Process Optimization of Plastic Injection Molding for Minimal Residual Stress

by

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Submitted to the Sloan School of Management and the Department of Mechanical Engineering in partial fulfillment of the requirements for the degrees of:

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and
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Abstract

This thesis summarizes the progress made in developing a procedure to optimize a plastic injection molding process by minimizing the dimensional instability of a critical feature. It documents the steps taken by a development team at the Visteon facility in Belfast, Northern Ireland to apply Design of Experiments (DOE) in process research for the production of a plastic throttle body. The team demonstrated the feasibility of using designed experiments to understand the effects of five main process parameters; melt temperature, injection speed, hold pressure, mold temperature, and cooling time, on the deformation caused by thermal cycle exposure. The experiment results and analysis were successful in establishing a prediction model for the critical dimensions of the component before and after thermal exposure. The prediction model and additional testing indicated that adjustments to the process would reduce the dimensional shift of the bore radius by over fifty percent. The thesis stresses the use of a team approach and the application of analytical methods to better understand the process. The report also includes a brief discussion of the use of Computer Aided Engineering (CAE) techniques to improve the product development process.

Thesis Advisors:
Roy Welsch, Professor of Statistics and Management Science
David Hardt, Professor of Mechanical Engineering

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I am grateful to Visteon of Ford Motor Company and all my colleagues at the Belfast Plant that made my internship such a rich learning experience. In particular, I extend my gratitude to Vince Trupiano and Alex Connor for their interest in the project, and to Gordon Stephens, Eoin O'Neill and Kevin Agnew for sharing their time, experience, and knowledge. Their friendship and the "craic" will not be forgotten.

I would also like to thank my advisors, Roy Welsch and Dave Hardt, for their support and guidance throughout my internship. They helped me to explore complex issues and develop the scope of this thesis.

Most of all, I wish to thank my family and friends for the love and support they have always given me. In a world that changes so quickly I am fortunate that some things do remain the same, I can always count on them.

I dedicate this thesis to my father, Chester G. Bazel, and my brother-in-law, Martin A. Gallogly, both of whom succumbed to cancer. Fond memories of them will always live in my heart. Through their perseverance and courage, I better appreciate how precious life is and have a new perspective on life's challenges.

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1.0 Introduction

Technological changes effect every business. Companies capable of quickly adapting new technologies gain competitive advantages in their industries while companies resistant to change find themselves struggling to survive. In order to remain competitive in the automotive components industry, Visteon has identified strategic process technologies to develop in order to align capabilities with trends in the industry. Plastic injection molding technology is one area in which they are focusing.

The use of plastic is a growing trend for the automotive components industry, however there are many challenges in adapting the technology, especially for the demanding environment under the hood of an automobile. One major challenge in the development of precision plastic injection molded components is the dimensional instability, also known as creep. Plastic is a viscoelastic material that subtly changes shape over time to relieve stresses. These stresses are attributed to residual stress from the manufacturing process as well as loads applied during assembly and usage of the component. Assembly and service loads are typically accounted for during the component design phase, however residual stresses are hidden loads that are much more difficult to account for during product development.

This thesis summarizes efforts taken to minimize dimensional instability due to residual stress in a plastic injection molded component, and it will outline a process used to better understand the effects of molding process parameters on residual stress. The process for evaluation was developed through previous development work and experimentation at the Visteon Belfast Plant of Ford Motor Company. The results demonstrate the feasibility of using design of experiments (DOE) to establish process settings to reduce deformation of critical design features due to residual stresses relieved during thermal cycling.

1.1 The Use of Plastic

There has been an explosive growth in the use of plastics in the design and development of new products and redesign of existing ones. In many cases plastic offers advantages over metal such as: weight reduction, part consolidation, corrosion resistance and cost reduction. Plastic material suppliers report annual growth of 20 to 25 percent the last several years led by metal-replacement applications (*Grande. 9*). This trend is likely to continue as new materials with improved performance and processing capabilities are developed.

