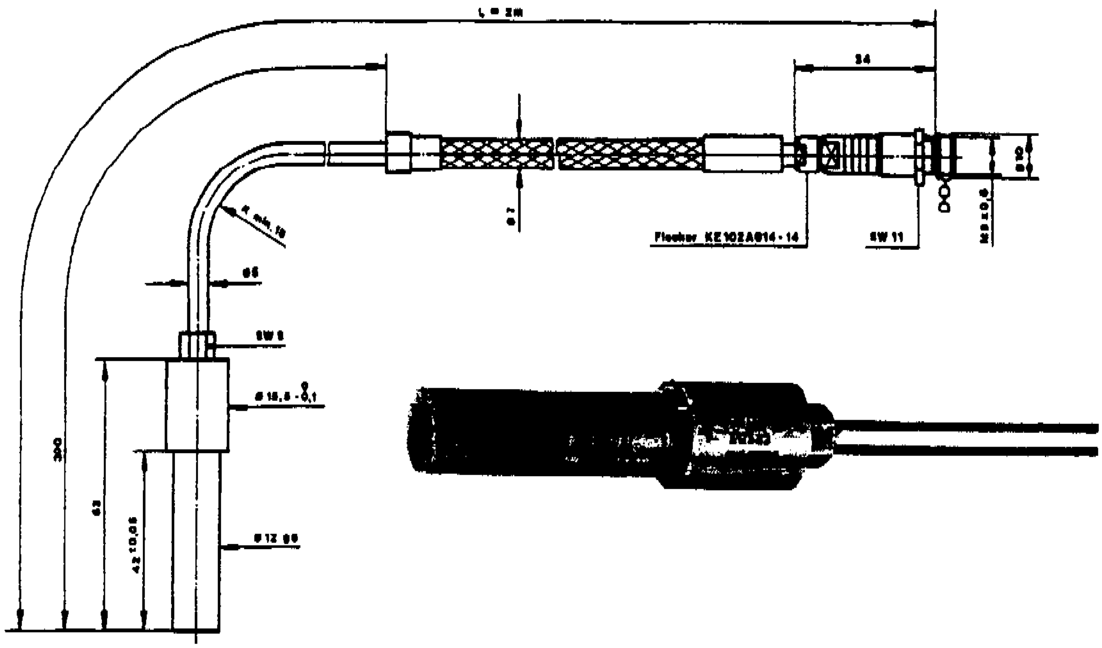
Figures 3.1 and 3.2 illustrate the basic geometry and technical capability of a sample commercially available indirect and direct pressure sensor, respectively. A wide choice is available with respect to commercial indirect pressure sensors using load cells or transducers mounted behind ejector or pressure pins. However only one company, Kistler Instrument Corporation, was identified as a commercial source of pressure sensors capable of measurement by direct contact with the alloy in the die cavity. Concurrent to the objectives of this project, it was decided to obtain the direct pressure sensor marketed by the Kistler Instrument Corporation for evaluation and application in this study. This direct pressure sensor consists, essentially, of a piezo-electric crystal that generates a voltage when elastically deformed by the applied pressure. This output voltage is a direct



Technical Data

Range	kN	0 ... 10
Calibrated partial range	kN	0 ... 1
Overload	kN	12
Threshold	N	<0,01
Uniform sensitivity	pC/N	–3,45
Linearity, also for partial ranges	% FSO	≤±1
Hysteresis	% FSO	≤1
Rigidity	N/µm	≈160
Natural frequency	kHz	≈60
Operating temperature range	°C	–50 ... 200
Temperature coefficient of sensitivity	%/°C	–0,02
Temperature error	N/°C	<±5
Insulation resistance at 20 °C	Ω	≥10¹³
at 120 °C	Ω	≥10¹²
Weight	g	280

Fig. 3.1 : Indirect Pressure Sensor [Kistler Specifications]



Technical Data

Range	bar	0 ... 2000
Overload	bar	2500
Uniform sensitivity (at 250 °C)	pC / bar	-6.7
Linearity, all ranges	% FSO	≤±2
Natural frequency	kHz	~30
Acceleration sensitivity	bar / *g*	<0,07
Operating temperature range		
Sensor, cable	°C	0 ... 300*
Connector	°C	0 ... 200*
Temperature coefficient of sensitivity	% / °C	±0,01
Insulation resistance		
at 20 °C	Ω	10^{13}
at 300 °C	Ω	10^{11}
Weight (Type 6152AA0,4)	g	280

Fig. 3.2 : Direct Pressure Sensor [Kistler Specifications]

function of the extent of deformation of the crystal and, hence, the pressure that causes this deformation. The measuring range and other technical characteristics of the sensor indicate its suitability for die casting applications. Two probes were obtained for use in the die casting campaign conducted as a part of this study.

Prior to their application in the experimental die casting campaign, the Kistler probes were evaluated by comparing the measured output pressure against a known applied pressure. The probes were configured, in terms of operating range and sampling rate, as they would be for the die casting campaign. A known load was applied by means of a press on a fixed and known area of each quartz crystal. The measured pressure that is provided by the Kistler probe as an instantaneous output was recorded. This was repeated several times for each probe for varying applied pressures in alternating incremental and decremental steps. Hence the applied pressure (= load/area) can be compared to the pressure measured and recorded by the Kistler probe. Figures 3.3 and 3.4 relate the average measured and applied pressures for probes 1 and 2, respectively. The maximum deviation of the measured pressure from the applied pressure over the range of 0 to 1000 bars was found to be 30 and 50 bars for probes 1 and 2, respectively. The evaluation was performed at room temperature. The Kistler Instrument Co. specifies the temperature coefficient of sensitivity for the probe as 0.01 %/°C. Hence, at the maximum cavity temperatures of 400 to 450 deg. C and at the maximum pressure setting of 1000 bars, the maximum deviation from the actual can be expected to be 70 to 100 bars. Realistically, however, the maximum deviation is not estimated to be over 50 bars. The divergence of measured pressure of probe 2 from applied pressure with an increase in loading can be attributed to a misalignment of the pin used to apply the load. This misalignment increases with an increase in loading and hence the divergence. Also, for both probes, the maximum deviation from the actual pressure occurs when the probe

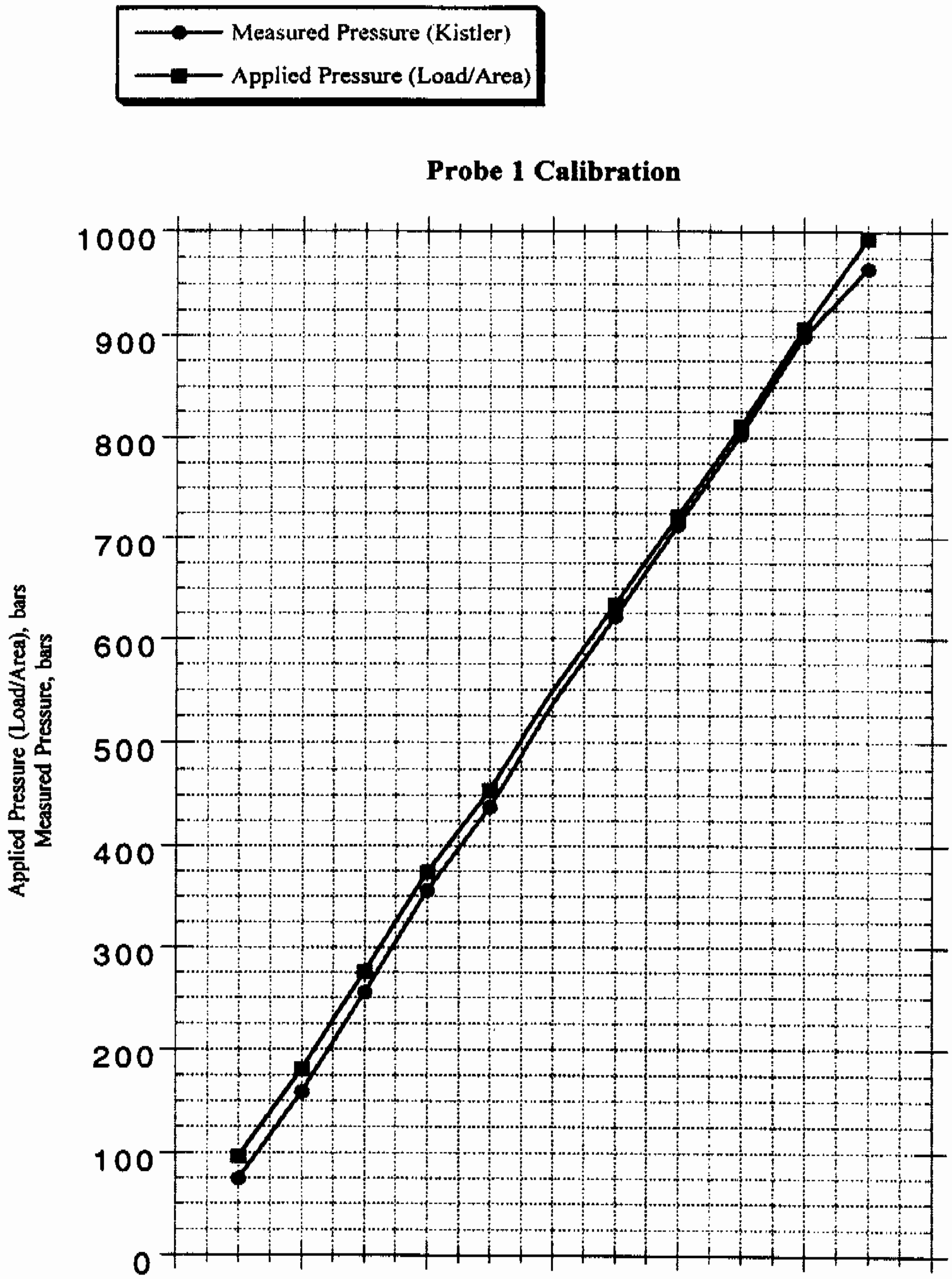


Fig. 3.3: Kistler Probe 1 Calibration

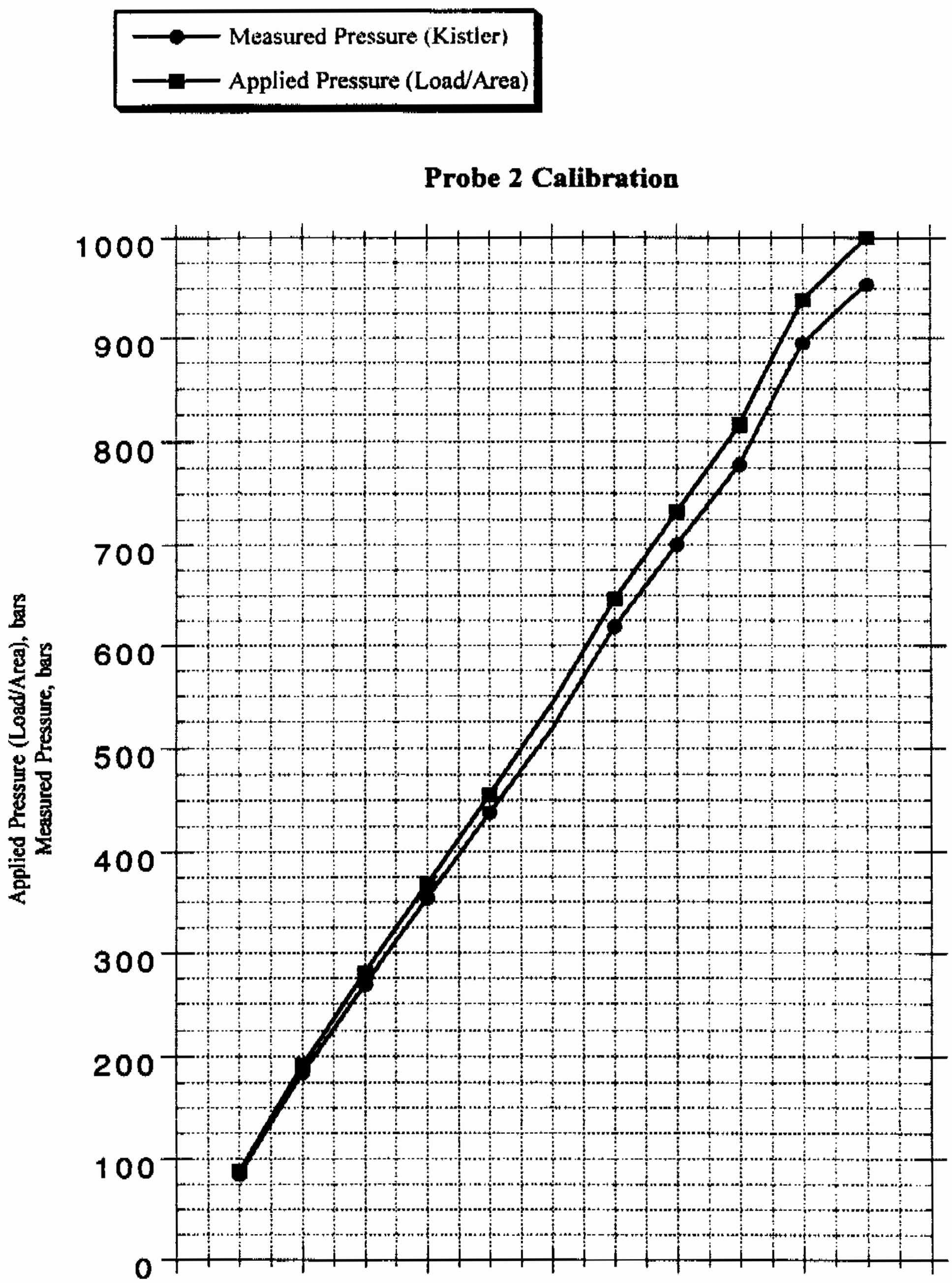


Fig. 3.4: Kistler Probe 2 Calibration

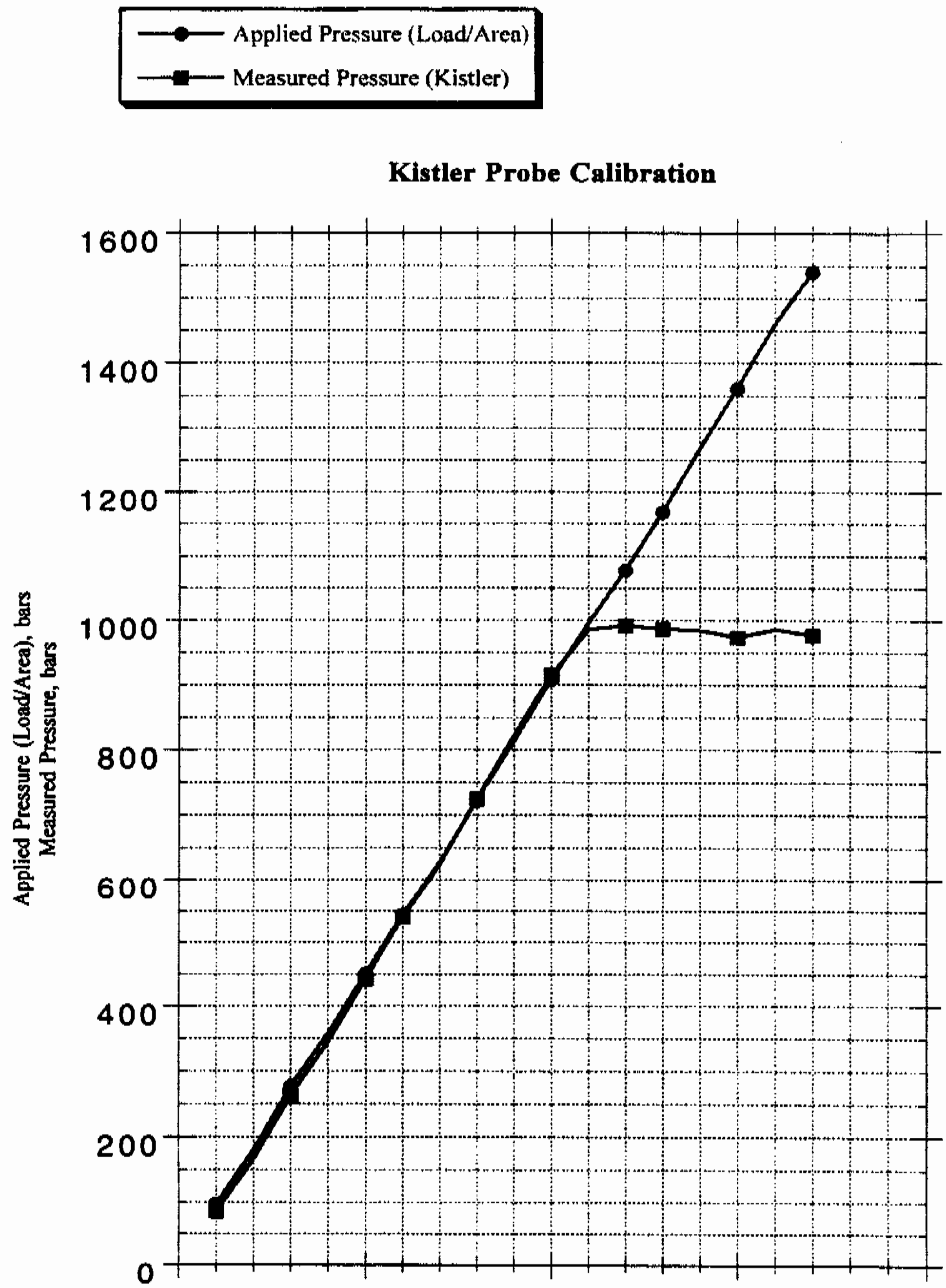


Fig. 3.5: Calibration loading beyond configured operating limits

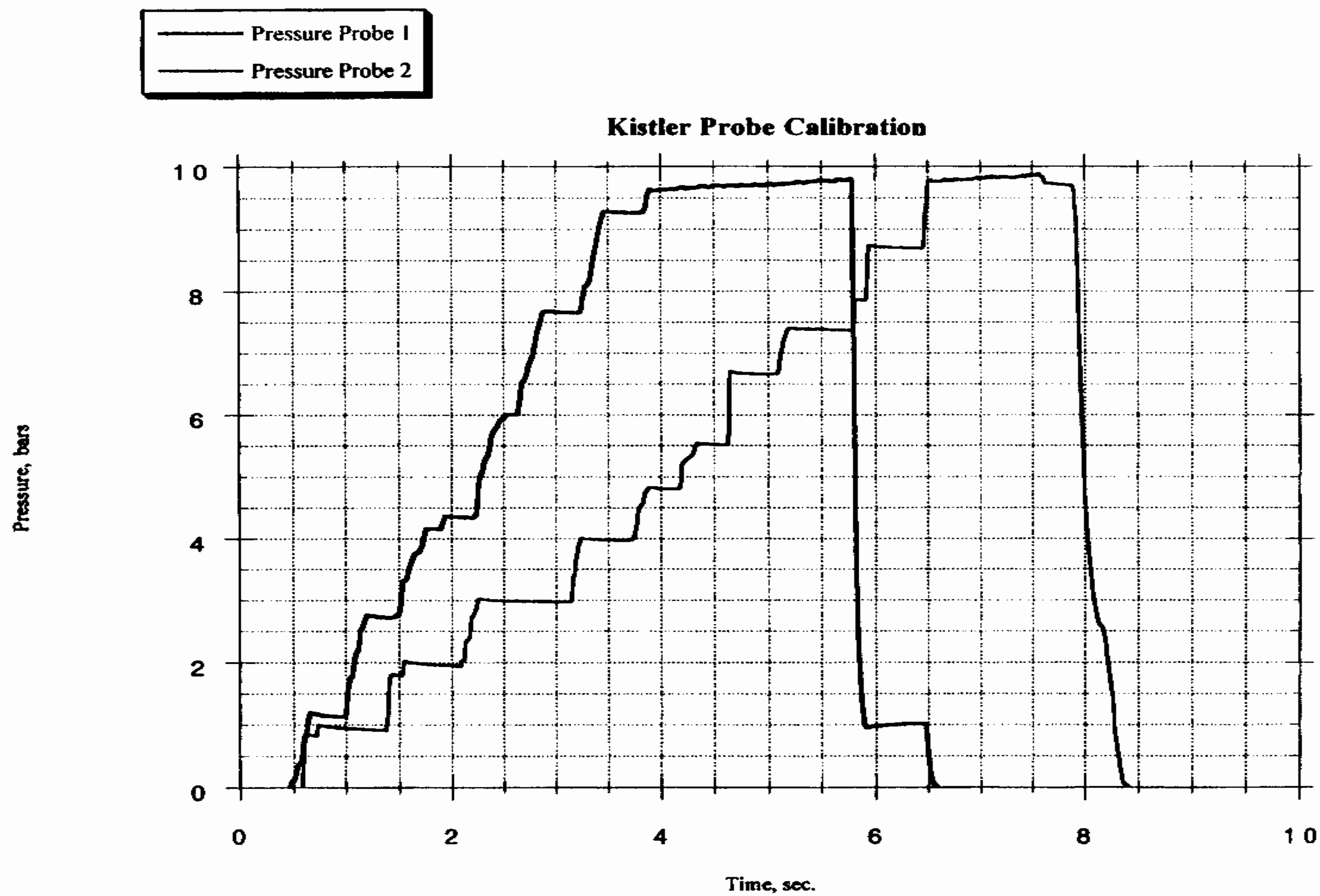


Fig. 3.6: Dynamic Calibration of Kistler Pressure Probes

reaches the limit of its operating range (in this case 1000 bars). Figure 3.5 depicts the output when the input exceeds the configured operating range. The output was found to stabilise at a little below 1000 bars. Figure 3.6 depicts the ouput for a dynamic loading and unloading. The probe output was found to be stable and did not possess any oscillations due to damping or any interference from external circuitry or other signals.

3.2.2 Thermal Sensors

Thermal field characterization, as previously mentioned in the research objectives, is an essential component of this study. This characterization, comprising primarily temperature and heat flow measurements, is required at previously determined locations in the die, one important location being the gate. No commercially available sensor was identified that could satisfy these requirements of the study. Prior research, performed at The Ohio State University, using a thermal probe consisting of three or more thermocouples in a linear array relative to the casting-die interface has shown that such a probe allows characterization of the die thermal fields at the location of the probe that is adequate for the thermal field measurement requirements of this study. A representative record from such a probe is depicted in Figure 3.7. Hence it was decided to develop a thermal sensor, based on this previous work, to meet the requirements of this study.

The primary restriction in the development of such a sensor was dimensional, as mutual interchangeability of pressure and thermal sensors at all probe locations in the die was deemed desirable. The probe designed on such dimensional restrictions is depicted in Figure 3.8. It is comprised of a carrier and an insert made of the same material (H-13 die steel) as the die insert. The carrier (Figure 3.9) has the same external dimensions of the commercially obtained direct pressure sensor. Based on previous work, the shape and

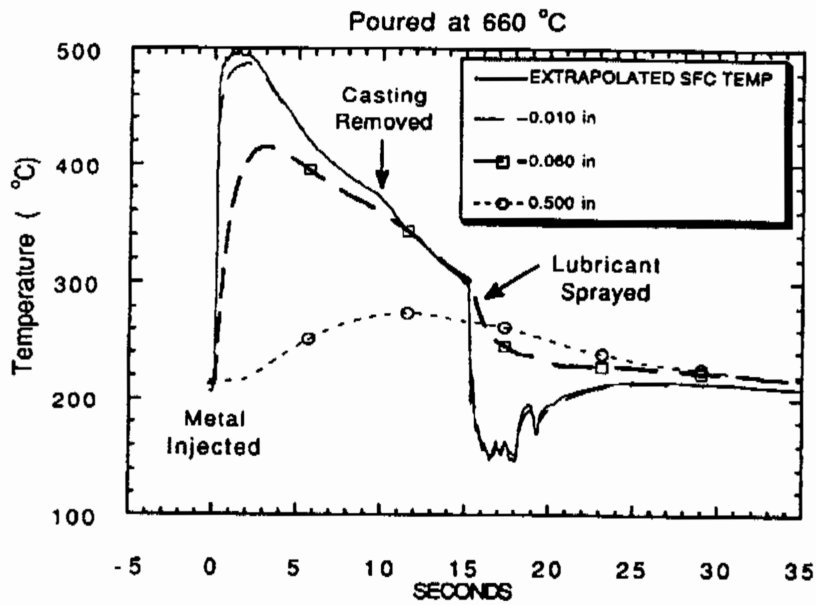


Fig. 3.7 : Representative Thermal Probe Record [17]

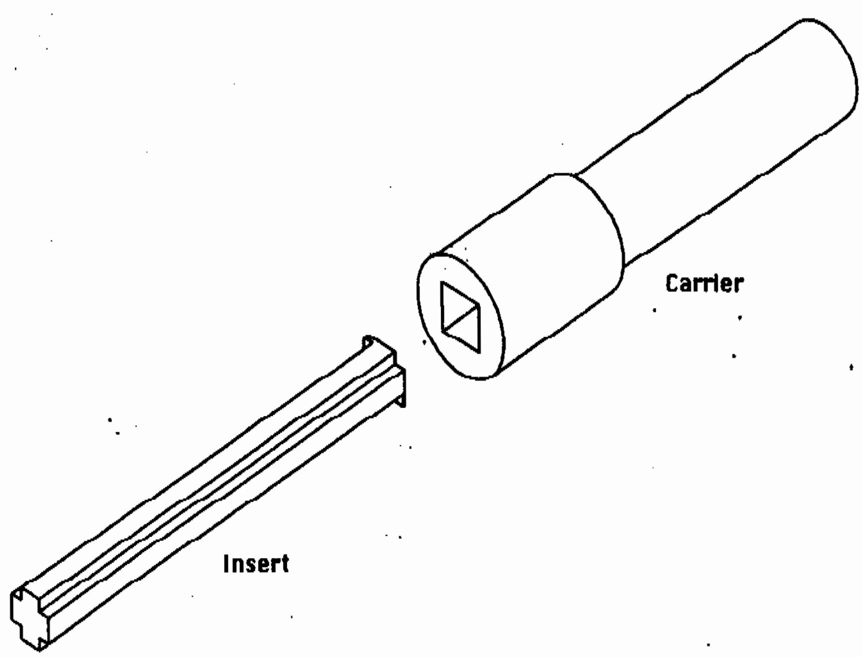


Fig. 3.8 : Thermal Probe : Exploded View

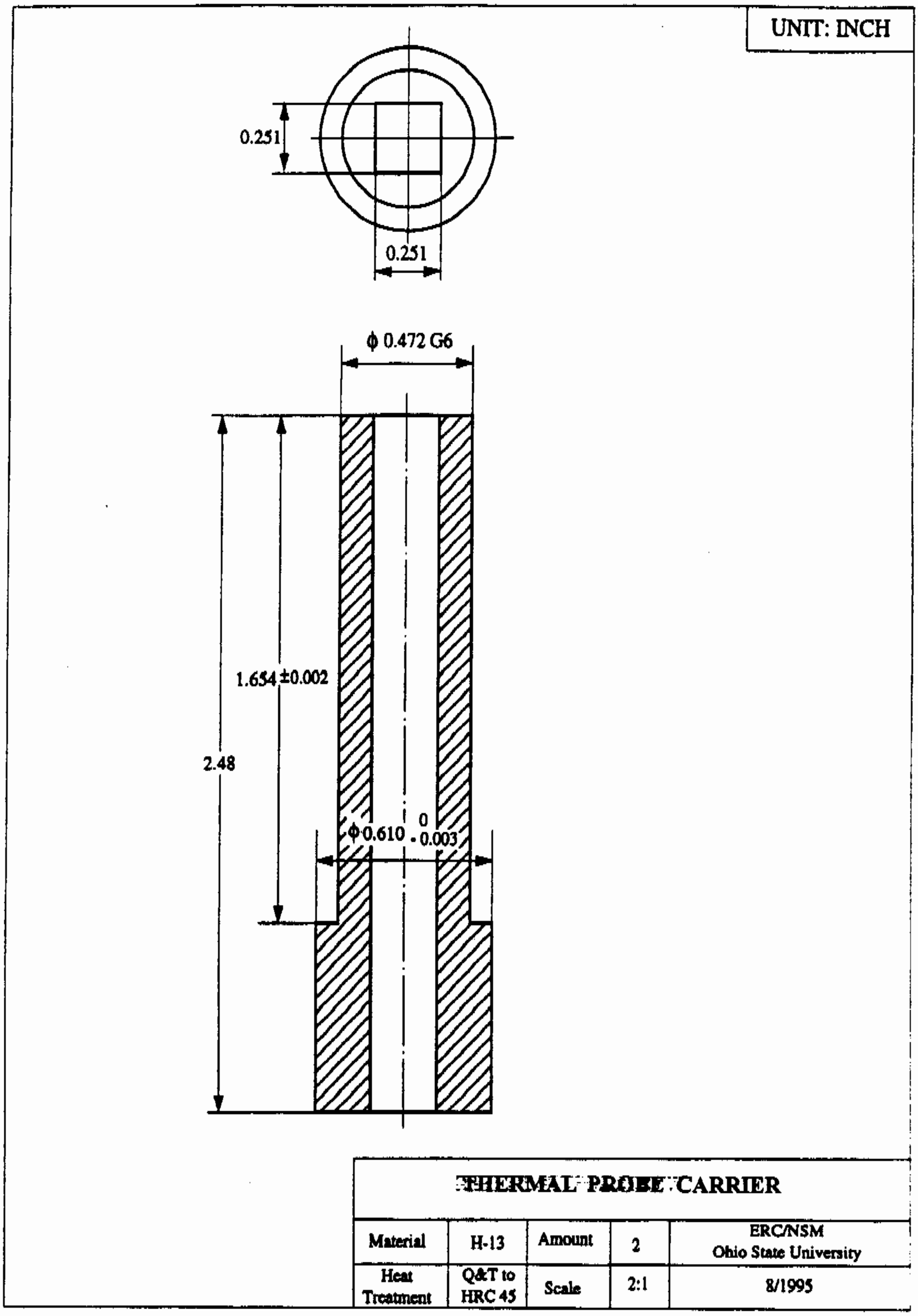
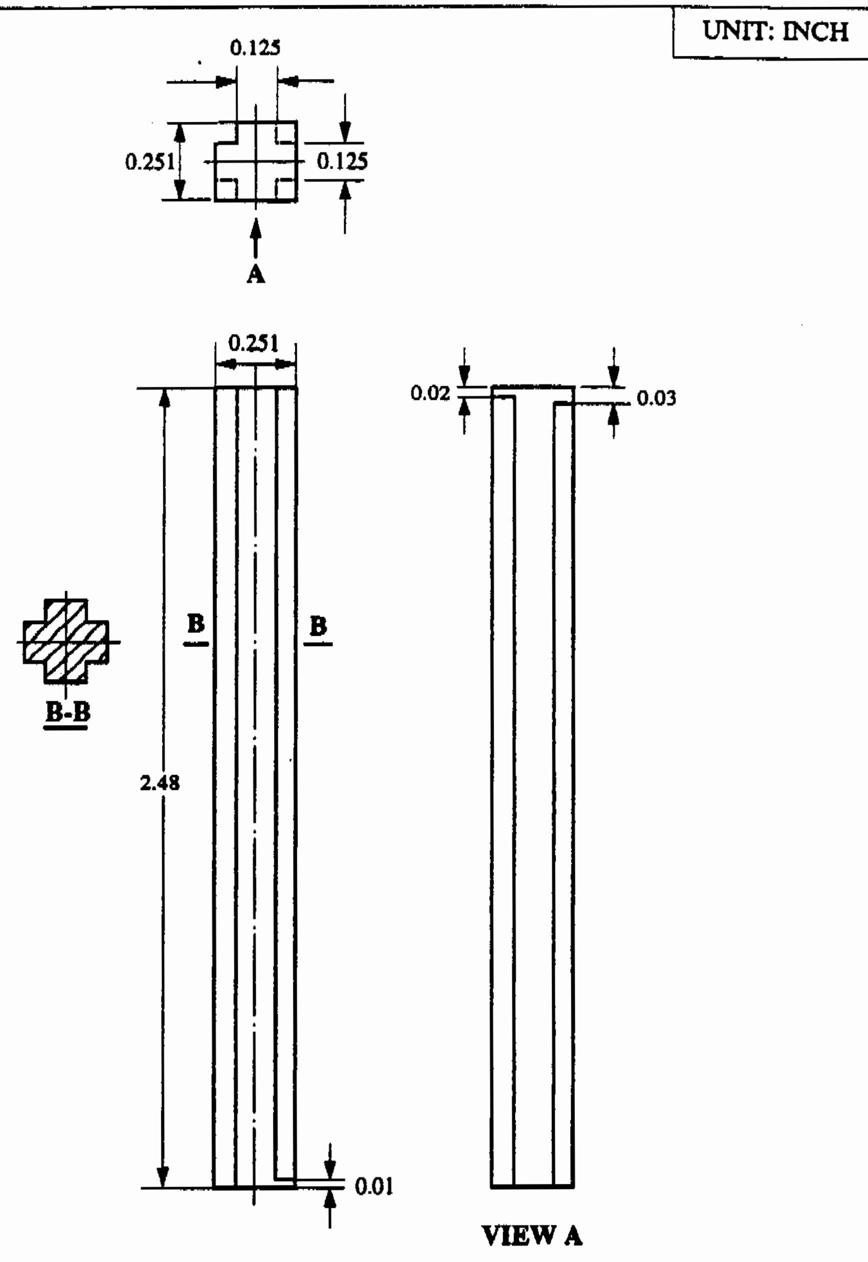


Fig. 3.9 : Thermal Probe Carrier

dimensions of the insert were designed to minimize errors in measurement due to lateral heat flow and signal interference from adjacent thermocouples in the same probe. The insert (Figure 3.10) has slots that at depths of 0.030", 0.020", 0.010" and 0.000" (through slot) from the end that is at the die surface. A type K (chromel-alumel) thermocouple is present in each slot. The type K thermocouple was chosen based on its suitability for the requirements of this study and its satisfactory performance in previous research. The thermocouple wires were 0.010" in diameter and were isolated by a powder of 99.6% MgO. They were further sheathed in Inconel with an outer diameter of 0.063". These specifications were chosen based on the response time required of the thermocouples and the hostile nature of the die casting environment. Each thermocouple was silver soldered to the end of its respective slot using AWS BAg -13a (56% weight Ag, 42% weight Cu, 2% weight Ni) from Lucas-Milhaupt (Braze 559) blended with Lucas-Milhaupt flux Handyflo 110. The thermocouple are thus at known distances from the die surface. To prevent the thermocouple tip losing contact with the insert due to mechanical stress, the sheathing of each thermocouple was spot welded to the side of its respective slot. The insert was then press fit into the carrier and held in place by a cross pin to prevent it from being pushed out by the high pressures in the cavity. A satisfactory thermal probe (Figure 3.11) with the same dimensions as the commercially obtained direct pressure sensor was fabricated.

3.3 Experimental Set-up

The die casting machine used for the campaign was a Buhler 350 SC located at the Engineering Research Center for Net Shape Manufacturing (ERC/NSM) at The Ohio State University. The technical data relating to the die casting machine used are provided in Appendix B.



THERMAL PROBE INSERT				
Material	H-13	Amount	2	ERC/NSM Ohio State University
Heat Treatment	Q&T to HRC 45	Scale	2:1	8/1995

Fig. 3.10: Thermal Probe Insert

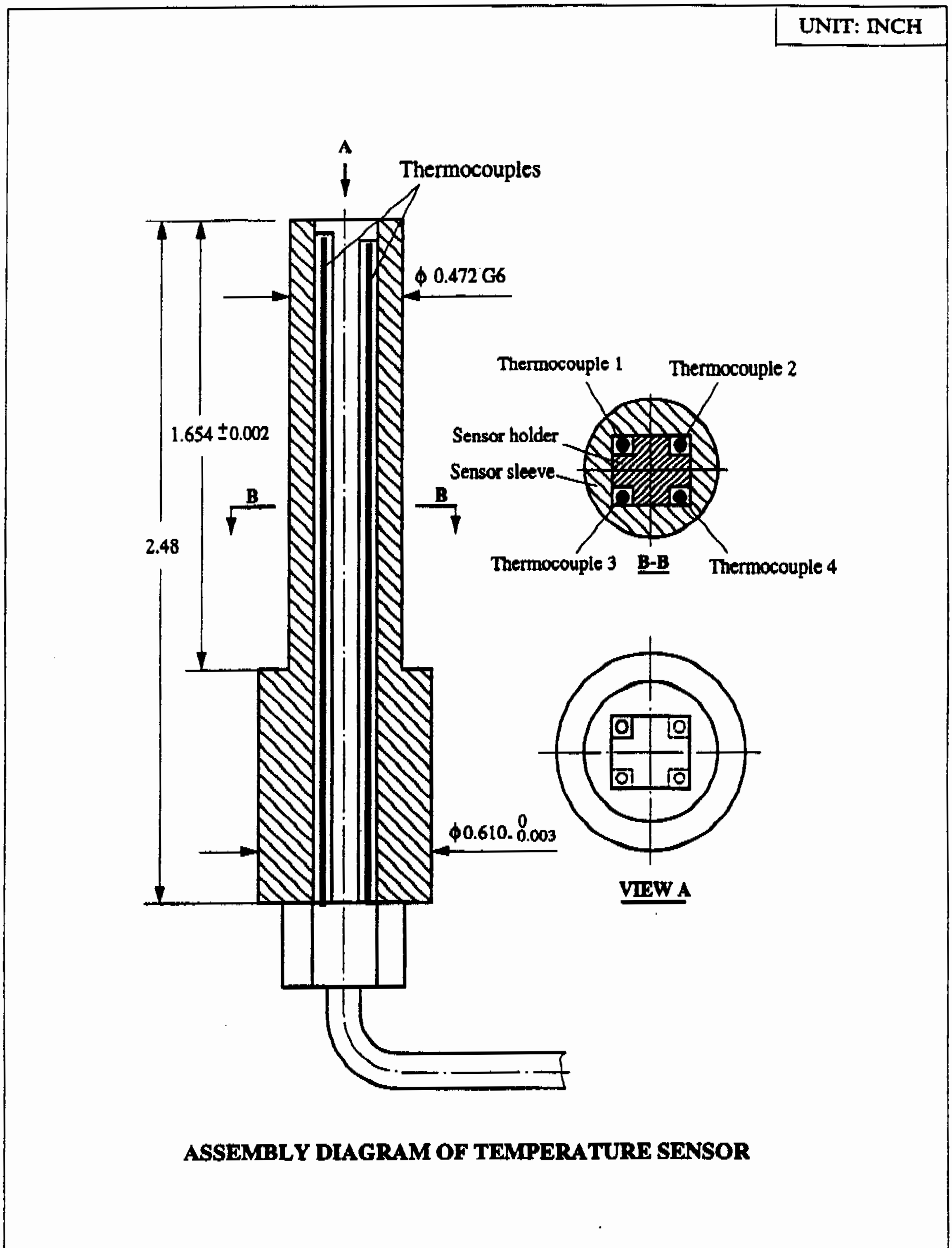


Fig. 3.11: Thermal Probe : Assembly Diagram

The selection of a die casting geometry and the associated die is an important factor in the evaluation of the process variables and the sensors measuring them. The die casting part and the associated die that was selected for characterization in this study is known as the wall die casting. A schematic and a simple illustration of the wall die casting are provided in Figures 3.12 and 3.13. Features of this casting that are advantageous for this study and related future work include:

- the presence of a relatively flat, uniform thickness gate area, which is preferred for the location of opposing thermal probes for an accurate measurement of gate freezing time,
- the availability of flat, uniform thickness regions in the casting for the location of both pressure and thermal probes,
- the convenient location of vents which allow for future die cavity flow measurement and related study,
- the presence of walls which allow for future assessment of the effect of the process variables on the quality of the casting in the blind or unvented areas versus the vented plate area, and
- the suitable size and shape of the die casting that allows for easy radiographic determination of porosity distribution and Archimedes' density measurements.

The limited scope of this study requires two pressure probe for direct cavity pressure measurements, two thermal probes inside the cavity for cavity thermal characterization and two opposing thermal probes at the gate for thermal field characterization in the gate area. A pair of thermocouples were added, in the flat plate area of the casting shortly past the gate, for useful additional information regarding the thermal fields in the cavity and as a guidance for future work. Figure 3.14 illustrates the location