Companies developing plastic components must stay abreast of this dynamic industry in order to leverage the latest developments in material, manufacturing processes and equipment as well as improvements in predictive analysis tools for component and tooling designs. Material prices and availability are constantly fluctuating due to supply and demand, therefore material selection criteria must be evaluated regularly. Injection molding capabilities are being influenced by the use of computers that monitor and control the equipment and the process. The advancement in computer technology has also resulted in significant strides in the predictive analysis tools for injection molding product and tooling development.

Plastic component designers and manufacturers must overcome several challenges in converting designs to plastic. The quality of the plastic part is dependent on the type of material, the tooling and the processing parameters, as shown in Figure 1-1. Balancing the development of these areas of the process to achieve the desired dimensions can be a difficult task. The many interactions between each of these areas of development is so complex it is not possible to evaluate each independently.

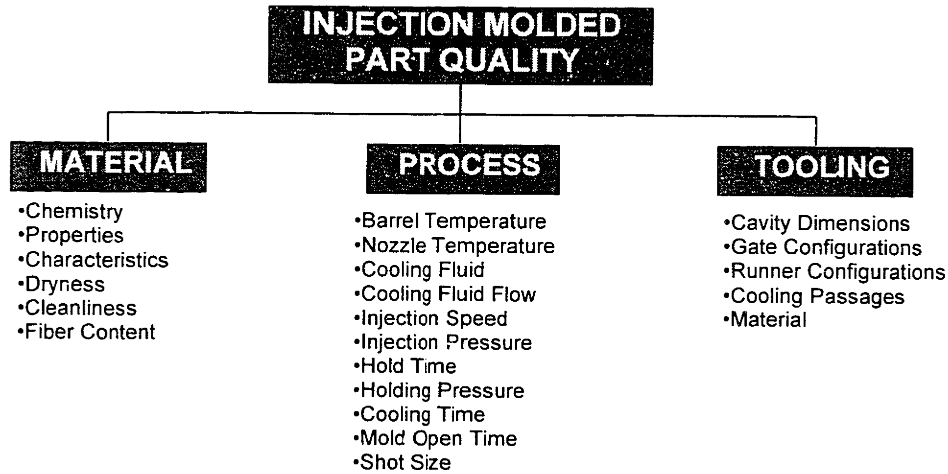

Figure 1-1. Influences on Part Quality.

1.2 Goals and Motivation

Visteon has recognized the increasing trend towards the use of plastic under-the-hood components. In order to remain competitive as an engine component supplier, the Visteon Belfast Plant has invested heavily in capital equipment and process development in plastic injection molding. The general goal of the division is to continuously improve their level of competence in plastic injection molding. In support of this goal the company plans to apply analytical methods to:

- better understand the process and identify the optimal process conditions
- improve the precision and performance of their products
- reduce the tooling development time

A more specific goal of the plastic group is to evaluate the impact the process has on the dimensional stability of the plastic throttle body. Thermal cycling of the throttle body assembly causes a shift in the airflow characteristics, known as "ambient creep." With a better understanding of how the process parameters effect the deformation of the part during thermal cycle, Visteon may be able to optimize the process and tooling designs to use common materials such as PBT (polybutylene terephthalmite) rather than switching to a higher cost, amorphous plastic.

Establishing the process parameters by minimizing residual stress will improve the dimensional stability of the part. A precision component must not only meet the stringent in-house quality checks, it must remain within tolerance over its desired service life providing consistent performance over time.

Another objective of the project is to investigate the use of analysis tools such as computer aided engineering (CAE) software to predict shrinkage and warpage for molded components. Effective use of these tools may minimize the tool development time.

The Visteon Belfast Plant is motivated by the potential of future business in plastic injection molded engine components. They are striving to be the best in the development of air/fuel components so they can market their abilities to obtain new business.

1.3 Summary of Research

The use of designed experiments in the development of the injection molding process has proven to be a feasible means of reducing the dimensional instability of critical features due to residual stress. Variations in the amount of deformation that occurred as a result of thermal cycle testing correlate to the injection molding machine settings. Optimal process parameters set to minimize this deformation reduce the amount of dimensional shift by over 50 percent. DOE has proven to be a powerful tool in understanding the injection molding process and its effect on the component dimensions.