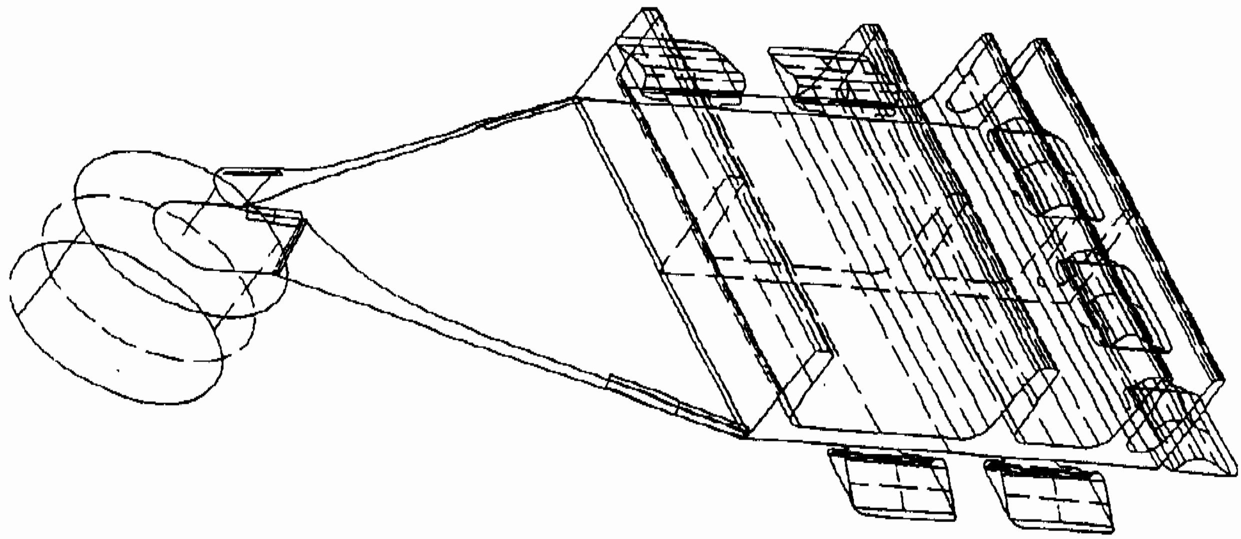


Fig. 3.12 : Schematic of Wall Die Casting

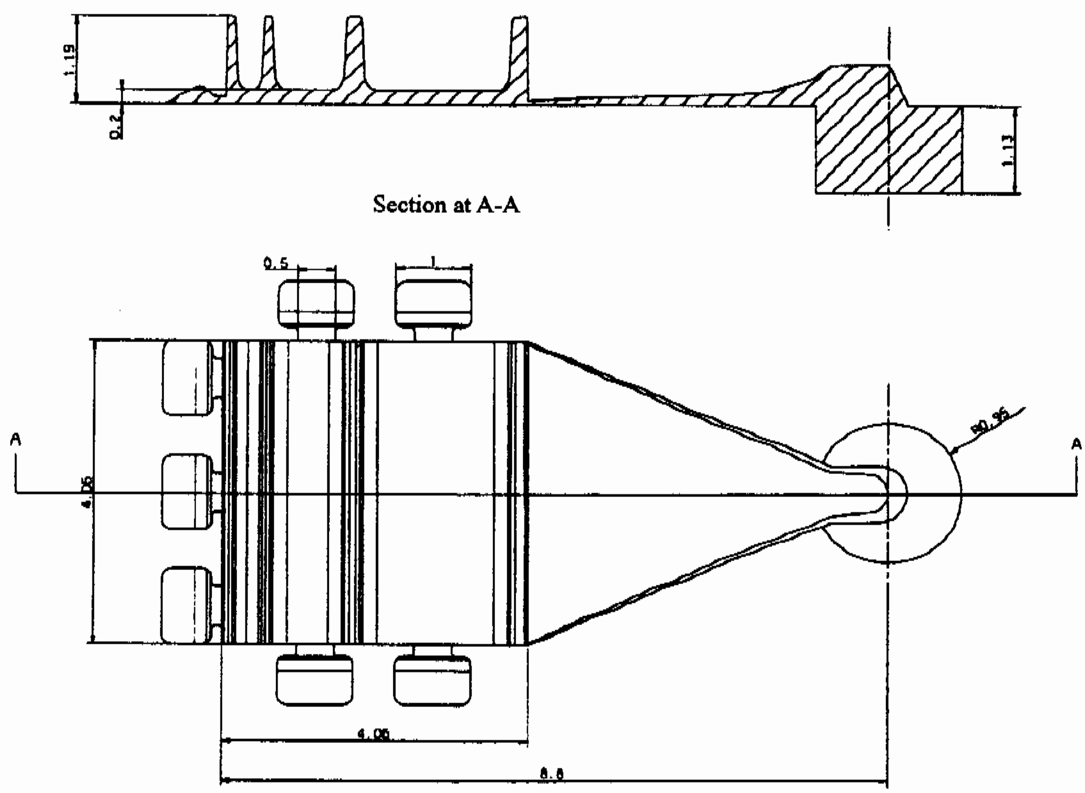


Fig. 3.13: Illustration of Wall Die Casting

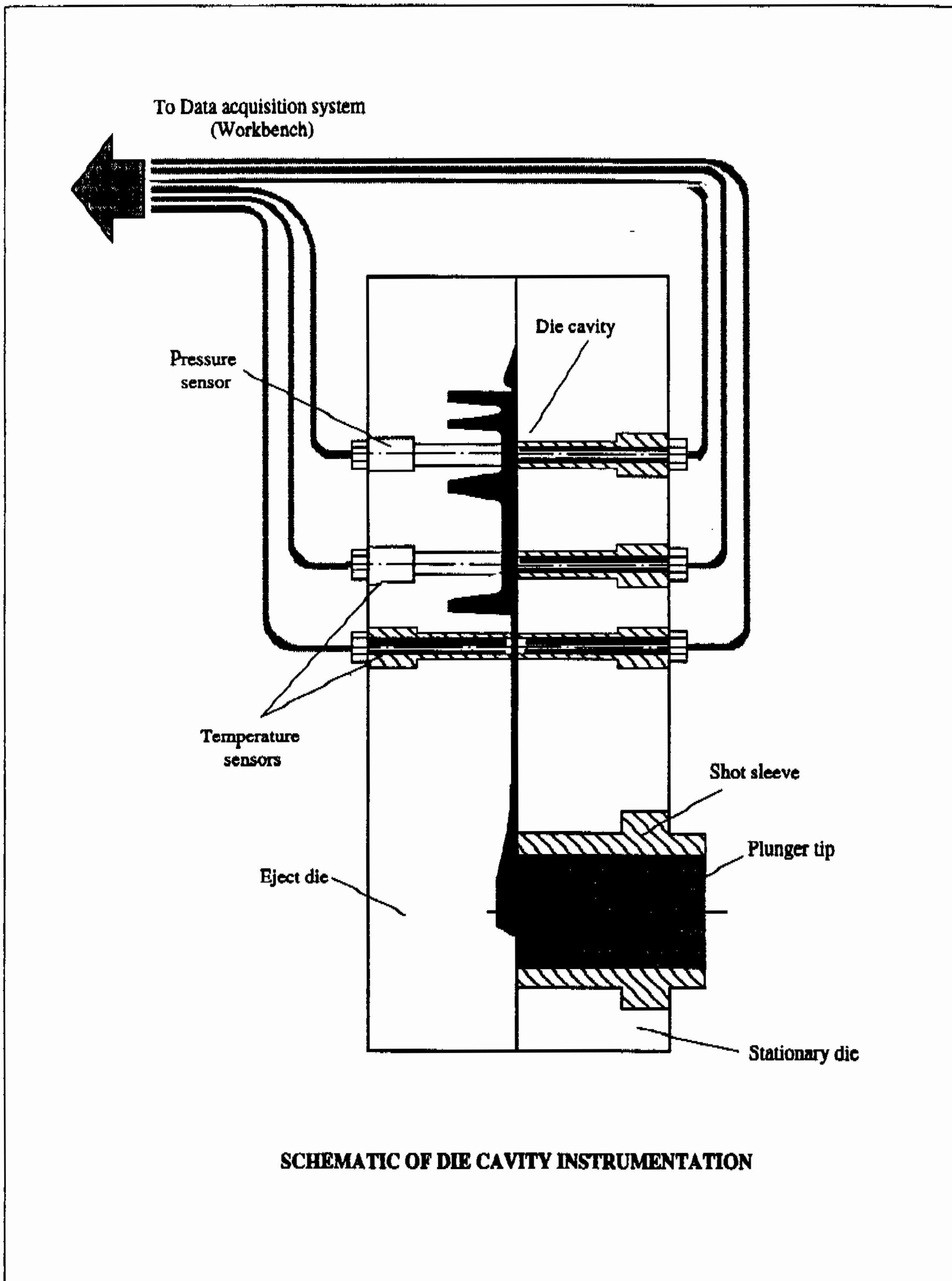


Fig. 3.14 : Schematic of Probe Layout

of the probes on the casting surface. The pressure probe and, in concurrence, the dimensionally identical thermal probes were mounted in the die based on the guidelines provided by the pressure sensor manufacturer. The sensors necessary for the measurement of the process variables that characterize the injection system were provided by Buhler as part of the process monitoring capability of the shot control system of the die casting machine.

The pressure and thermal probes were connected to dedicated pressure and thermal data acquisition systems, respectively. The pressure data acquisition was configured based on the manufacturer's recommendations, while the thermal data acquisition system was configured based on previous work in similar data acquisition. Thermal data was collected at a frequency of 10 Hertz over the entire campaign while the pressure data acquisition, triggered by the shot sleeve advancement, had a sampling frequency of 200 Hertz. The injection characteristics were recorded on the separate data acquisition component of the shot control system.

An outline of the machine set-up analysis performed to arrive at the base line operation process variables for the chosen alloy, die and machine is provided in Appendix C. In summary, 11.05 cubic inches of Al 390 melt was to be injected into the cavity at a gate velocity of 1400 inches/sec. and at an injection pressure of 70.64 psi to achieve a cavity fill time of 12.1 millisec. A locking force of 63,505 lbs. was required to counter the intensification pressure of 1413 psi. Further a PQ^2 analysis was performed and the flow rate of 8.26 liters/sec at the required injection pressure was found to be well within the capabilities of the machine for a plunger diameter of 49.2 mm as shown in Appendix D.

CHAPTER 4

ANALYTICAL APPROACH

4.1 Introduction

An analysis of the effect of various process variables by computer simulation is a simple and efficient method of characterizing the process and thereby predicting the quality of a die cast component for the given corresponding set of process variables. However, before the application of such methods in the die casting industry, the veracity of the software used for the prediction has to be confirmed by comparison with experimental data. To this end, this study aims to verify the gate area thermal characterization of BINORM using the data acquired from the experimental campaign.

4.2 BINORM

BINORM, formerly called DIECAST, is a FORTRAN program written by J. Papai and C. Mobley that describes the binormal solidification of a casting assuming one-dimensional heat transfer. It predicts the thermal field of a die casting system as a function of time. A schematic of the geometry associated with the BINORM computer model is provided in Figure 4.1. The input to this model comprises variables like casting and die material properties, die thickness and initial temperature, liquid superheat, ambient and coolant temperature, heat transfer coefficients at all major interfaces of the die casting cycle (namely metal-die, die-coolant and die-air), die open and close times and coolant delay and duration values. As output, the model predicts all major thermal characteristics associated with the die casting process including initial, minimum and maximum die surface temperatures, casting ejection temperature, heat flux to the dies when they are closed, initial, maximum and minimum thermal gradients and the casting solidification time.

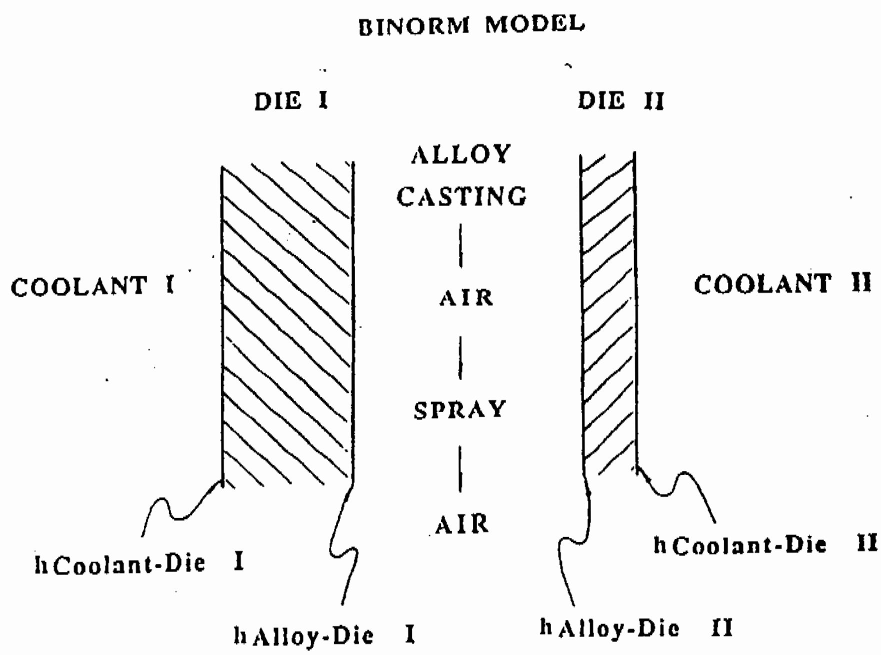


Fig. 4.1 : Schematic of BINORM Geometry Model

The simulated die casting cycle consists of a four period sequence as follows

- melt contact with the dies for the specified die closed time,
- die exposure to the ambient environment after the casting is ejected,

- duration of coolant/lubricant spray on die face, and
- die exposure again to the ambient environment before the next cycle begins.

Based on the input data, BINORM assigns an initial temperature heat content and thermal conductivity to each element of the die and casting and thermal resistance at the die-casting, die-coolant and die-ambient atmosphere interfaces. A temperature difference and a thermal resistance between each adjacent element is then calculated. The gradient is divided by the resistance for a net heat flow from one element to another. The heat fluxes into and out of each element are summed for a net heat flux into the element. This flux is multiplied by the time step to arrive at the heat flow into each element after each time step. This heat flow is added to the heat content of the element before the time step for a new heat content. The new temperature and thermal conductivity of each element is calculated based on the heat content. This procedure is repeated over the entire cycle, with the output of each cycle serving as the input for the next cycle, for the specified number of die casting cycles [27].

BINORM was chosen for this study as it facilitates direct observation of the effects of process variables on solidification times and die thermal history. It also considers various periods of heat transfer and allows simulation over many cycles to enable the attainment of 'quasi-steady-state' system conditions. Finally, its use of one-dimensional, time dependent heat transfer equations allows for short computational times that are advantageous in the industrial environment. However, BINORM does not facilitate the computation of die and casting thermal fields associated with complex castings, as possible using such commercially available computer models as MAGMAsoft, FLOW-3D, ProCast or EKK.

4.3 Sensitivity Analysis

It is necessary to determine the importance of each input variable of any computer simulation, in order to better understand the computation involved in the process. Thus, a sensitivity analysis can be defined as basically a determination of the change in the value of the output for a given change in the value of each input, all other inputs remaining constant. It was also necessary, in this study, in determining the extent of variations of the major thermal parameters associated with the die casting process. To this end, a sensitivity analysis was performed using BINORM.

Certain 'base case' input conditions were chosen for comparison purposes. Appendix E lists these base case conditions. Effectively, the base case consists of a 0.4 centimeter thick Al 390 casting in 5.08 centimeter thick H-13 dies. The initial die temperatures of both the cover and ejector dies is 25 degrees Celsius. The air and coolant temperatures are 35 degrees Celsius. The heat transfer coefficients at the die-alloy, die-coolant and die-ambient air interfaces are 1.09, 0.1 and 0.003 cal/cm^2.C.sec., respectively. The initial melt superheat is 10 degrees Celsius. The die open and close times are 25 and 15 seconds, respectively, with a spray duration of 5 seconds that begins 15 seconds after the die opens. These process conditions were varied individually, keeping all other variables constant over the change, and the change in the thermal characteristics in the quasi-steady-state predicted. Due to the limited objectives of this study, the effect, of the changes in these input variables, on only the quasi-steady state freezing time and initial die surface temperature was determined. Figures 4.2 to 4.19 illustrate the effect of changes in these variables.

Figures 4.2 and 4.3 illustrate the effect of a variation in spray temperature on the freezing time and initial die surface temperature, respectively. A slight increase in freezing time is noted corresponding to an increase in spray temperature and can be attributed to the decrease in thermal gradient at the die-coolant interface. The decrease in the thermal gradient, with an increase in spray temperature, is illustrated by the increase in initial die surface temperature.

Figures 4.4 and 4.5 illustrate the effect of a change in the spray timing on the freezing time and initial die surface temperature, respectively. A decrease in freezing time was noted with an increase in spray start delay. All other variables remaining constant, this decrease in freezing time can be attributed to the decrease in initial die surface temperature as it does not have sufficient time to increase after the cooling due to the spray.

Figures 4.6 and 4.7 illustrate the effect of spray duration variation on the freezing time and initial die surface temperature, respectively. It was found that an increase in spray duration decreases both the freezing time and the die surface temperature by a considerable extent. This decrease is to be expected as the not inconsiderable heat transfer from the die to the coolant occurs over increasing time periods.

Figures 4.8 and 4.9 illustrate the change in freezing time and initial die surface temperature, respectively, due to a change in the initial superheat of the melt. The increase in freezing time with an increase in initial melt temperature is due to the correspondingly greater amount of heat to be removed for the metal to reach a solid state. The initial die surface temperature is not affected much as the cycle time is sufficiently large to allow for the greater heat removal.

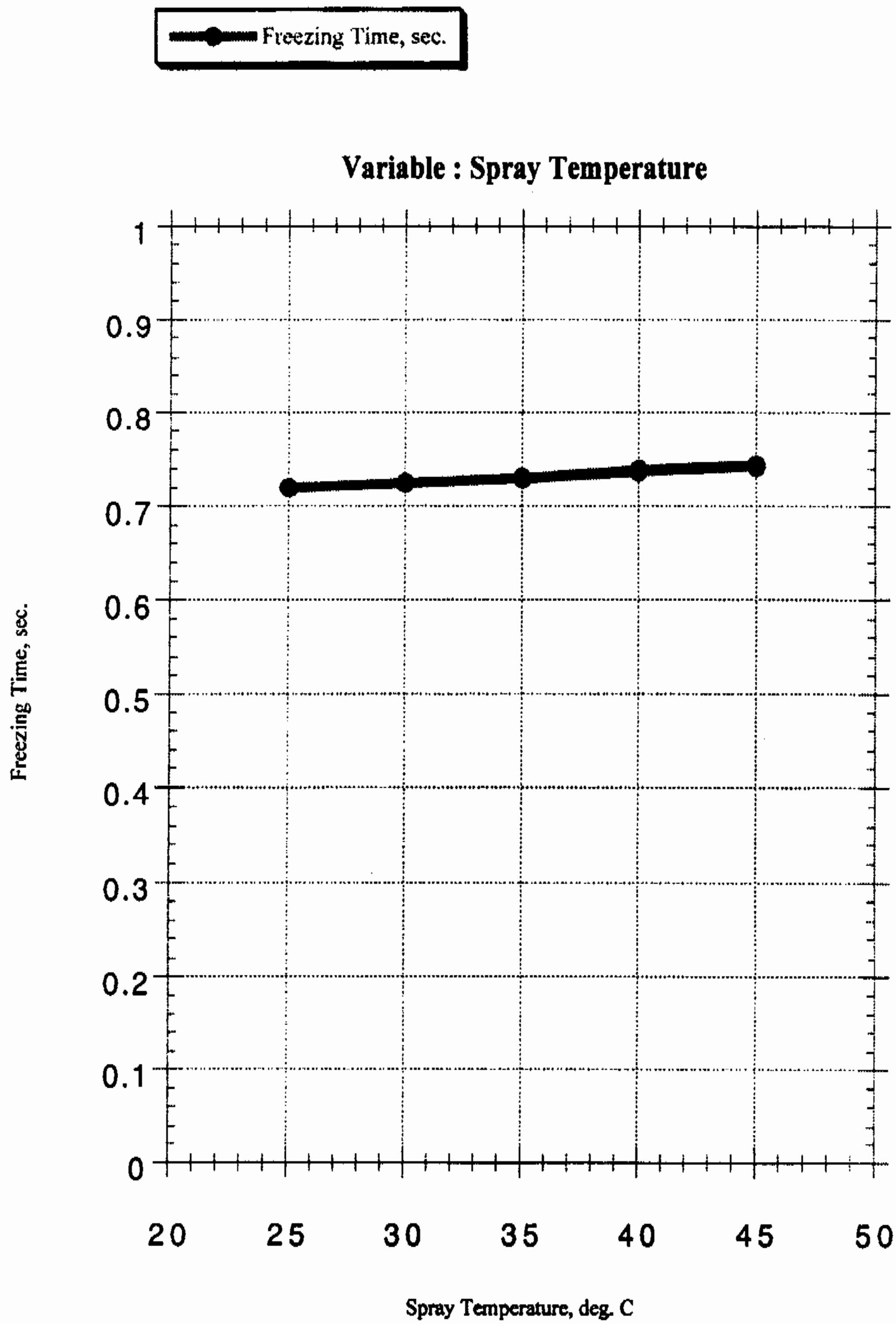


Fig. 4.2: Freezing time Vs. Spray Temperature

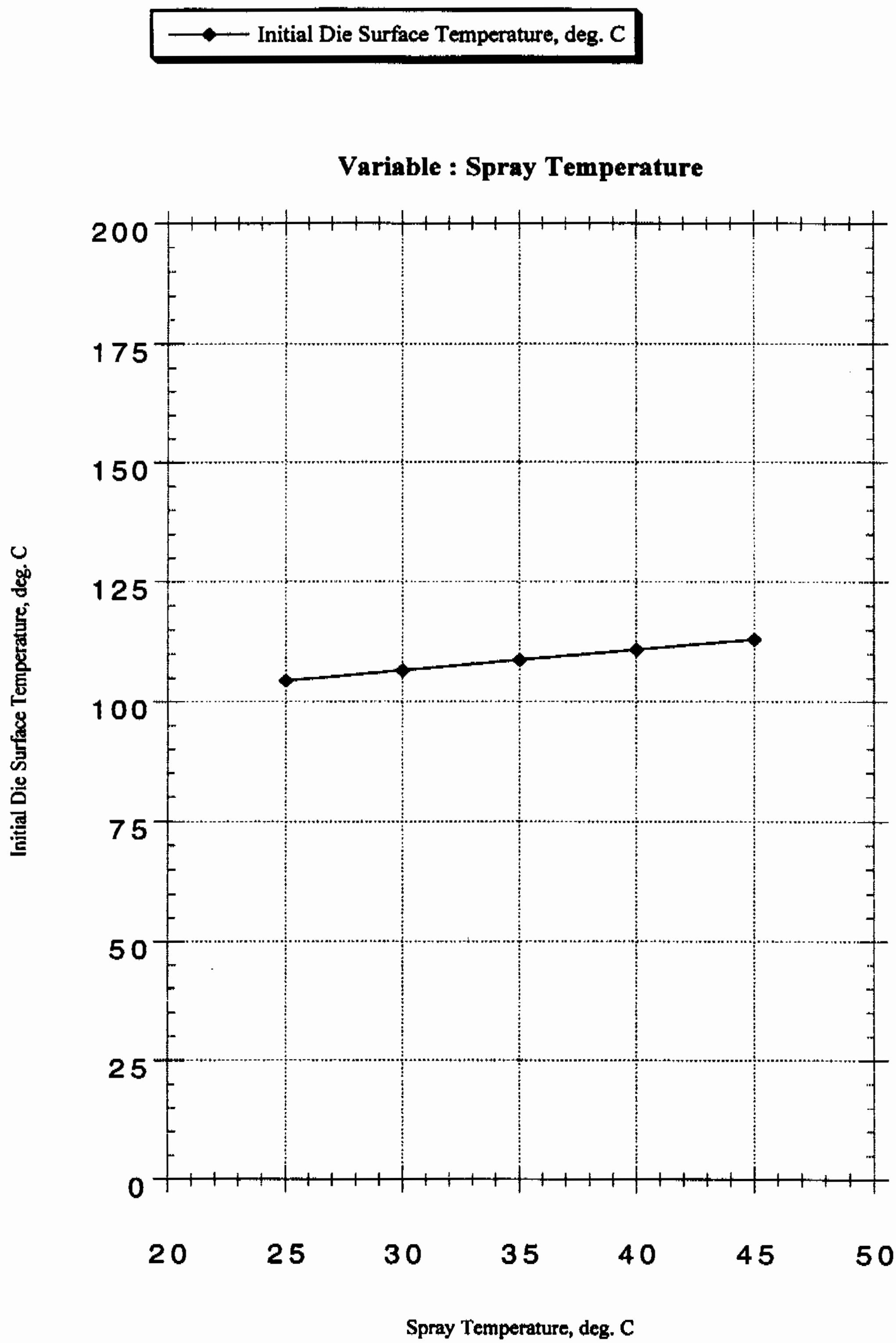


Fig. 4.3: Initial Die Surface Temperature Vs. Spray Temperature

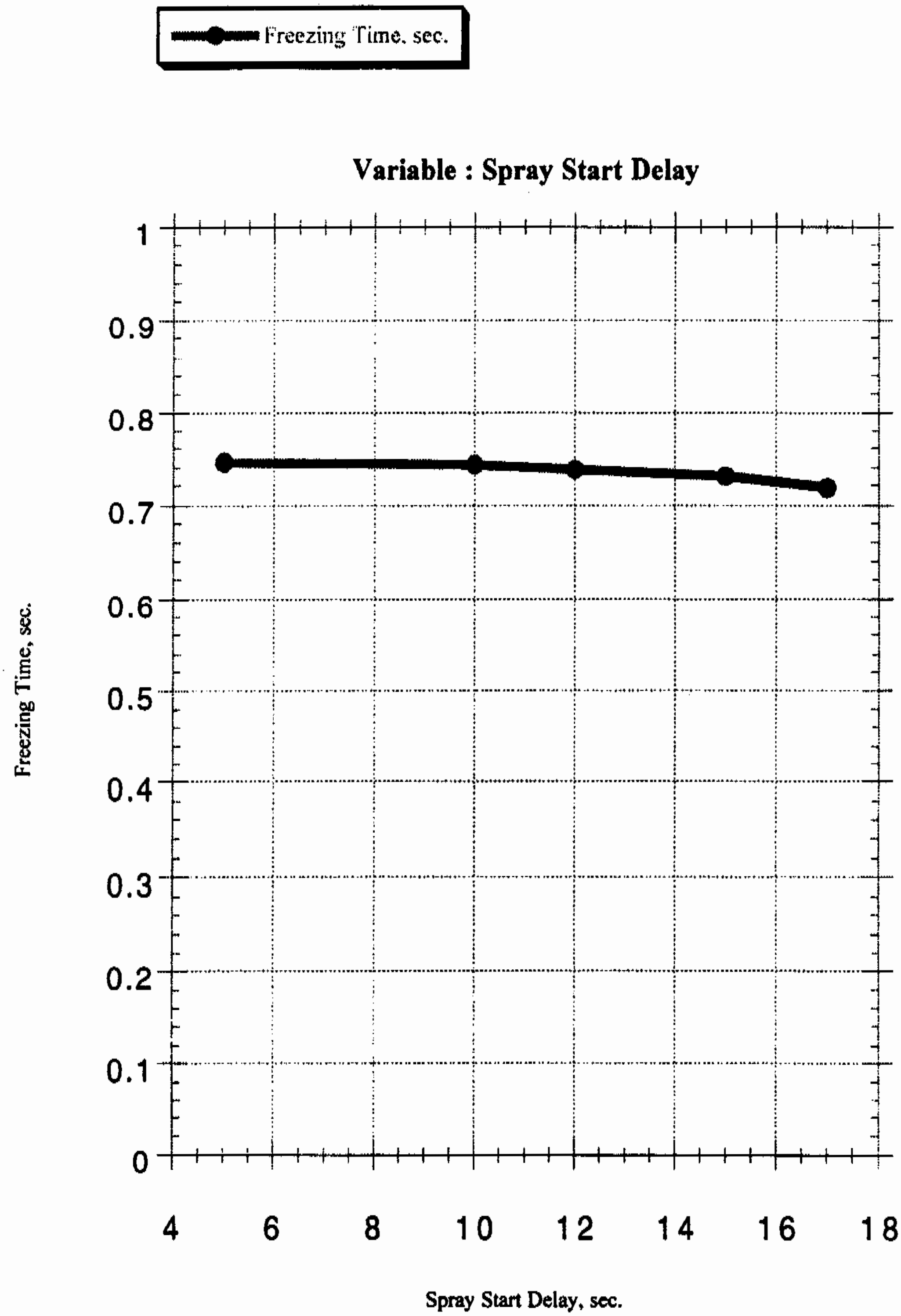


Fig. 4.4: Freezing Time Vs. Spray Start Delay

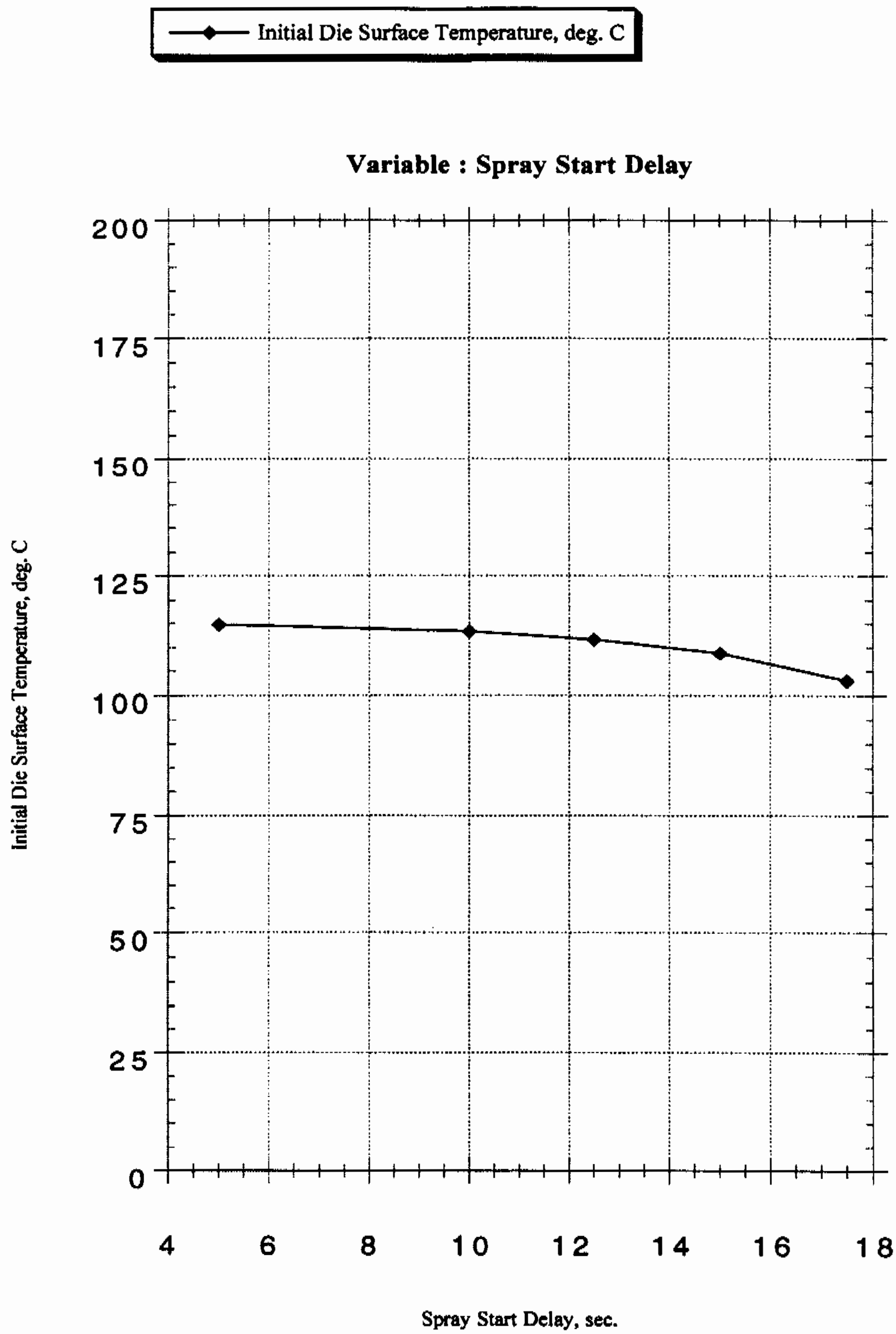


Fig. 4.5: Initial Die Surface Temperature Vs. Spray Start Delay

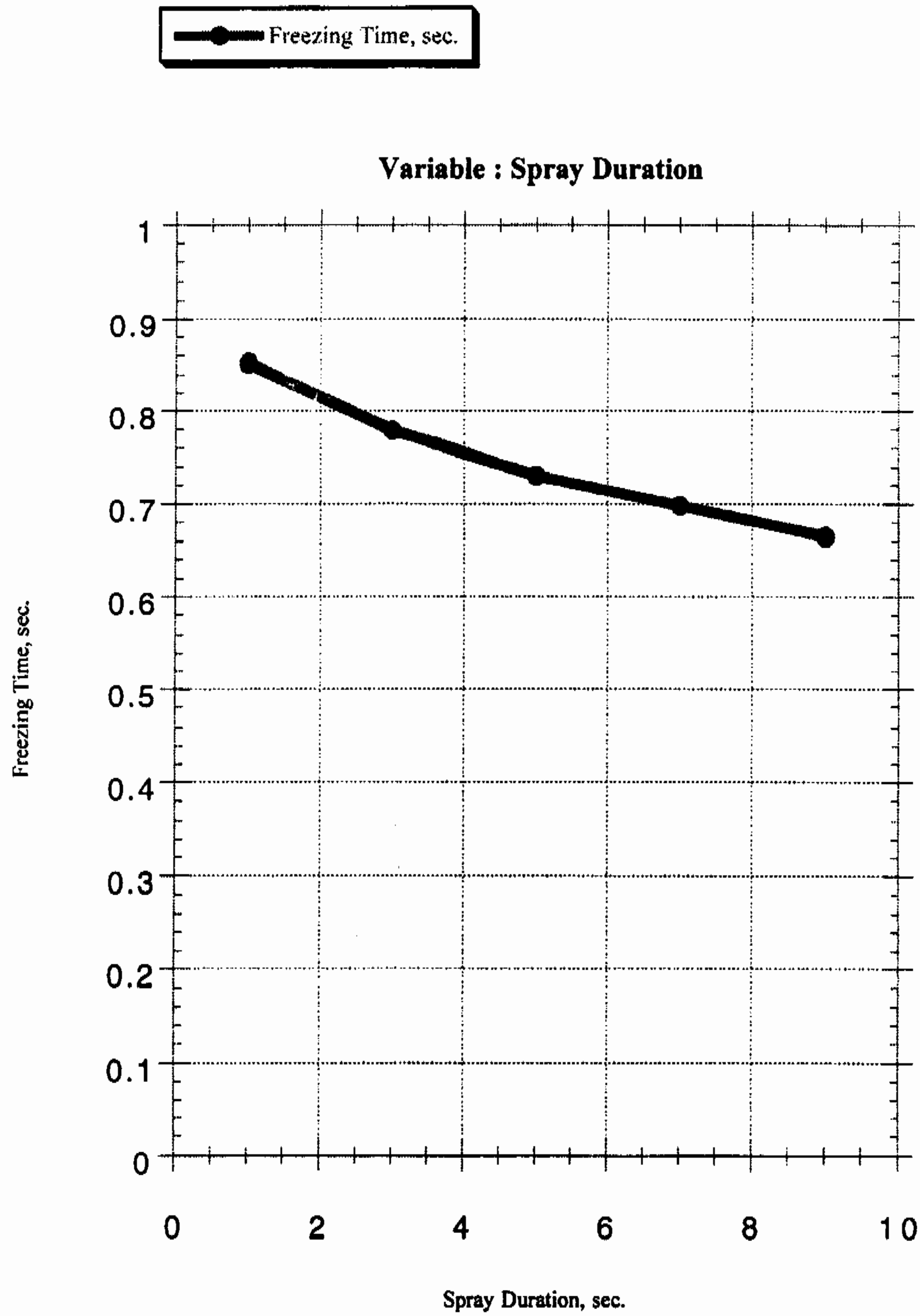


Fig. 4.6: Freezing Time Vs. Spray Duration

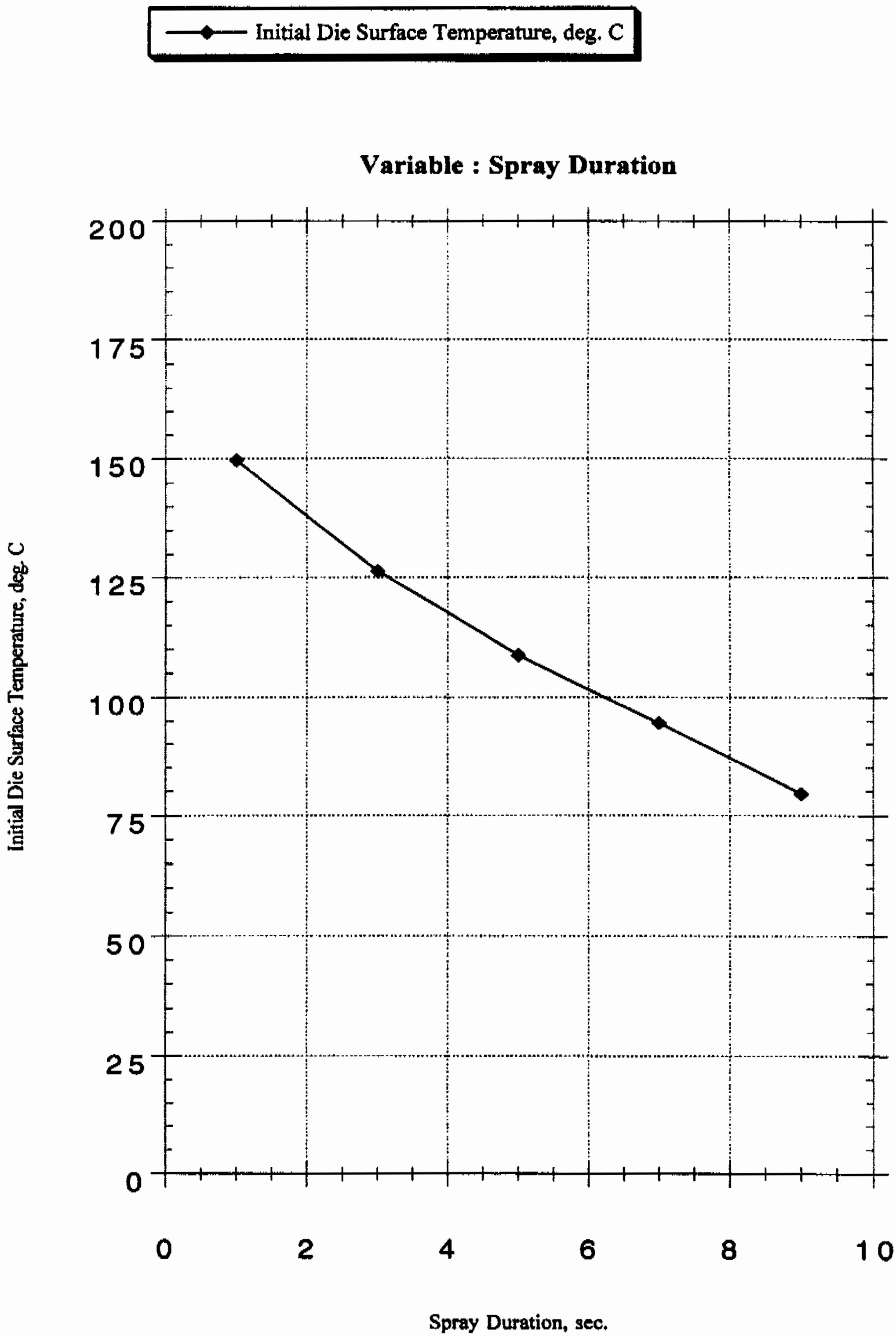


Fig. 4.7: Initial Die Surface Temperature Vs. Spray Duration

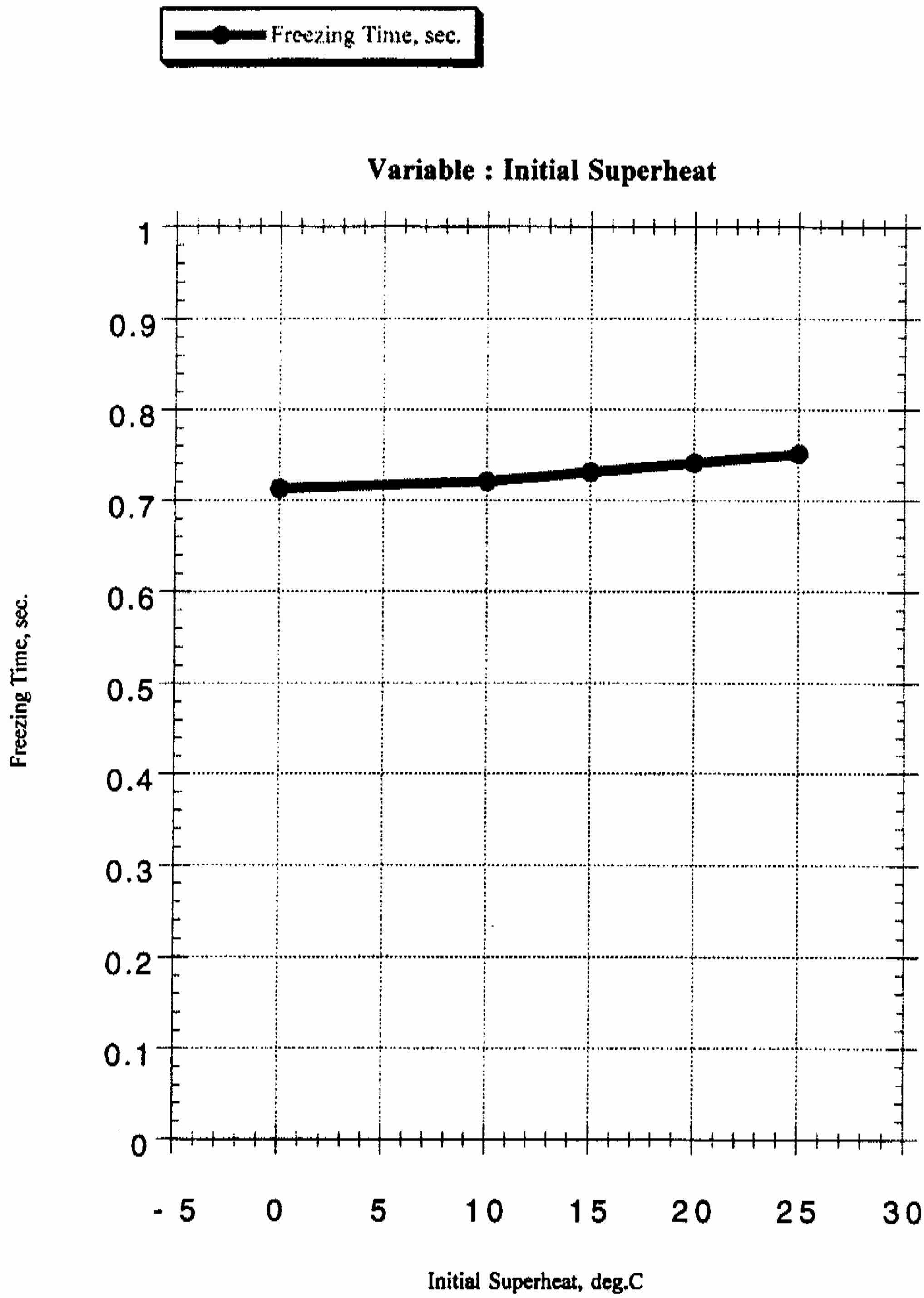


Fig. 4.8: Freezing Time Vs. Initial Superheat

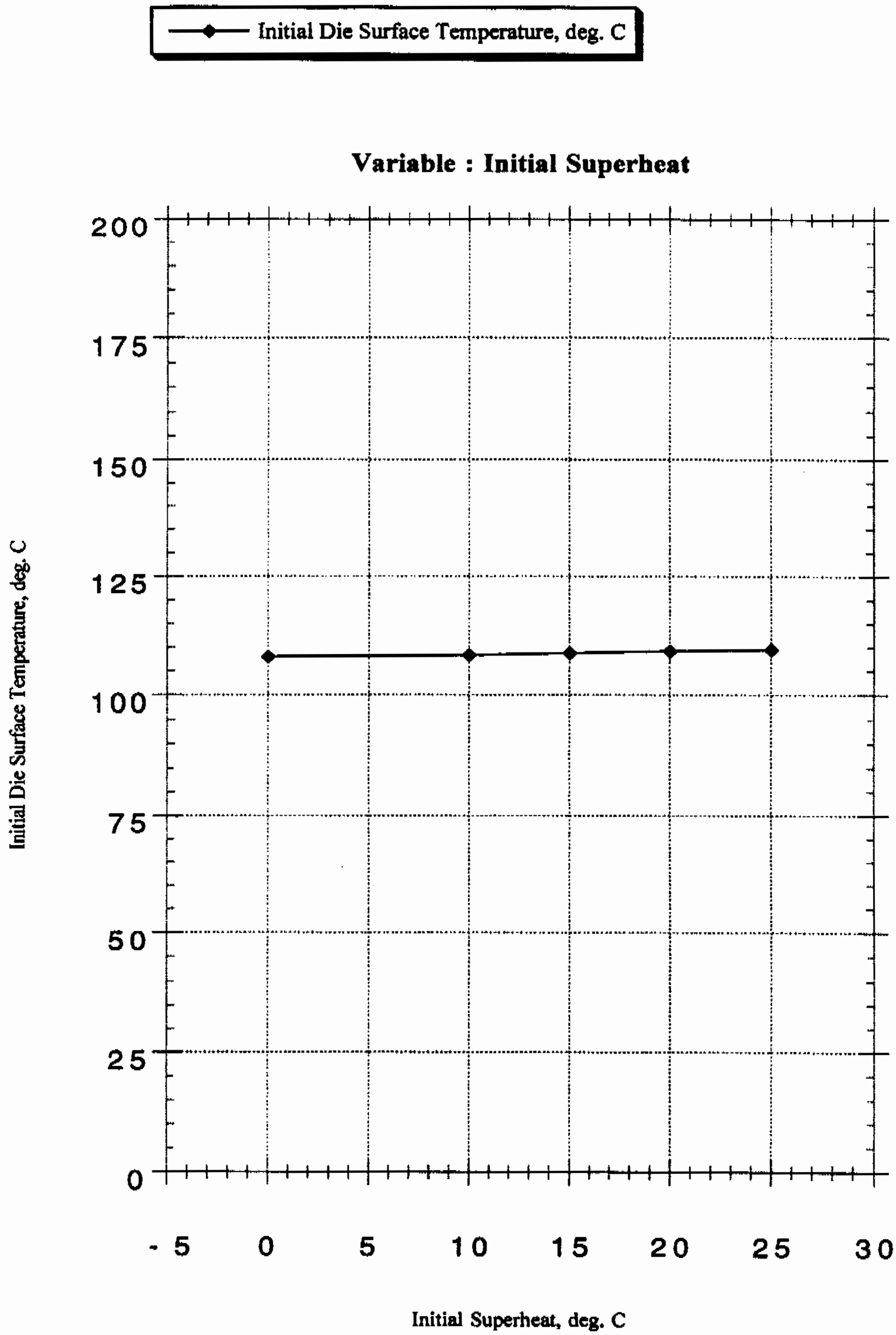


Fig. 4.9: Initial Die Surface Temperature Vs. Initial Superheat

Figures 4.10 and 4.11 illustrate the effect that a variation in the die close time, for the same total cycle time, has on the freezing time and initial die surface temperature, respectively. The observed decrease in both freezing time and initial die surface temperature, with an increase in the duration the die is closed, can be attributed to several factors, the primary being the longer time period available for the casting-die heat transfer and corresponding decrease in die temperature when the casting is ejected.

Figures 4.12 and 4.13 illustrate the effect on freezing time and initial die surface temperature, respectively, of any variation in the total cycle time. All other variables remaining constant, it was found that the freezing time increases negligibly and then decreases with an increase in total cycle time. The initial increase in freezing time is due to an increase in initial die temperature after the coolant spray. The gradual decrease in initial die surface temperature and, correspondingly, freezing time with a further increase in total cycle time is due to the increased heat transfer out of the die.

Figures 4.14 and 4.16 depict the effect, on the freezing time, of the heat transfer coefficients at the casting-die and die-coolant interfaces respectively. Figures 4.15 and 4.17 show the effect of changes in the heat transfer coefficients at the casting-die and die-coolant, respectively, on the initial die surface temperature. The freezing time and the initial die surface temperature asymptotically approach, from the Newtonian heat transfer region, the minimum values corresponding to ideal thermal interface conditions. The variation of the initial die surface temperature with the heat transfer coefficient at the casting-die surface, although asymptotic, is negligibly small. Heat transfer during the die casting process occurs, typically, in the mixed mode region. Careful consideration must be made in the choice of heat transfer coefficients for numerical analyses as even small changes in the heat transfer coefficient towards to the Newtonian region will result large variations in the predicted thermal characteristics like freezing time.

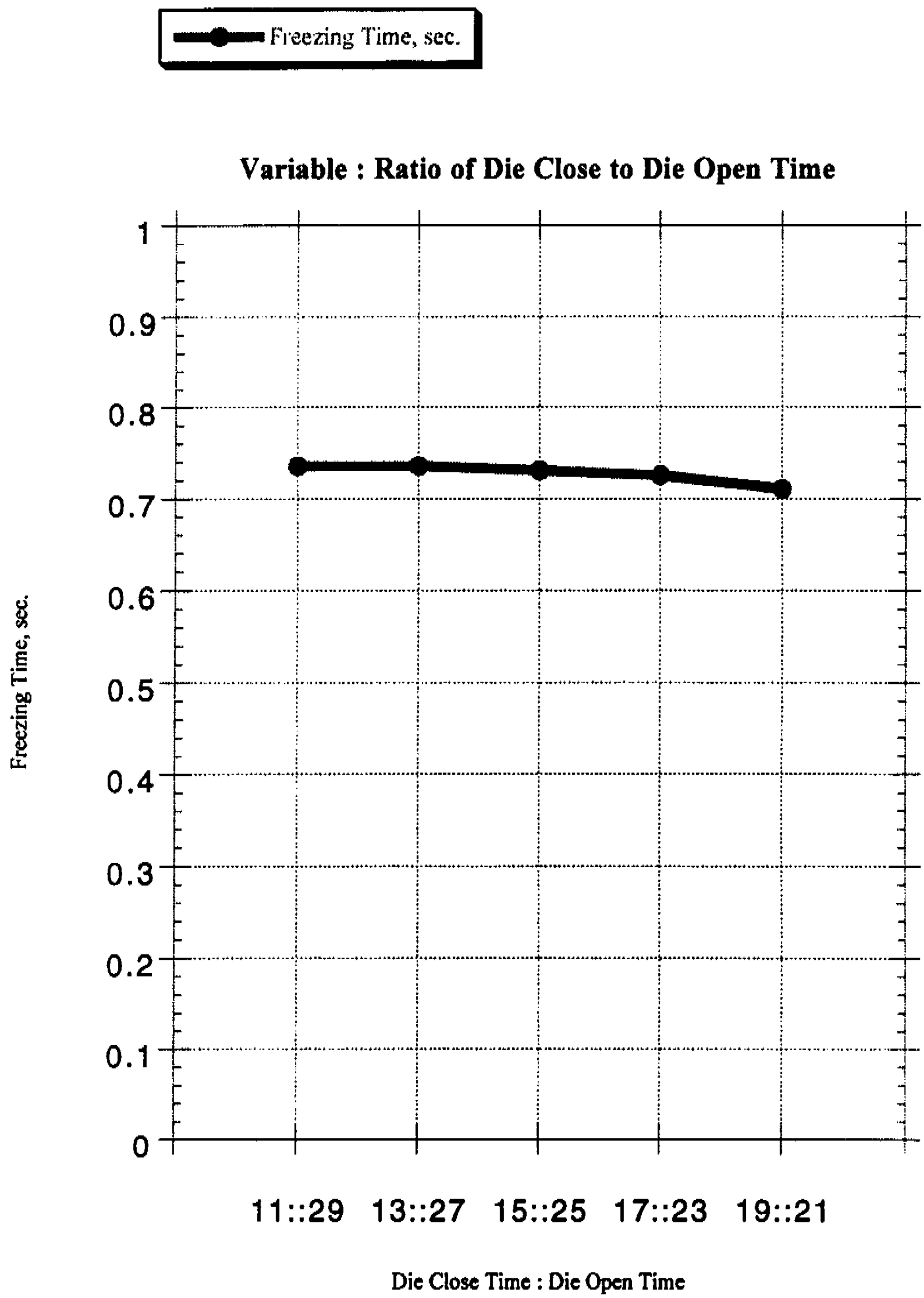


Fig. 4.10: Freezing Time Vs. Die Close to Die Open Ratio

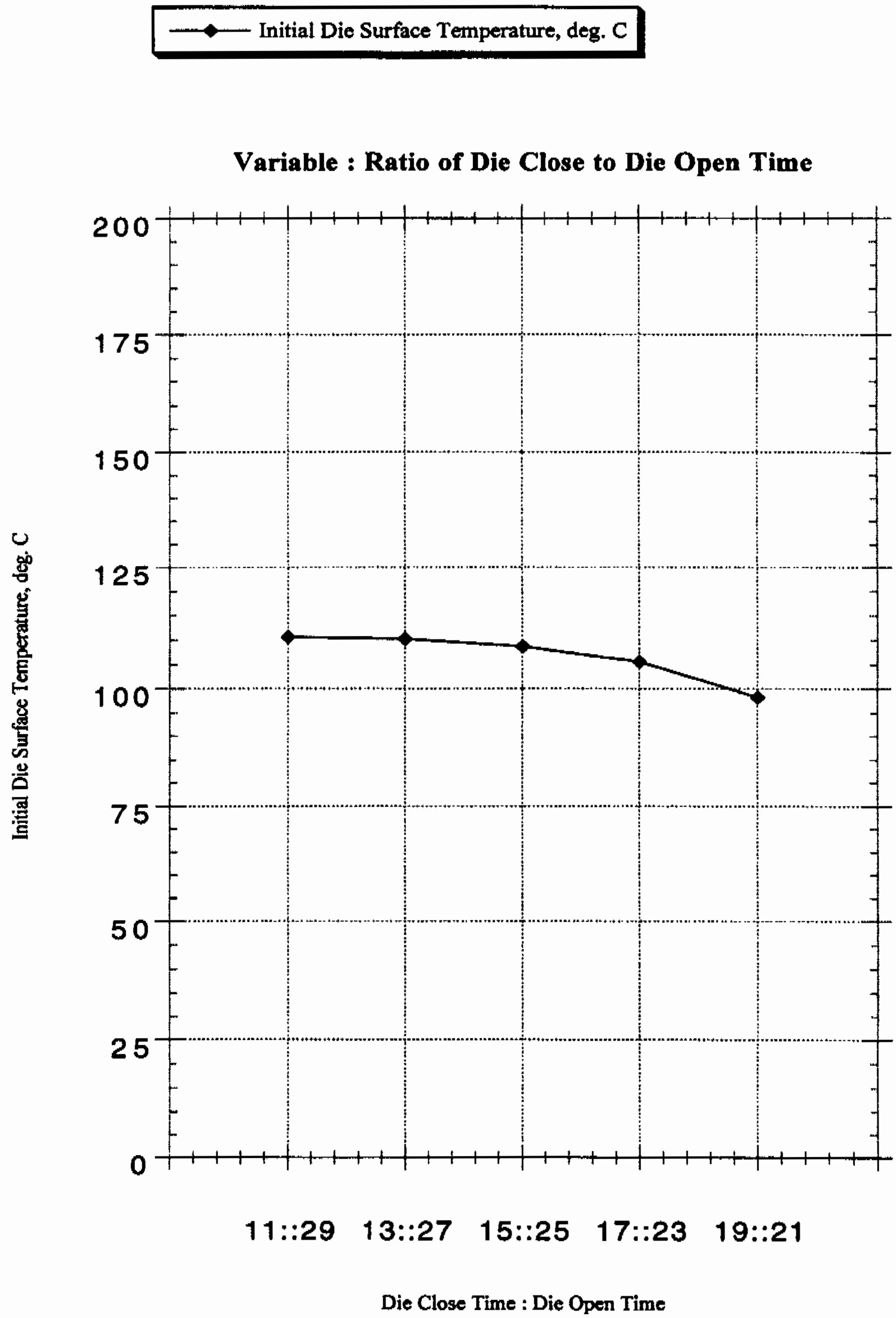


Fig. 4.11: Initial Die Surface Temperature Vs. Die Close to Die Open Ratio

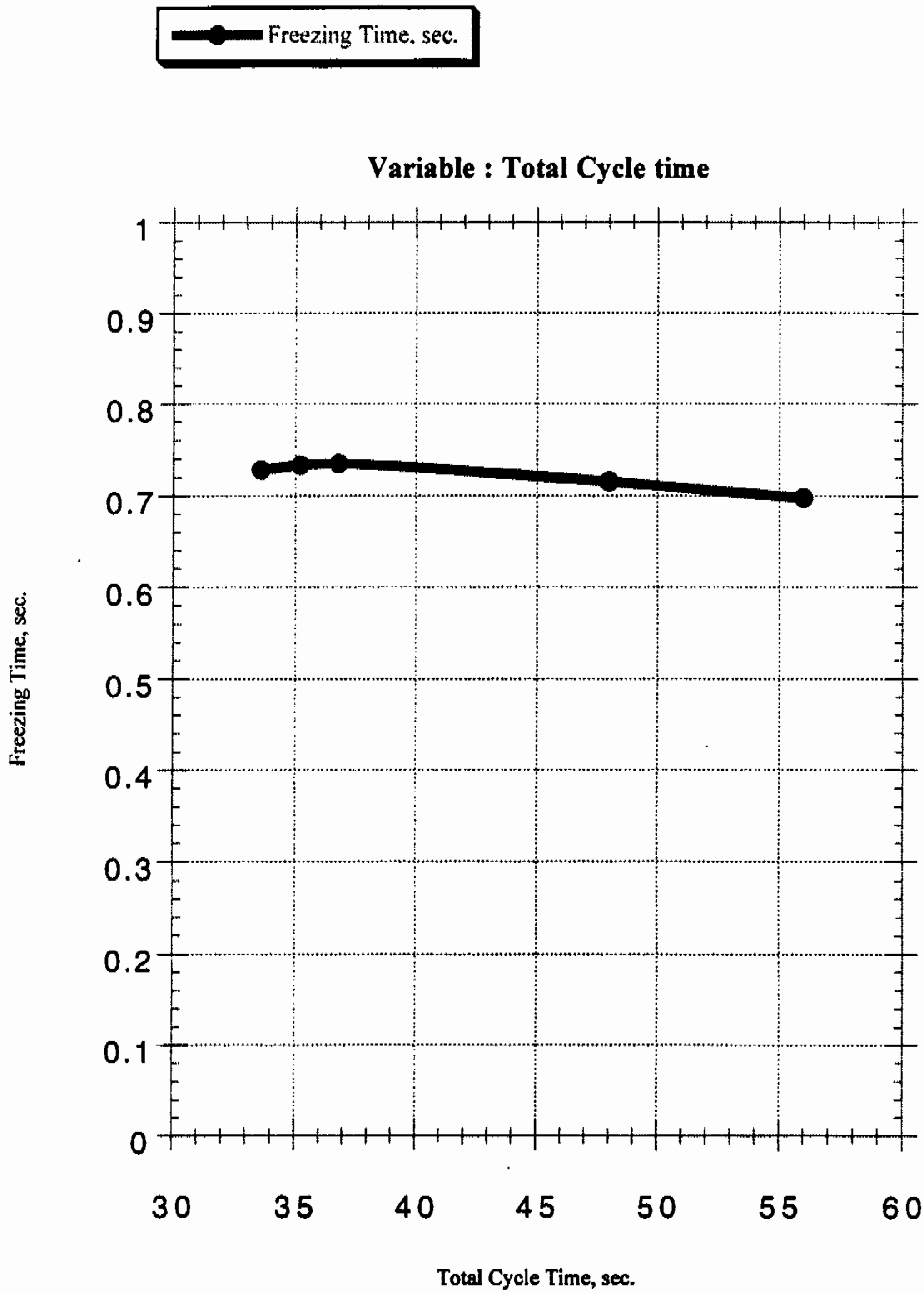


Fig. 4.12: Freezing Time Vs. Total Cycle Time

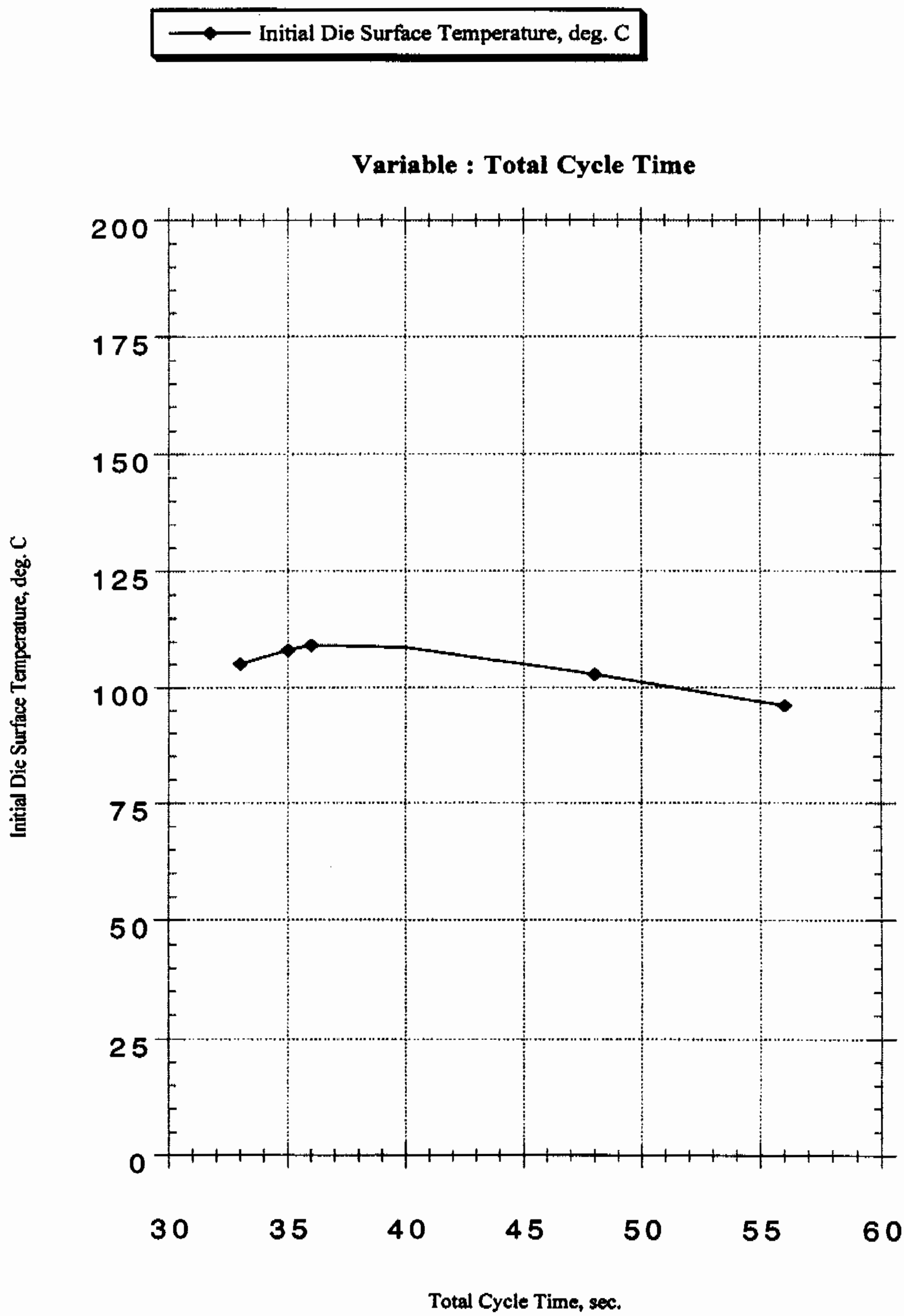


Fig. 4.13: Initial Die Surface Temperature Vs. Total Cycle Time

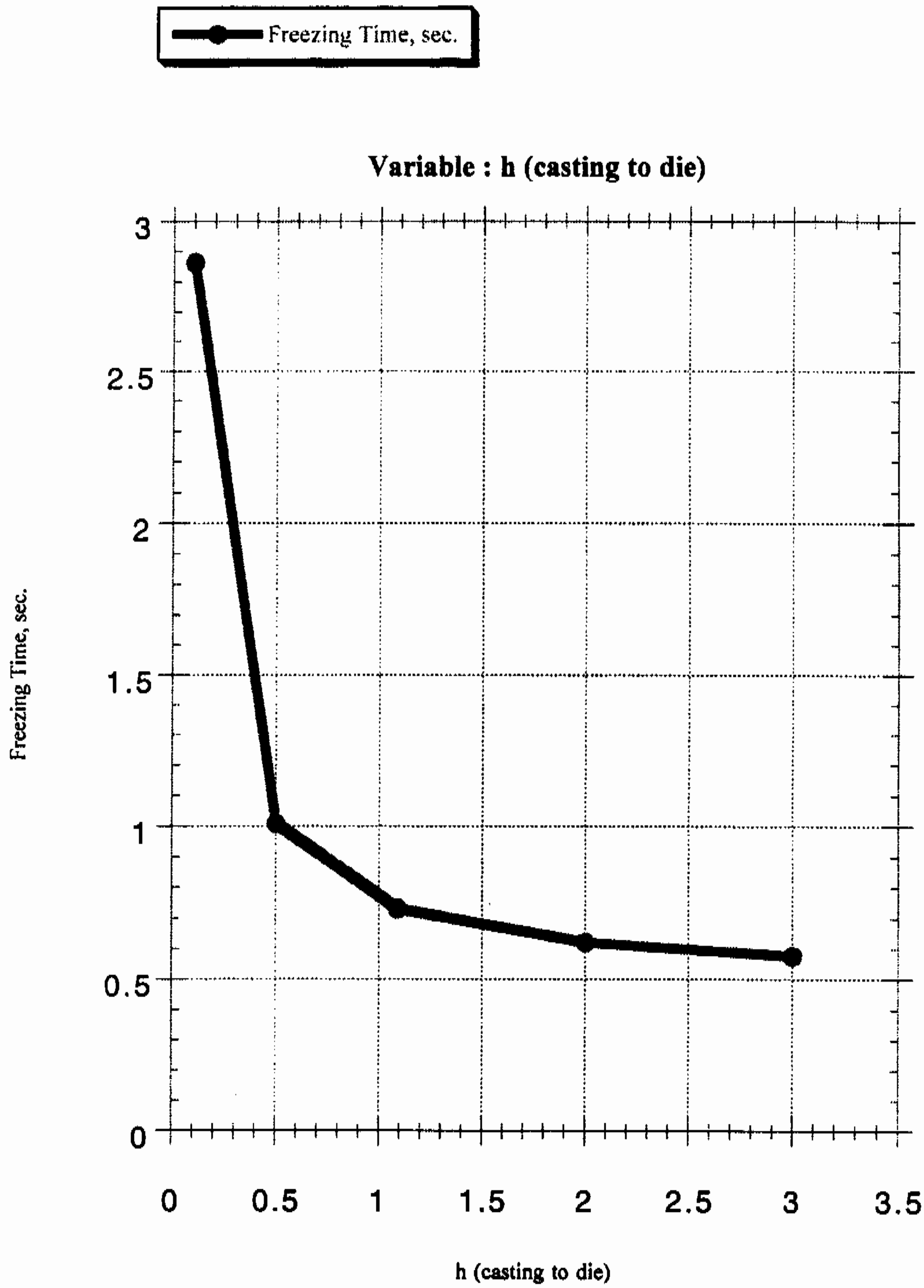


Fig. 4.14: Freezing Time Vs. h (casting to die)

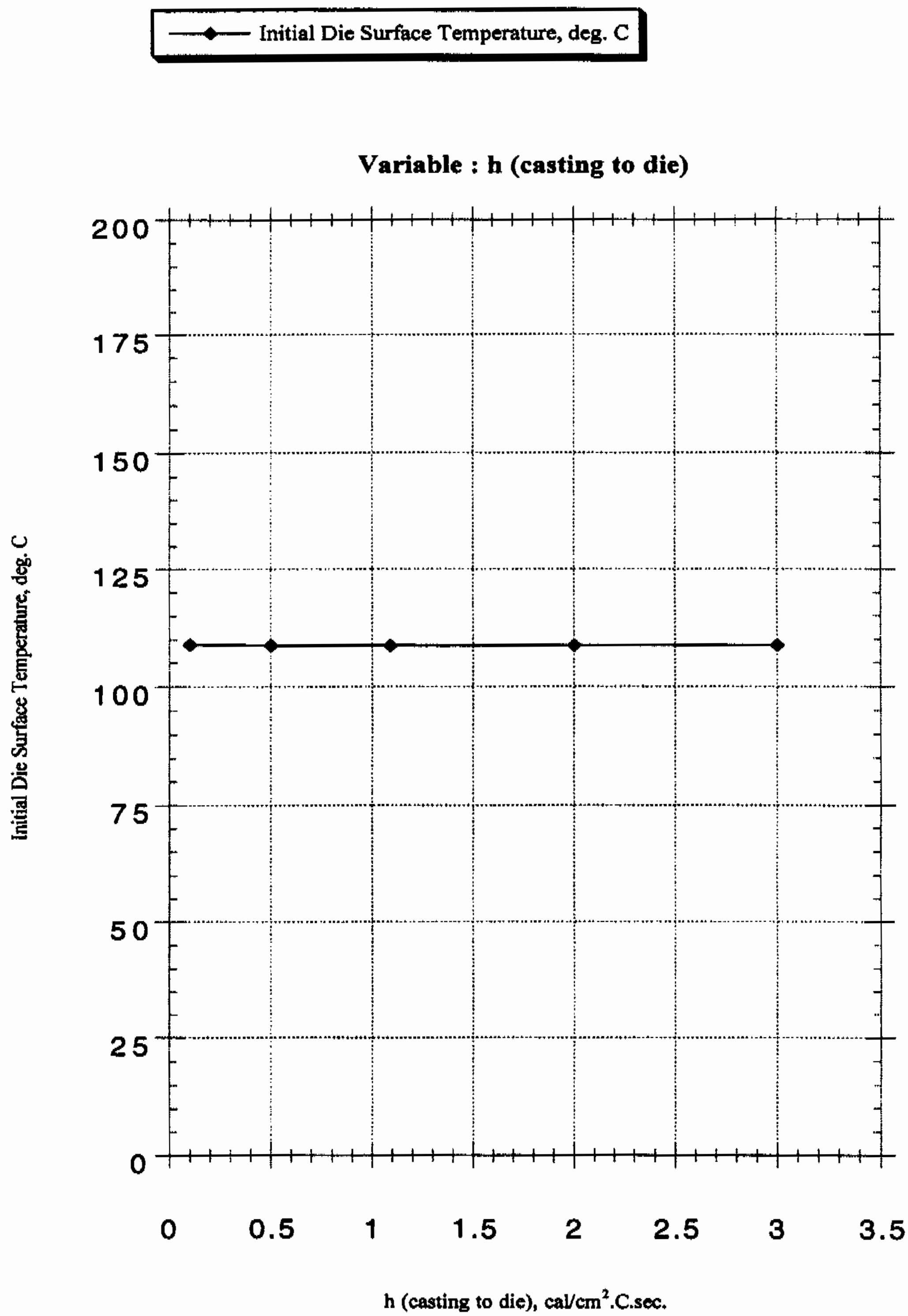


Fig. 4.15: Initial Die Surface Temperature Vs. h (casting to die)

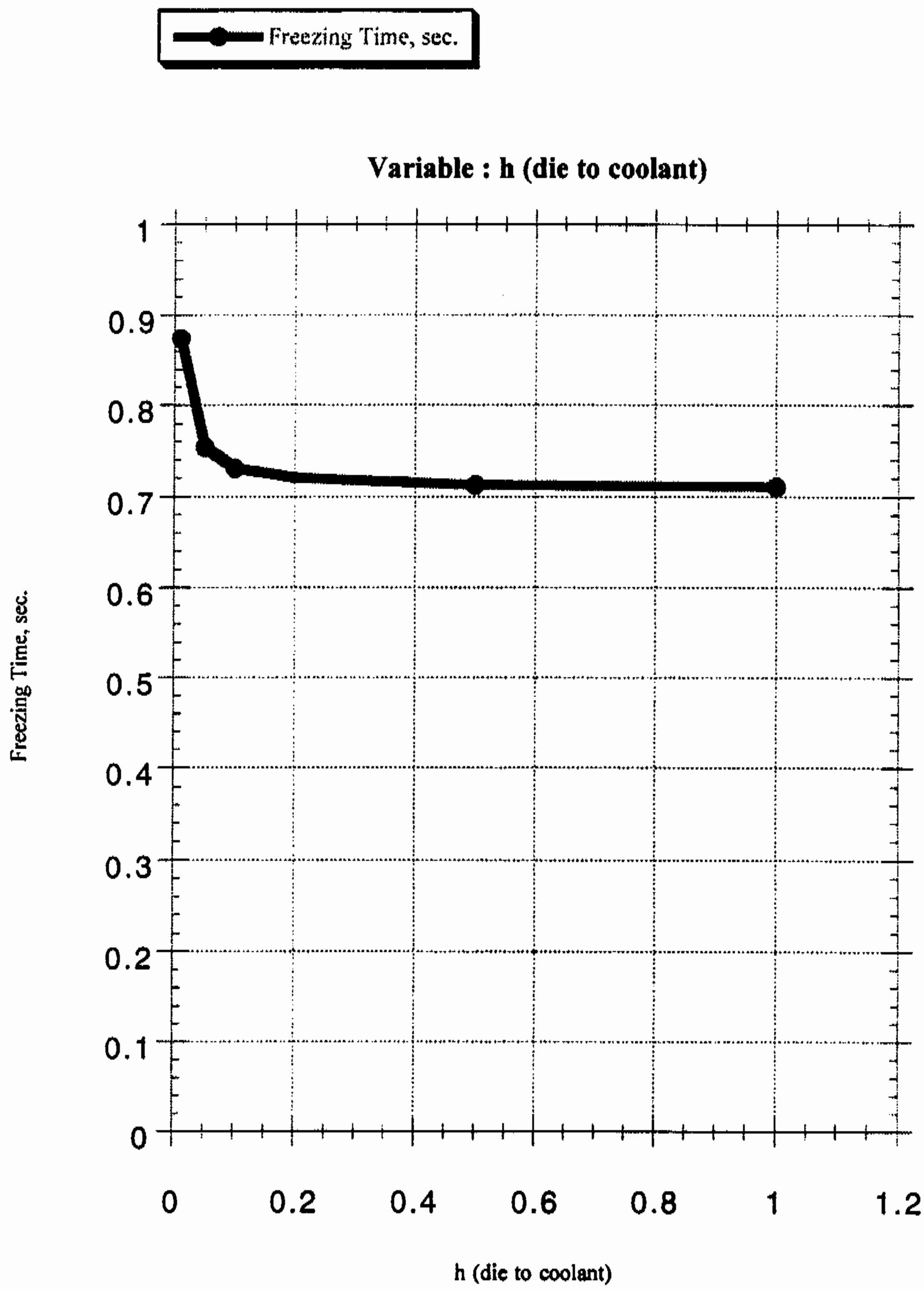


Fig. 4.16: Freezing Time Vs. h (die to coolant)

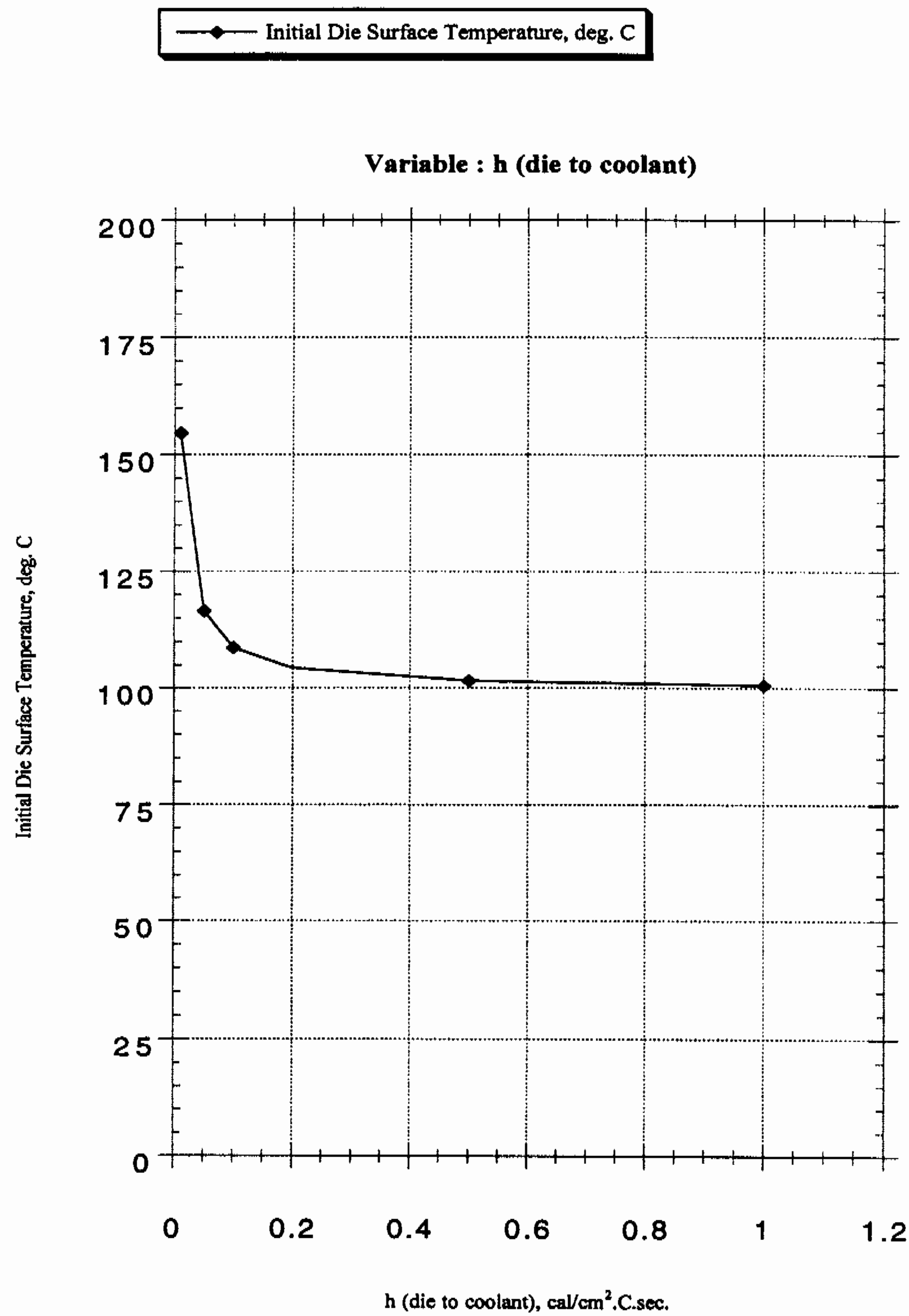


Fig. 4.17: Initial Die Surface Temperature Vs. h (die to coolant)

Finally, Figures 4.18 and 4.19 illustrate the considerable effect of casting thickness on the freezing time and the initial die surface temperature. This is understandable as, with an increase in casting thickness, correspondingly greater heat transfers have to occur for the casting to freeze and, further, for the die to reach lower temperatures.

Also, analysis revealed that changes in initial die temperatures have no effect on the quasi-steady state freezing time or quasi-steady state die surface temperatures, except in increasing the number of die casting cycles required to reach the required quasi-steady-state thermal conditions.

The sensitivity analysis provided an understanding of the calculations performed by BINORM in any thermal analysis and the effect of individual operating variables on the die casting process. It identified the casting thickness, the spray duration and the heat transfer coefficients as having the most effect on the freezing time. It served as a basis for an accurate modeling of the thermal characteristics of the experimental set-up. For the numerical analyses, process variable values were chosen that best duplicated the experimental conditions. Heat transfer coefficient values were chosen in the mixed mode region based on values identified by Stuhrke and Wallace [30], Hong, et al [31], Riegger [32] and Papai and Mobley [17] as best representing the die casting process. Repeated iterative analyses were then performed in order to contrast the analytical predictions of BINORM with experimental results of the die casting campaign, in accordance with the objectives of this study.

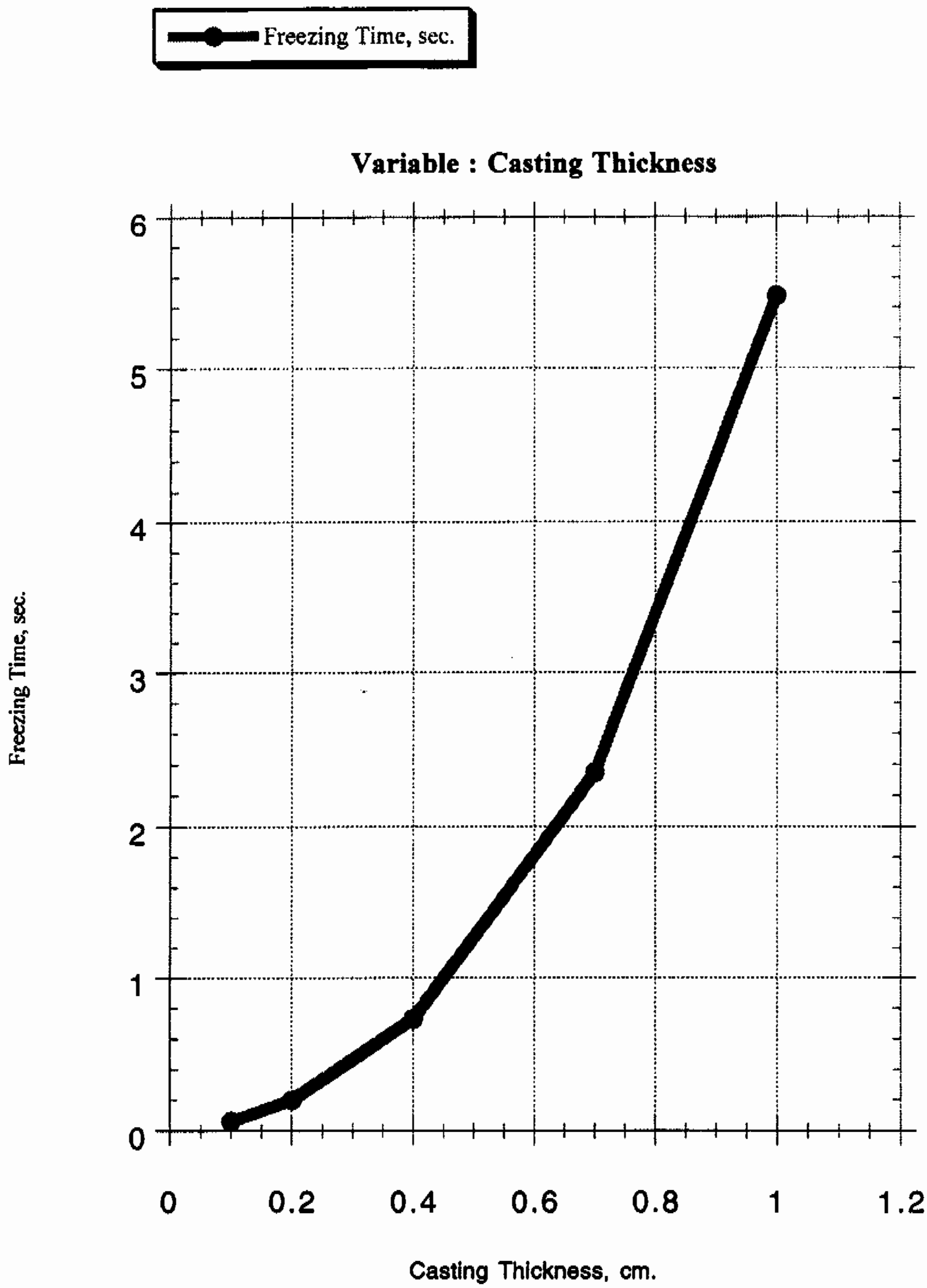


Fig. 4.18: Freezing Time Vs. Casting Thickness

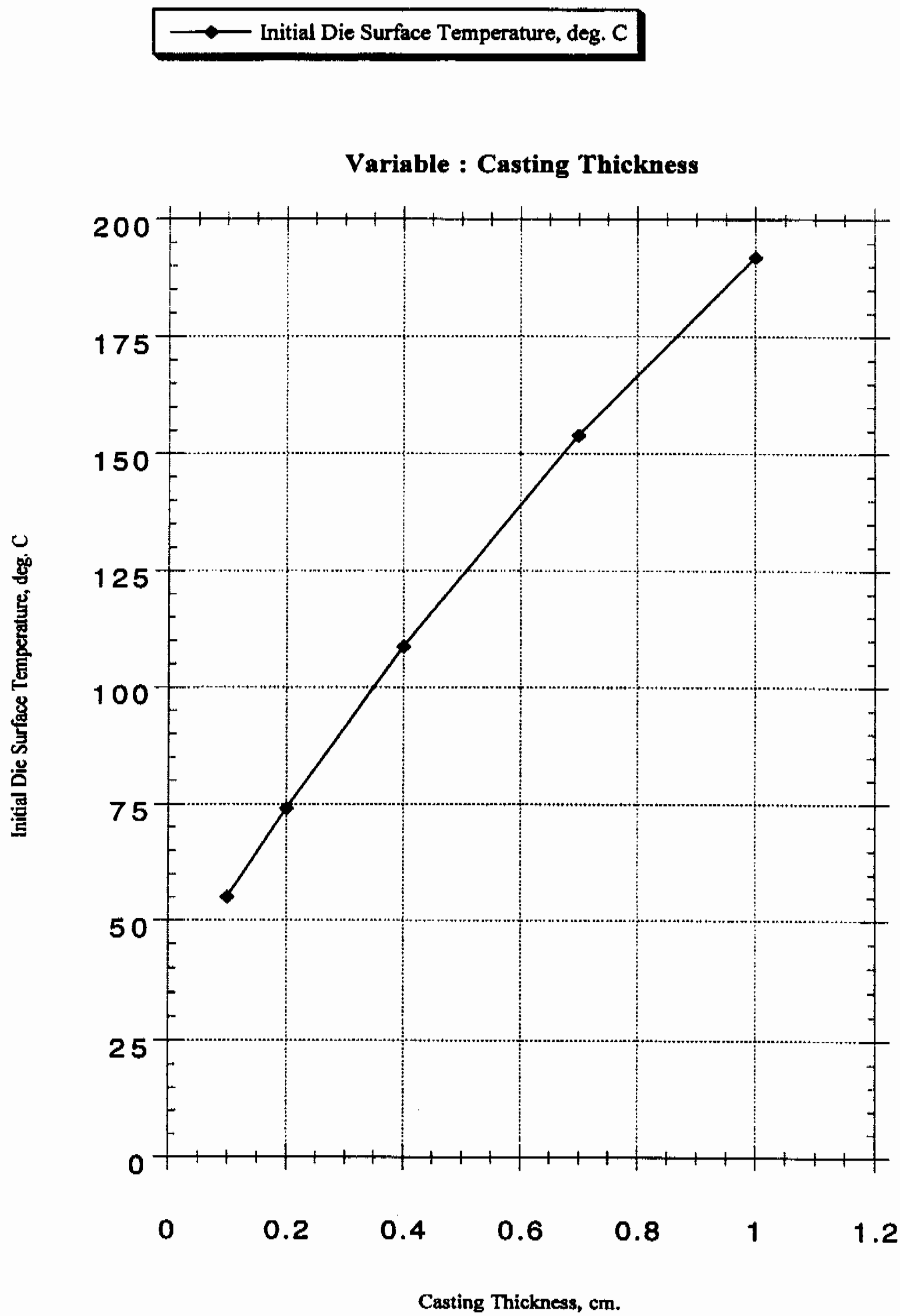


Fig. 4.19: Initial Die Surface Temperature Vs. Casting Thickness

CHAPTER 5

RESULTS

Introduction

The underlying objective of this study is to facilitate effective control of the die casting process. A two pronged approach was used to achieve this objective. The experimental approach aimed to address the problems in the measurement of process variables. The analytical approach attempted to identify a reliable method of determining the ideal values for the variables in a die casting process. These are essential requirements for an effective process control system as the process variables have to be first measured and then compared to the standard or ideal values before they can be adjusted to control the process.

The experimental approach concentrated on the measurement of in-cavity pressure and thermal characteristics under base line operating conditions. Kistler Instrument Co. direct pressure sensors were evaluated and utilized in the die casting campaign for cavity pressure measurement. Thermal pressure sensors using staggered thermocouples were developed and utilized for the simultaneous measurement of die surface temperatures and heat flow rate through the die. The pressure and thermal measurements were related to the injection characteristics measured using the shot control equipment of the Buhler H-250SC die casting machine used in the campaign.

The analytical approach concentrated on the verification of the predictions of a computer numerical solidification analyses, namely BINORM. Particular attention was paid to the predictions of freezing time and initial die surface temperature. A sensitivity analysis was performed to determine the effect of changes in individual variables on the freezing time and initial die surface temperature predictions.

Results

A die casting campaign was conducted on the Buhler H-250SC die casting machine using the wall die insert with the pressure and thermal probes mounted. The machine was programmed according to the results of the performed machine set-up analysis (Appendix C). Due to problems in the control of the injection pressure, no intensification pressure was applied and the injection pressure was set at 200 bars and not the calculated value. Also, the machine was run in the manual mode. Hence, the actual cycle times do not correspond to typical die casting cycle times. Further, quasi-steady state conditions were not reached. To facilitate correlation of measured data, all results shown are for the same shot.

Figures 5.1, 5.2 and 5.3 depict the output from the thermal probes A, C and D, respectively. Probe A was located at the gate in the ejector die half. Probe C was located in the cavity close to the gate in the cover die half. Probe D was also located in the cavity in the cover die half, but was farther from the gate. Probe B output was not considered as it was erroneous due to infiltration of molten aluminum between the probe insert and the

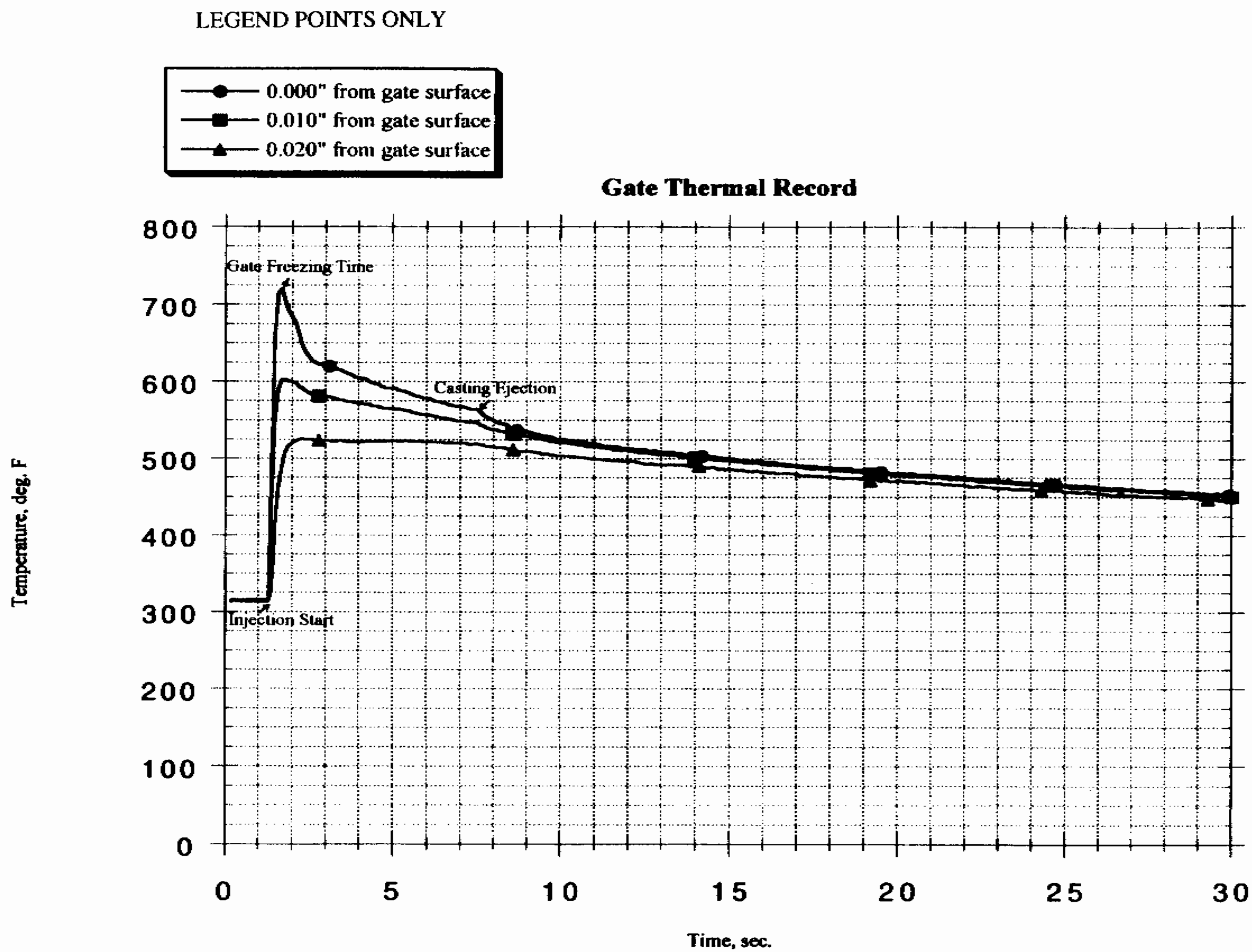


Fig. 5.1: Gate Thermal Record : Probe A

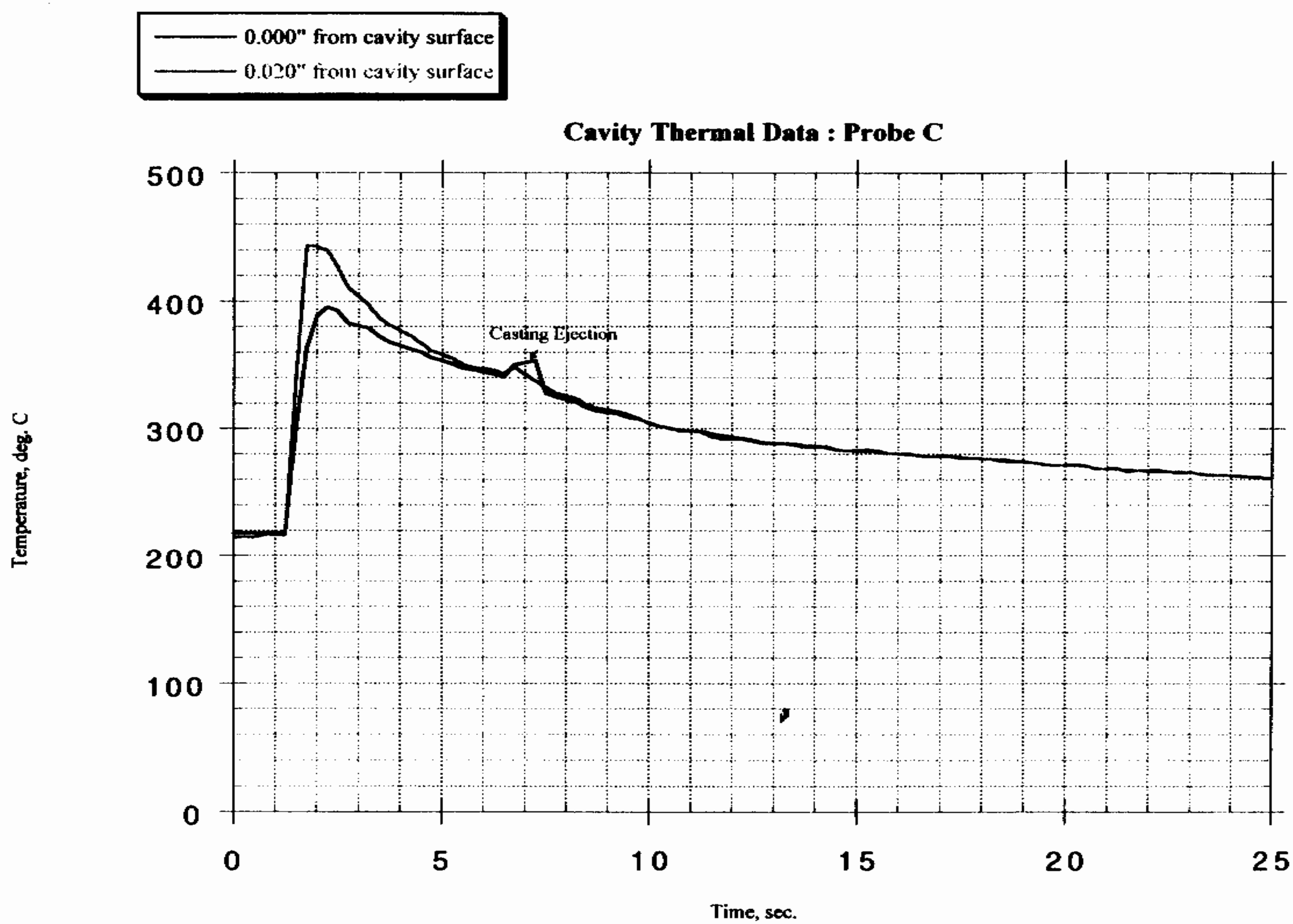


Fig. 5.2: Cavity Thermal Record : Probe C

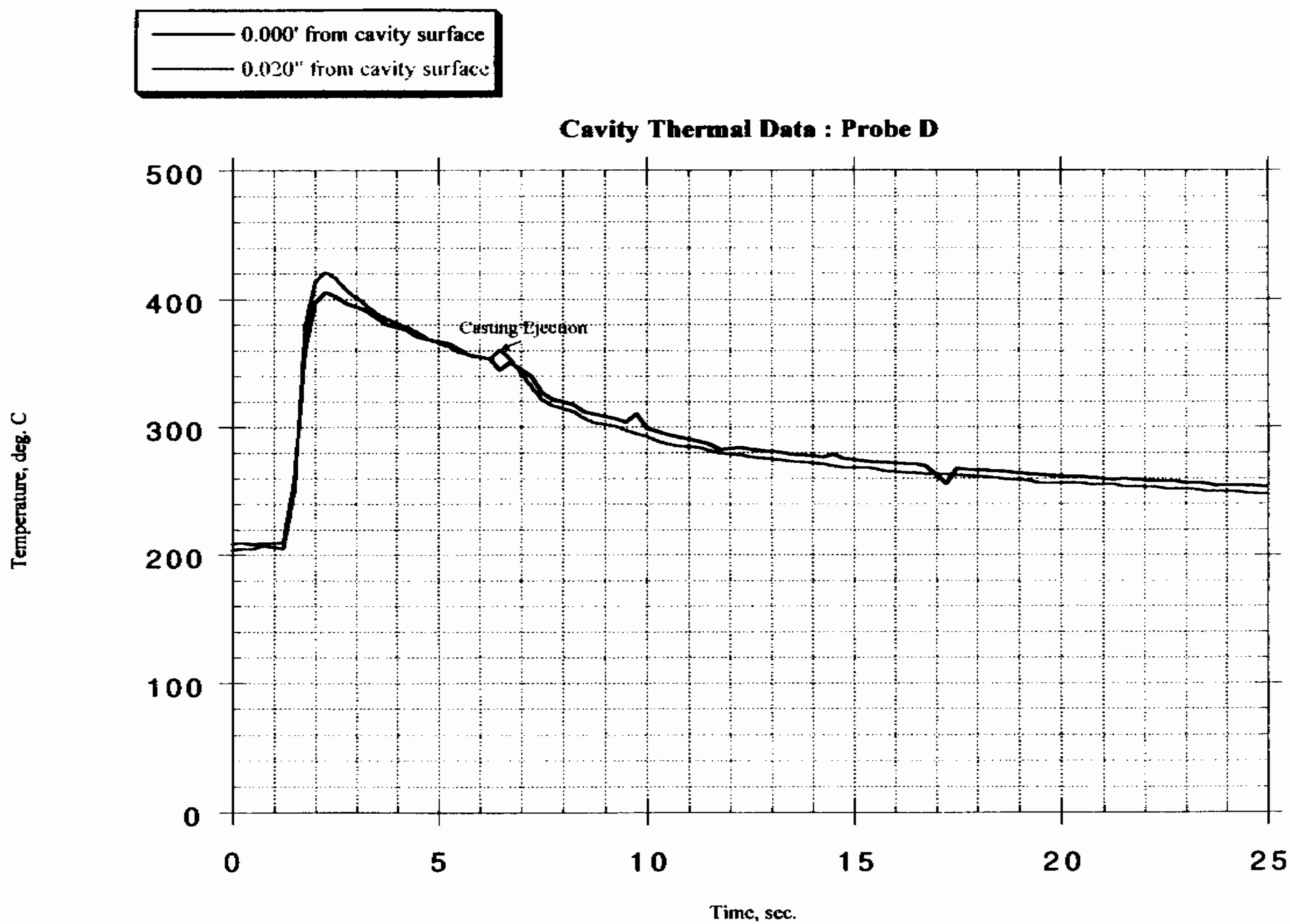


Fig. 5.3: Cavity Thermal Record : Probe D

sleeve, and into the thermocouple slots. The thermocouple located at 0.040" from the die surface in probe A was also not considered as the thermocouple tip had broken contact with the insert. Also, data were collected from only two thermocouples in probes C and D due to insufficient data acquisition channels. The thermocouples used were those located at the die surface and at 0.020" from the die surface.

It can be noted in Figure 5.2 and 5.3, that the surface thermocouples measure a lower peak value than the thermocouples located at 0.020" from the surface. This error can be attributed to the infiltration of the aluminum into the slot of the surface thermocouple and the formation of a new thermocouple junction at an unknown location further from the surface. The start of injection can be identified accurately in Figure 5.1 as the point when the thermocouples at the gate start measuring a rise in temperature. The freezing time of the aluminum in the cavity at any location can be identified as the instant when the surface thermocouple present at that same location reaches a peak and starts to record a fall in temperature. This has been proven by previous work and is due to the lack of availability of latent heat of fusion for transfer from the aluminum into the die. Since the surface thermocouple of probe A is the only effective surface thermocouple, only the freezing time at that location can be accurately identified using the experimental data. The gate freezing time was, hence, experimentally found to be 0.4 seconds. The die temperatures then decrease depending on the rate of heat transfer from the casting to the die.

The casting ejection instant can also be identified on Figures 5.1, 5.2 and 5.3 as that instant when the die cooling rate suddenly increases due to the exposure of the die surfaces to the atmosphere with the resultant heat transfer from the die to the atmosphere. The time difference between the casting ejection point indicated by probes C and D and that indicated by probe A is due to the manual operation of the die casting cycle. The die was first opened, leading to the exposure of the cover die half probes C and D to the atmosphere with the resultant increase in cooling rate. The casting was then ejected by the ejector pins, leading to the exposure of the ejector die half probe A with its resultant increase in cooling rate. The decrease in die temperatures with the spraying of lubricant is not seen as this was the last shot of that day in the campaign. A noticeable design defect is the deformation of the insert corners at the ends of the thermocouple slots due to the high cavity pressures. This results in the flow of aluminum into the slots with the resultant errors in temperature measurement. Also, the thermocouple-insert junction is not strong enough to withstand frequent and rough handling of the thermal probe and the thermocouple lead wires.

Figures 5.4 and 5.5 depict the output of the Kistler direct pressure probes 1 and 2, respectively. The probes start recording an increase in pressure when the metal enters the cavity. The probes measure an initial peak that is considered uncharacteristic of die casting. This was due to the loss of control of the applied pressure during injection, as shown by Buhler shot record (Figure 5.6). The pressure then decays to the programmed injection pressure of 200 bars until the gate freezes. Once the gate freezes, there is no external hydraulic pressure to maintain the cavity pressure at 200 bars. The pressure continues to decrease as the aluminum in the cavity freezes. The instant when the cavity freezes at any location can be identified as that point where the pressure measured at the same location reaches zero. The experimental pressure output gives a cavity freezing time of approximately 1.5 seconds.

One strange phenomenon of the pressure measurements is the "ringing" or oscillations in the Kistler pressure probe outputs. A uniform oscillation of 50 bars amplitude and 20 Hz frequency is noticed over the entire pressure measurement of both probes. Both the frequency and the amplitude remain constant throughout the measuring

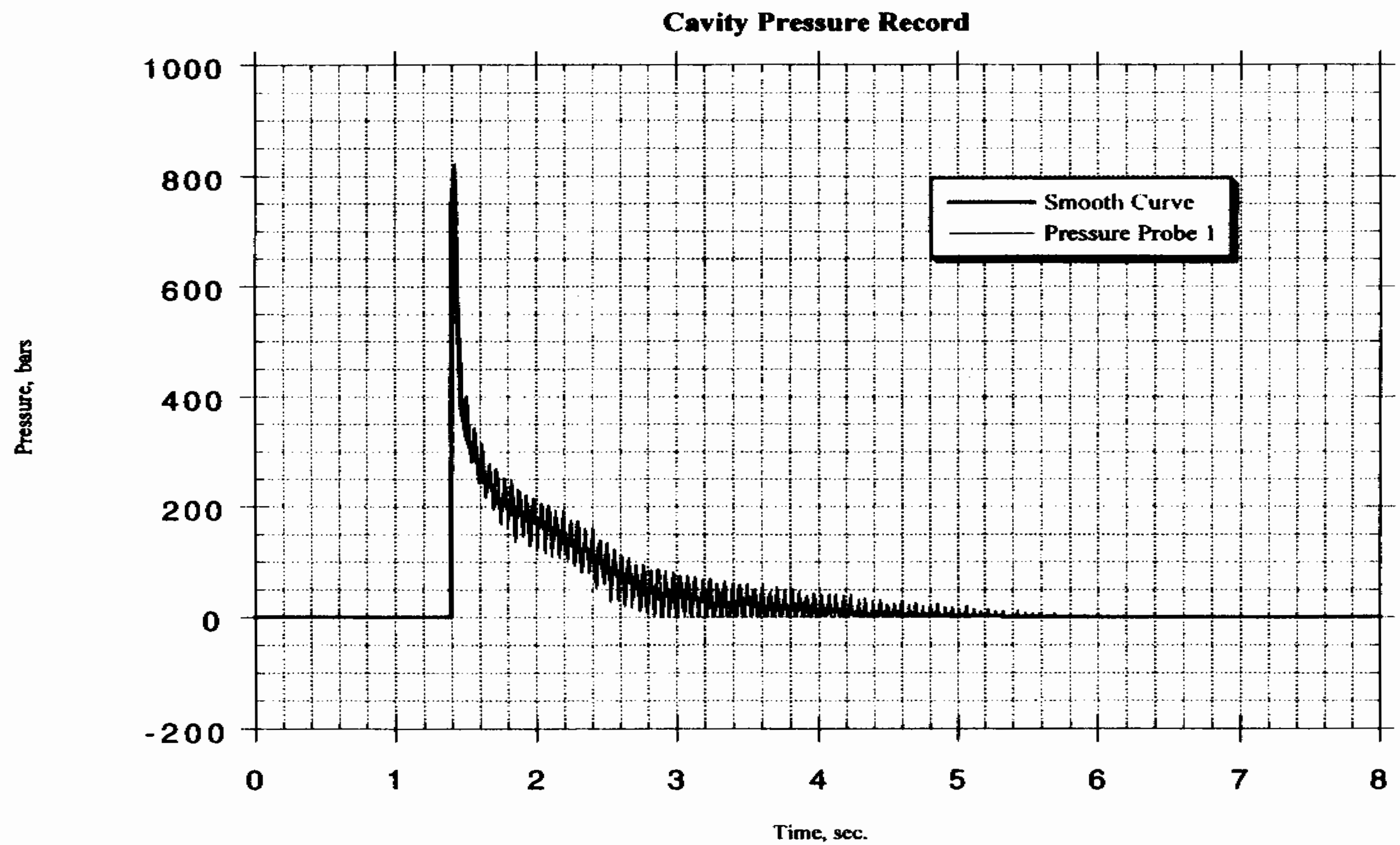


Fig. 5.4: Cavity Pressure Record : Kistler Probe 1

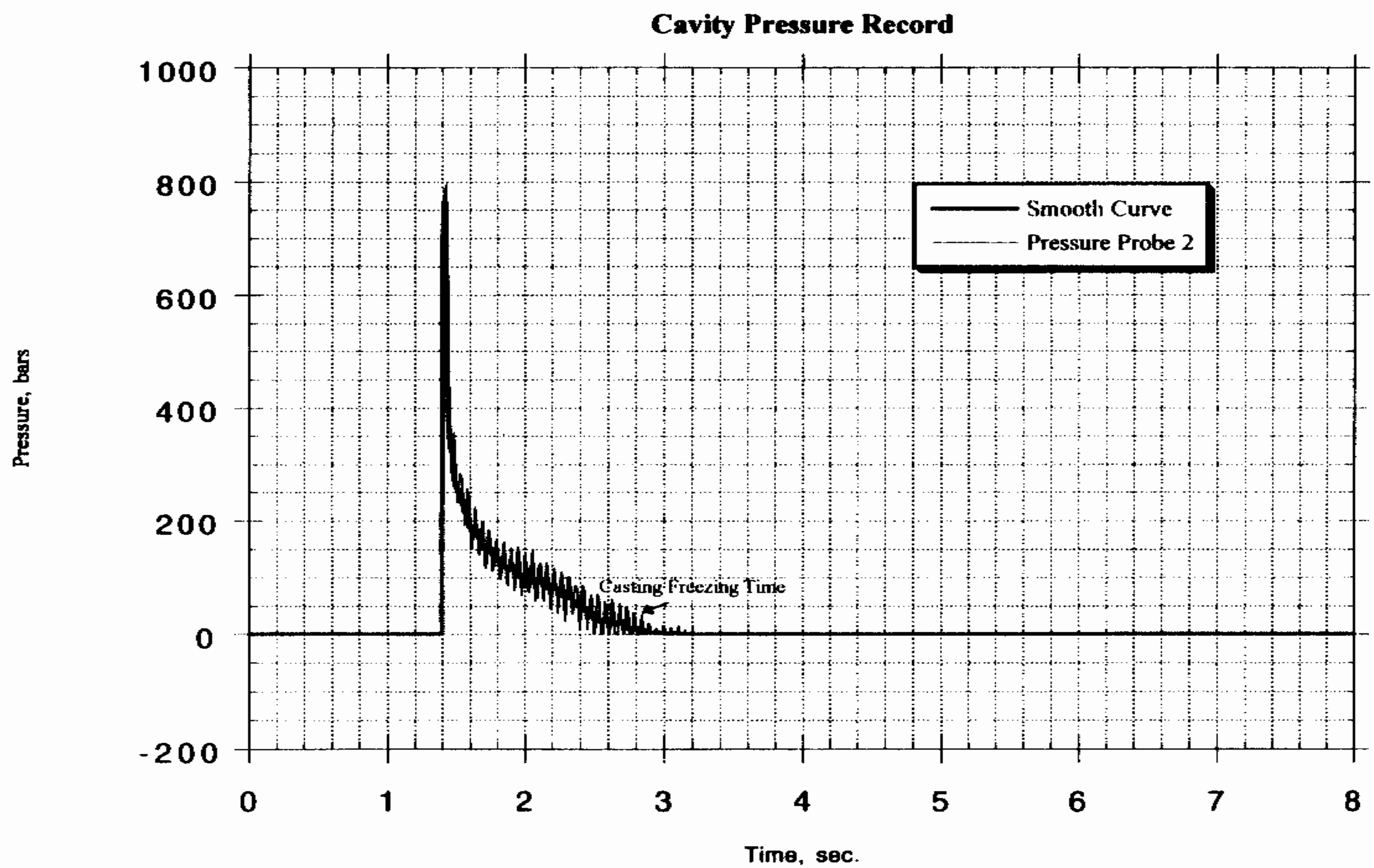


Fig. 5.5: Cavity Pressure Record : Kistler Probe 2

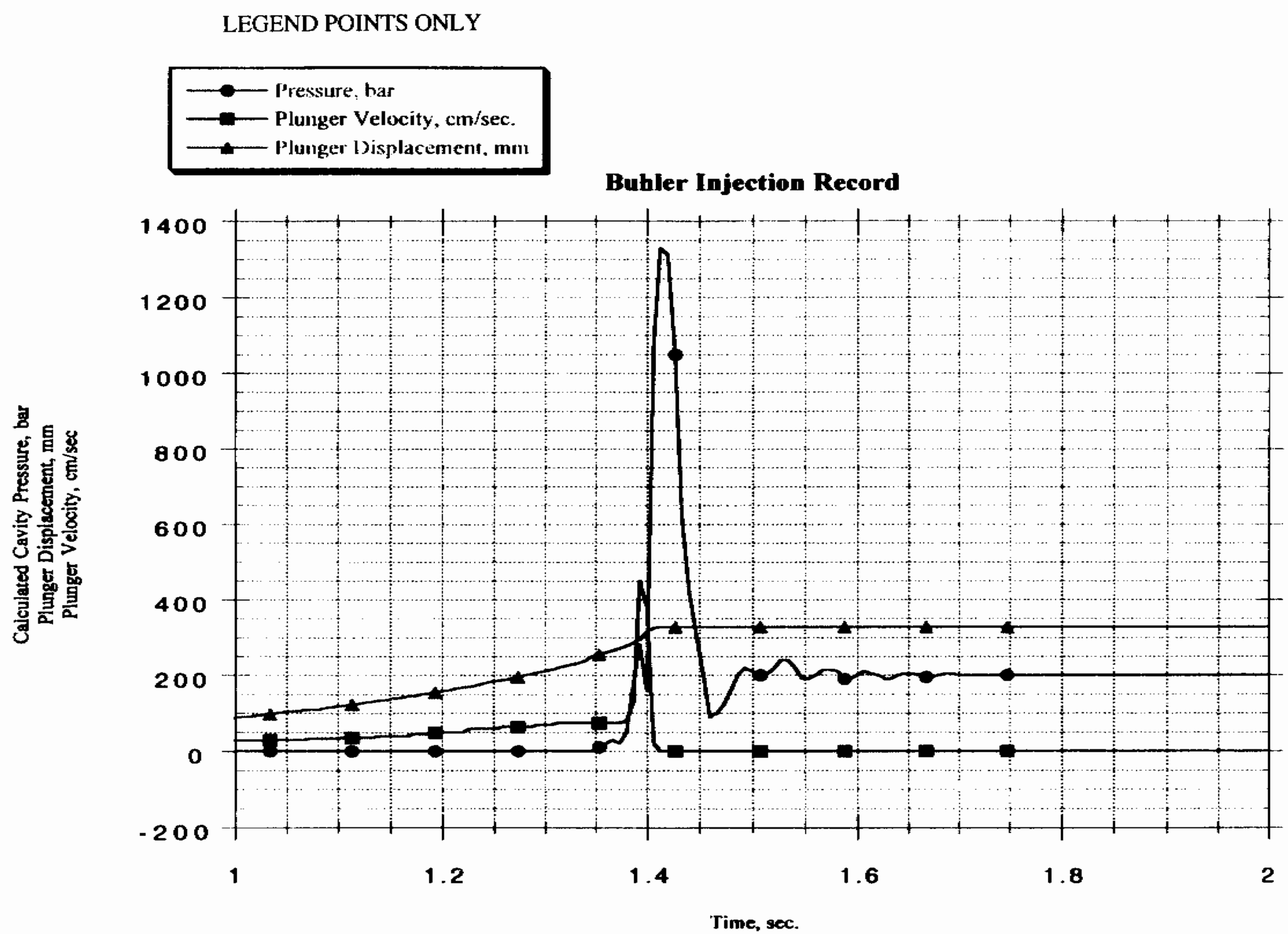


Fig. 5.6: Buhler Injection Record

period. Since the hydraulic pressure data does not display this oscillation and since it continues after the gate freezes, the oscillation is not thought to be a function of the applied pressure. It is not a characteristic of the probe circuitry as such oscillations were not noticed during the probe calibration. The frequency of oscillation also eliminates the possibility of interference due to electric currents. Pending further experimentation, this oscillation can only be attributed to the die casting process or its associated equipment. For comparison purposes, a smoothened curve passing through the mid point of these oscillations is taken.

Figure 5.6 depicts the shot profile record obtained from the Buhler shot control instrumentation. The pressure depicted here is the cavity pressure calculated as a function of the applied hydraulic pressure. The high pressure peak of 1330 bars is indicative of the loss of injection pressure control. The pressure then falls quickly to the programmed pressure of 200 bars. The velocity increases with constant acceleration during the slow shot to minimize air entrapment. As the metal reaches the gate, the plunger velocity increases rapidly to injection velocity before falling to zero when the plunger stops. The plunger displacement is representative of the movement of the plunger in the shot sleeve.

Figure 5.7 relates, on the same time scale, the die surface temperature at the gate, the cavity pressure as measured by the Kistler pressure probe 2 and the cavity pressure as calculated from the hydraulic pressure recorded by the Buhler. The injection can be seen to start at a little after 1.3 seconds. Both the pressure records reach their peaks at the same instant. The difference in the two peaks is due to the Buhler calculated pressure not taking into consideration the friction between the plunger tip and the shot sleeve. In this case, the high friction due to presence of aluminum between the plunger tip and the shot sleeve resulted in a comparatively large difference between the Kistler measured and Buhler calculated pressure peaks. The hydraulic pressure then falls rapidly to the

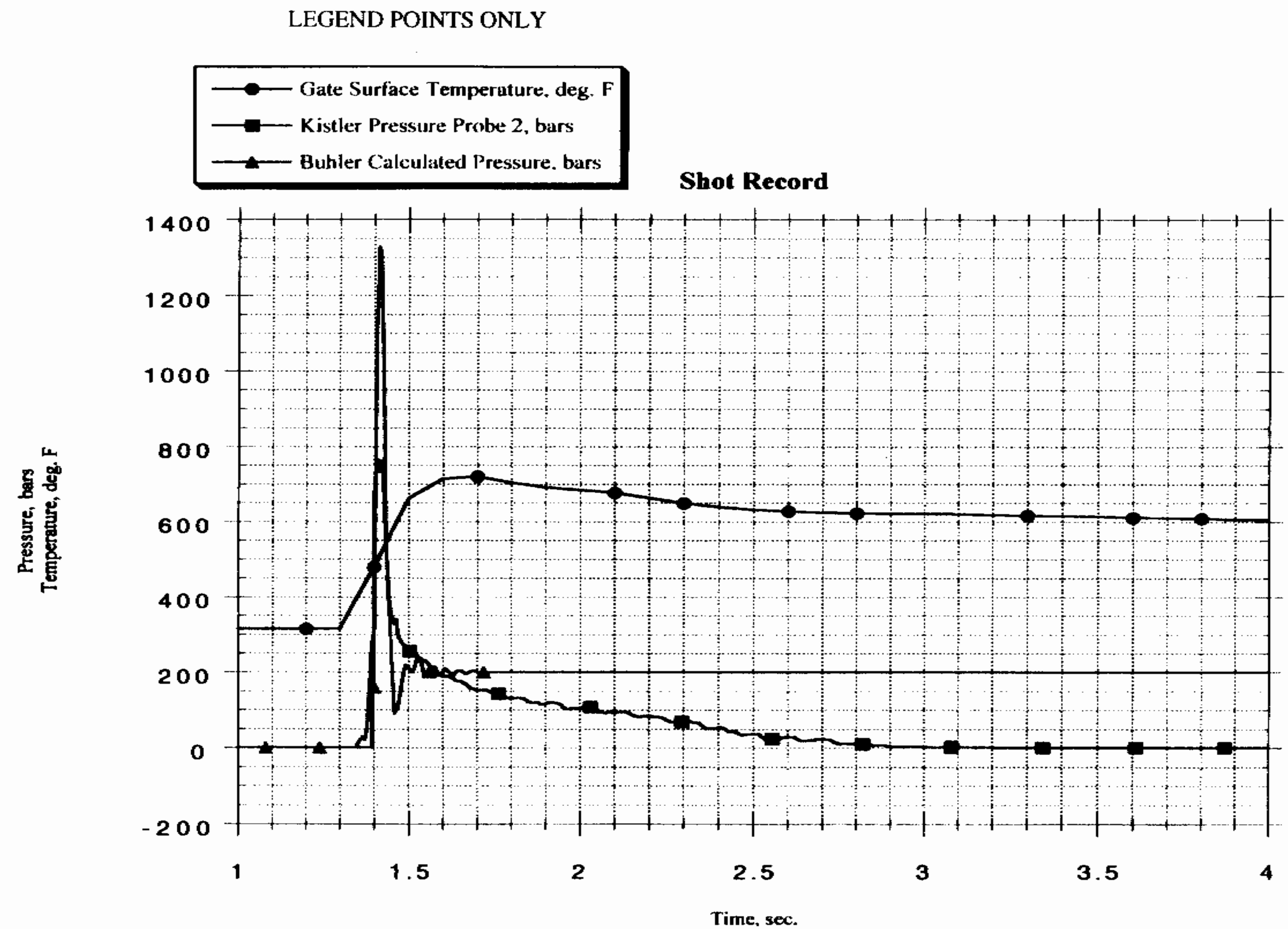


Fig. 5.7: Correlation of Measured Data

programmed 200 bars and remains constant. The Kistler pressure measurement falls rapidly to 200 bars until the gate freezes at about 1.7 seconds. The gate freezing is indicated by the peaking of the surface thermocouple at the gate. The Kistler pressure continues to fall as the cavity freezes. The instant when the Kistler pressure record reaches 0 bars gives the cavity solidification instant. This occurs a little before the 2.9 second mark. Hence, the gate and cavity freezing times are experimentally determined as 0.4 and 1.5 seconds, respectively.

BINORM was then used to simulate the experimental set-up. Process variable values that best represented the experimental conditions were used as input for the numerical analysis. Simulations were performed for both the gate and base plate thickness'. Figure 5.8 gives the input values used in the analytical approach. BINORM predictions of 0.45 and 1.55 seconds for the gate and cavity freezing times, respectively, correspond to the experimental gate and cavity freezing times of 0.4 and 1.5 seconds, respectively. Further the maximum temperatures of 435 deg. C and 465 deg. C predicted by BINORM at the gate and cavity die surfaces, respectively, correspond to the experimental maximum gate and cavity die surface temperatures of 390 deg. C and 440 deg. C, respectively.

Conclusions

The thermal probes were found to be effective and accurate but not rugged enough for the die casting conditions. The clearance between the insert and the carrier must be reduced to prevent the flow of aluminum into the thermocouple slots. In the case of the surface thermocouple, it might suffice to solder the thermocouple tip to the end of the insert after the probe has been assembled. Thereby, the solder itself can be used to seal the end of the slot. The soldered joint tended to break with frequent handling of the

```
CASTING IS 390 ALLOY (EXPERIMENTAL)
 CONDUCTIVITY OF CASTING  0.32000 + 0.00000000 *T
 DENSITY OF CASTING =              2.66000
 SPECIFIC HEAT OF CASTING =  0.20700 + 0.00000000 *T
 LIQUIDUS OF CASTING =             621.00000
 SOLIDUS OF CASTING =              500.00000
 HEAT OF FUSION =                128.29860
 LIQUID SPECIFIC HEAT =            0.26000
 DIE IS H13 HOT WORK, AIR HARDENABLE MARTENSITIC STEEL
 WITH ABOUT 5 WEIGHT PERCENT CHROMIUM
 CONDUCTIVITY OF DIE =   0.05870 +  0.0000086 * T
 DENSITY OF DIE =              7.70000
 SPECIFIC HEAT OF DIE =  0.11000 +  0.0000450 * T
 CASTING THICKNESS =               0.27178 CM
 DIE ONE THICKNESS =               5.40000 CM
 DIE TWO THICKNESS =               4.05000 CM
 NUMBER OF ELEMENTS IN CASTING =          8
 NUMBER OF ELEMENTS IN DIE ONE =         20
 NUMBER OF ELEMENTS IN DIE TWO =         20
 INITIAL SUPERHEAT =               60.0 DEG C
 THE INITIAL DIE ONE TEMPERATURE =     400.0 DEG C
 THE INITIAL DIE TWO TEMPERATURE =     315.0 DEG C
 THE AIR TEMPERATURE IS            35.0 DEG C
 THE COOLANT TEMPERATURE IS          175.0 DEG C
 H TO THE AIR =               0.00300 cgs UNITS
 H TO THE COOLANT FROM DIE ONE =    0.10000 cgs UNITS
 H TO THE COOLANT FROM DIE TWO =    0.10000 cgs UNITS
 H FROM THE CASTING TO DIE ONE =    1.09000 cgs UNITS
 H FROM THE CASTING TO DIE TWO =    1.09000 cgs UNITS
 DIE CLOSED TIME PER CYCLE =      30.00000 SECONDS
 DIE OPEN TIME PER CYCLE =       90.00000 SECONDS
 THE TOTAL NUMBER OF CYCLES SIMULATED IS   10
 HCONTACT AFTER AIR GAP FORMATION =   0.05000 cgs UNITS
 TEMPERATURE FOR AIR GAP FORMATION =  50.00000 DEG. C
 FROM 67.5 TO77.5 SECONDS AFTER DIE OPENING FOR DIE ONE
 FROM 52.5 TO67.5 SECONDS AFTER DIE OPENING FOR DIE TWO
 SPRAY AT A TEMPERATURE OF    30. DEGREES C
 CAUSING A HEAT TRANSFER COEFFICIENT OF
    0.1200 +   0.000001  TIMES TEMPERATURE
```

Fig. 5.8: Binorm input for simulation of experimental conditions

probe. To prevent this, the sheathing can be spot welded to the insert at several points, thereby reducing any structural stress on the thermocouple joint. Another design defect is the deformation of the slot ends, thereby allowing the aluminum to enter the slot. This can be easily eliminated by changing the design of the insert. This will, however, be at the expense of the spacing between thermocouples. It is not known, however, how many of these defects are due to the extreme operating conditions the probes were subjected to.

The identified Kistler direct pressure probes were found to be accurate and reliable and suitable for the die casting environment. They have survived extreme operating conditions and can be expected to perform suitably in the normal die casting environment. It has also been shown that the Kistler probe is not responsible for the phenomenon of oscillations.

The cavity pressure calculated, as a function of the measured plunger hydraulic pressure, by the shot control equipment of the Buhler die casting is not an accurate measure of the actual cavity pressure. This effectively eliminates the usefulness of the measured hydraulic pressure in process control.

The BINORM model is an accurate instrument for predicting thermal conditions in die castings with simple cross sections. Considering its other advantages, like short computational times, it can be used in the industrial environment for shop floor process design. An accurate prediction of the freezing time, for example, can be useful in determining the casting cycle times and the time to apply intensification pressure.

Future Research

This is only the first step in the development of a reliable die casting process monitoring equipment. A lot of subsequent work is necessary to make it possible and practical. Design alterations of the thermal probes have to be made to make them, and more importantly the surface thermocouple, more rugged. Both the thermal probes and the Kistler pressure probes have to be evaluated in industrial conditions. The cavity pressure and thermal characteristics have to be measured for different programmed process variables. The casting quality should be quantified by means of measurables, like surface finish, porosity extent and distribution, pressure tightness, total gas content, etc., and related to the pressure and thermal characteristics. Variations in process parameters must be related to the casting quality. The flow of gas through the vents must also be measured and related to the casting quality together with the pressure and thermal characteristics. These steps will help develop a system for effective die casting process control with a corresponding increase in the quality of die cast components.

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APPENDIX A

NADCA SURVEY OF DIE CAVITY INSTRUMENTATION

NADCA

North American Die Casting Association

9701 West Higgins Road
Suite 880
Rosemont, IL 60018-472
708.292.3600 Telephone
708.292.3620 Fax

NADCA® SURVEY ON DIE CAVITY INSTRUMENTATION

1. a. How many cold chamber die casting machines are in your plant? ______
   b. How many hot chamber die casting machines are in your plant? ______
2. a. How many cold chamber die casting machines is your plant currently operating? ______
   b. How many hot chamber die casting machines is your plant currently operating? ______
3. Do you have the capability of measuring the plunger position and velocity and cylinder pressure as a function of time during a shot? ☐ Yes ☐ No
4. Do you record plunger position and velocity and cylinder pressure?

   ☐ Every shot ☐ Every ______ shots

   ☐ Only during setup or when there is a problem with the process
5. How many dies that you use are instrumented with thermocouples? ______
6. Do you record the die thermocouple response as a function of time during a shot?

   ☐ Every shot ☐ Every ______ shots

   ☐ Only when there is a problem with the die or process
7. During a die use campaign, do you record die coolant temperature?

   ☐ Continuously ☐ Intermittently ☐ Never
8. During a die use campaign, do you record die coolant flow rate?

   ☐ Continuously ☐ Intermittently ☐ Never
9. Have you or do you make temperature or pressure measurements in or near the die cavity as part of your process monitoring or control? ☐ Yes ☐ No
10. Do you utilize any instrument or measurement device to monitor the extent to which the die cavity vents are open or functioning? ☐ Yes ☐ No
11. Do you use any method or device to measure the amount of gas removed from the die cavity during filling?

    ☐ Yes ☐ No
12. What instrumentation devices have you used to make die cavity or near die cavity process measurements?

    ☐ Thermocouples ☐ Transducers

    ☐ Strain Gauges ☐ Other *(Please explain)*: ______
13. Where or how did you obtain the die cavity instrumentation devices or units? For example, were they purchased as a complete unit from a commercial supplier or constructed from components by your engineering staff?

    ______

    ______

(over)

NADCA® SURVEY ON DIE CAVITY INSTRUMENTATION *(continued)*

14. If the die cavity instrumentation devices or units were obtained from a source outside your die casting facility, please give us the supplier's name and phone number or, whom at your company we can call for the information.

____

____

15. Were the die cavity instrumentation devices used to continuously monitor your process or as a means of solving a die design or part production problem?

____

____

16. What are the major capabilities and limitations of the die cavity instrumentation devices that you have used?

____

____

If you wish your company to remain anonymous, please skip questions 17 and 18.

17. As a member of NADCA, would you like to participate in the NADCA Process Technology Task Group die cavity instrumentation project? ☐ Yes ☐ No

☐ Please contact me about participation on the NADCA Process Technology Task Group.

18. Please provide the name of the individual completing this survey and your company's address, telephone and/or fax number:

Individual's Name: ______________________________

Company Name: ______________________________

Company Address: ______________________________

____

____

Company Phone: ______________________________

Company Fax: ______________________________

Please return your completed survey to:

Attention: Professor Carroll Mobley
c/o Ohio State University
Dept. MSE
Fontana
116 West 19th Avenue
Columbus, Ohio 43210
Fax: (614) 292-1537

APPENDIX B

TECHNICAL SPECIFICATIONS OF BUHLER H-250SC

TECHNICAL DATA (subject to modification without notice) BÜHLER

Horizontal Cold-Chamber Die Casting Machine H-250SC

Locking force (strain gauge tested)...................... kN		2850
Injection force, consolidation phase adjustable (dynamic) kN		280 - 55
Plunger stroke.. mm		380
Shot positions (standard)............................... mm		0, -50, -100, -150, -200
Ejection force.. kN		170
Ejector stroke (adjustable)............................. mm		120
Dimensions of fixed die platen (H x V).................. mm		840 x 947
Dimensions of moving die platen (H x V)................. mm		840 x 840
Clearance between the tie bars.......................... mm		550 x 550
Diameter of tie bars.................................... mm		95
Die height min. .... mm		200
Die height max. .... mm		650
Stroke of moving die platen............................. mm		560
Rated installed power................................... kW		30
Machine area L x W (incl. safety gate).................. m		5,9 x 2.3
Machine height.. m		2.5
Machine weight, ready for production.................... kg		10700
DATACESS SC control cabinet L x W x H................... m		1.8 x 0.5 x 2.5
and DATACESS SC power cabinet L x W x H................. m		0.8 x 0.5 x 2.0

Production data

Plunger diameter	mm	40	45	50	55	60	70	80	90
Theoretical shot volume (DIN 24480)	cm3	318	402	497	601	716	975	1273	1611
Max. shot weight for Al*	kg	0.9	1.1	1.4	1.7	2.0	2.75	3.6	4.5
Max. specific injection pressure	bar	2230	1760	1430	1180	990	730	560	440
Max. projected area**	cm2	128	162	200	241	288	390	509	648

* The max. shot weight is calculated as follows:
plunger stroke x plunger area x 0.75 x density

	Al	Zn	Mg	Cu
Density of g/cm3	2.5	6.25	1.63	8.0

** Max. theoretical projected area at max. specific injection pressure, without consideration of core locking and dynamic part of injection process.

APPENDIX C

MACHINE SET-UP ANALYSIS

Measured Plunger Diameter = 49.2 mm = 1.937 inch

Hydraulic Cylinder Diameter = 145 mm = 5.709 inches
(Page 2/33, Buhler Manual 1)

Hydraulic Cylinder Diameter / Measured Plunger Diameter = 2.947

Recommended Gate Velocity = 1400 inches/sec
(NADCA Guidelines)

Measured Gate Area = 0.32 $inch^2$

Volumetric Flow Rate = Gate Velocity * Gate Area = 504 $inch^3$/sec

Measured Cavity (i.e. casting + overflow) Volume = 6.1 $inch^3$

Cavity Fill Time = Cavity Volume / Volumetric Flow Rate
= 12.1 ms

Measured Total Casting (i.e. biscuit + runner + gate + casting + overflow) Volume
= 11.05 $inch^3$

Measured Shot Sleeve Length = 14.055 inches

Calculated Shot Sleeve Volume = $\pi/4$*(Plunger Diameter)^2*Shot Sleeve Length
= 41.44 $inch^3$

Percent Shot Sleeve Fill = 100 * Total Casting Volume / Shot Sleeve Volume
= 26.67 %

Calculated Injection Pressure	=	$(d/D)^2 * \rho * V_g^2 / 2 * g * C_D^2$
	=	70.64 psi

where

d	=	Plunger Diameter, inch
D	=	Hydraulic Cy;inder Diameter, inch
ρ	=	Alloy Density, $lb/inch^3$ = 0.087 $lb/inch^3$
V_g	=	Gate Velocity, inch/sec
g	=	Gravitational Acceleration, $inch/sec^2$ = 386 $inch/ sec^2$
C_D	=	Gate Coefficieny of Discharge = 0.6

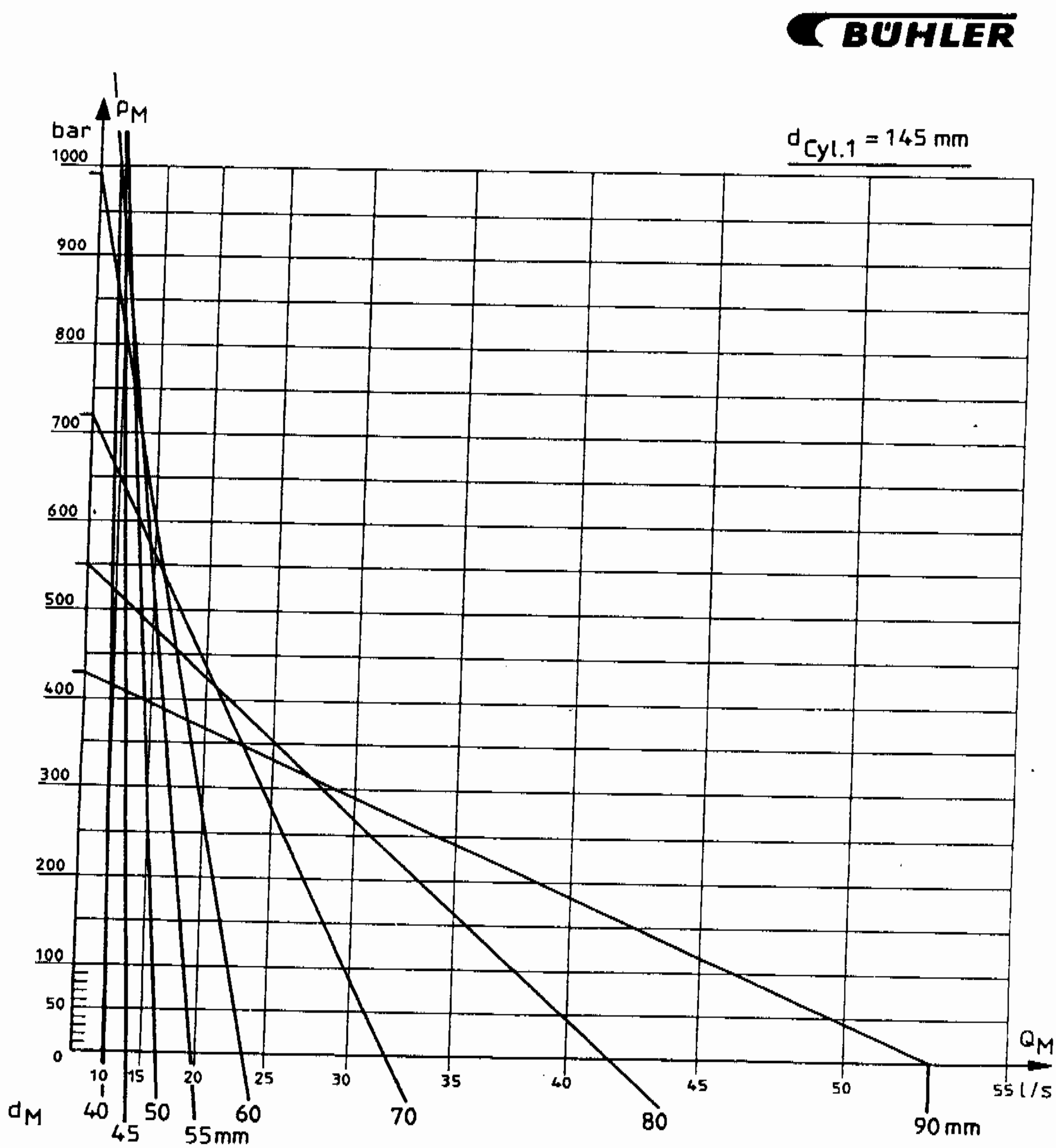
Intensification Pressure	=	20 * Injection Pressure = 1412.8 psi
Projected Area of Casting	=	44.95 $inch^2$
Locking Force	=	Projected Area of Casting * Intensification Pressure
	=	63505.36 psi
Plunger Cross Sectional Area	=	$\text{Plunger Diameter}^2 * \pi / 4$
	=	2.948 $inch^2$
Fast Shot Velocity	=	Volumetric Flow Rate / Plunger Cross Sectional Area
	=	170.96 inch/sec

Slow Shot Profile (Thome Model : Straight Line Acceleration)

Plunger Position, inch (m)	Plunger Velocity, inch/sec (m/sec)
0 (0)	0 (0)
9.07 (0.23)	24.98 (0.63)
10.31 (0.26)	24.98 (0.63)
11.19 (0.28)	170.96 (4.34)
13.26 (0.34)	170.96 (4.34)

APPENDIX D

PQ^2 ANALYSIS



APPENDIX E

BINORM : Base Line Process Variables

```
CASTING IS 390 ALLOY (EXPERIMENTAL)
 CONDUCTIVITY OF CASTING  0.32000 + 0.00000000 *T
 DENSITY OF CASTING              =      2.66000
 SPECIFIC HEAT OF CASTING        =      0.20700 + 0.00000000 *T
 LIQUIDUS OF CASTING             =      621.00000
 SOLIDUS OF CASTING              =      500.00000
 HEAT OF FUSION                  =      128.29860
 LIQUID SPECIFIC HEAT            =      0.26000
 DIE IS H13 HOT WORK, AIR HARDENABLE MARTENSITIC STEEL
 WITH ABOUT 5 WEIGHT PERCENT CHROMIUM
 CONDUCTIVITY OF DIE             =      0.05870 +  0.0000086 * T
 DENSITY OF DIE                  =      7.70000
 SPECIFIC HEAT OF DIE            =      0.11000 +  0.0000450 * T
 CASTING THICKNESS               =      0.40000 CM
 DIE ONE THICKNESS               =      5.08000 CM
 DIE TWO THICKNESS               =      5.08000 CM
 NUMBER OF ELEMENTS IN CASTING       =      8
 NUMBER OF ELEMENTS IN DIE ONE       =      20
 NUMBER OF ELEMENTS IN DIE TWO       =      20
 INITIAL SUPERHEAT                   =      10.0 DEG C
 THE INITIAL DIE ONE TEMPERATURE     =      25.0 DEG C
 THE INITIAL DIE TWO TEMPERATURE     =      25.0 DEG C
 THE AIR TEMPERATURE IS                     35.0 DEG C
 THE COOLANT TEMPERATURE IS                 35.0 DEG C
 H TO THE AIR                        =      0.00300 cgs UNITS
 H TO THE COOLANT FROM DIE ONE       =      0.10000 cgs UNITS
 H TO THE COOLANT FROM DIE TWO       =      0.10000 cgs UNITS
 H FROM THE CASTING TO DIE ONE       =      1.09000 cgs UNITS
 H FROM THE CASTING TO DIE TWO       =      1.09000 cgs UNITS
 DIE CLOSED TIME PER CYCLE           =      15.00000 SECONDS
 DIE OPEN TIME PER CYCLE             =      25.00000 SECONDS
 THE TOTAL NUMBER OF CYCLES SIMULATED IS    50
 HCONTACT AFTER AIR GAP FORMATION          =      0.05000 cgs UNITS
 TEMPERATURE FOR AIR GAP FORMATION         =      50.00000 DEG. C
 FROM 15.0 TO20.0 SECONDS AFTER DIE OPENING FOR DIE ONE
 FROM 15.0 TO20.0 SECONDS AFTER DIE OPENING FOR DIE TWO
 SPRAY AT A TEMPERATURE OF                        35. DEGREES C
 CAUSING A HEAT TRANSFER COEFFICIENT OF
    0.1200 +   0.000001  TIMES TEMPERATURE
```