1.4 Thesis Overview

The following chapters of this thesis will provide further background on the company, the process and the product. The application of the designed experiments will be reviewed in detail. Final chapters will review of use of engineering analysis software and define the conclusions.

The second chapter provides some background on Visteon and the Belfast Plant. It illustrates the competitive environment of the industry and defines the situation in the plant when the research was being conducted.

The third chapter gives details about the product that was manufactured during the designed experiments. Understanding the product, the process and the company helps set the stage for the research.

The fourth chapter contains a general overview of the process for those not familiar with plastic injection molding. It outlines the stages of the process and some details about the equipment.

The fifth chapter outlines a process used to set up and execute the designed experiments. The details of the results and products of the analysis are presented.

The sixth chapter reviews the benefits of using computer aided engineering (CAE) software in the development of the design, tooling and process for manufacture of a plastic injection molded component.

The seventh chapter presents the conclusions of the study and recommendations for future work.

2.0 Background

2.1 Introduction

The following sections will provide an overview of the Visteon environment at the time this thesis was written. This will include descriptions of the company and the plant to provide background as to the industry and the company's situation. The final section of this chapter will review the team approach for the project.

2.2 Visteon

Ford Motor Company established Visteon as a separate entity in September of 1997. At the time of this writing Visteon is an enterprise of Ford, however there have been several predictions that the company will separate in the future (*Tait, 25*). The objectives of the distinction between the automotive and supplier businesses are:

- to make each section of the company more competitive
- to allow Visteon to better establish itself as an independent supplier to sell components to other automobile companies
- to allow Ford to establish itself as an independent purchaser of components
- to separate the businesses for independent valuation of the stock

The competitiveness of the automotive supplier industry and the pending separation of Visteon has put additional pressure on the company to further improve the quality of their products while reducing costs to ensure its success independent of Ford Motor Company.

2.3 The Belfast Plant

In 1964 Ford purchased the Belfast Plant from a carpet manufacturer and converted the premises to an automotive components division. At that time the British government was offering employment grants to encourage investment in the city (*Ford 7*). They developed an expertise in carburetor and distributor design and manufacturing, but with the evolution of engine technology this product become obsolete in the mid-1980s, forcing the plant to switch to the production of oil and water pumps and fuel rail assemblies. The evolution of its product lines and process technology shows the flexibility of the organization to adapt to the changing business environment.

Today the Belfast Plant produces approximately 4.4 million components per year (*Visteon Website, 26*). The product portfolio consists of oil and water pumps, fuel injection assemblies and throttle modulators. Over the past year the organization has been challenged by the aggressive launch of five new products into the production lines.

The plant has approximately six hundred workers with a strong union presence. The ratio of hourly to salary employees was approximately four to one at the time of the writing of this thesis. The Visteon Belfast plant offers one of the most competitive salaries within the city and attracts a highly skilled workforce.

2.4 The Team Approach

Visteon management has expressed the desire for the company to be a "learning organization", a term used by Peter Senge in his book, "The Fifth Discipline" (*Senge 22*). They recognize the importance of teamwork within an organization, and are working to break down the barriers that inhibit this approach. At this point the organizational structure is still departmentalized, but functional project teams exist in many areas.

The injection molding operation is a relatively new area of the plant that presents an opportunity to develop a work culture that focuses on the process development and problem solving with a teamwork approach. In order to be successful at team learning the employees must be able to overcome the mindset of functional responsibilities. This is not an easy transition for a large company that has been operating with a departmental organization for over thirty years. During the product launch of the plastic throttle body the team was small and each member took on overlapping responsibilities to achieve their overall objective of meeting the production schedule. However, as conflicts arise and the department expands, it will be important for management to maintain the team focus and establish a standard for learning together as this area.

Organizations are complex networks, and it is the people that make things work. If they are willing to cooperate, an organization can change and thrive. So while it is necessary to understand the processes and technology for a business, there is a need for innovative, coordinated action to take the understanding to a higher level.

3.0 The Product

The following section provides information regarding the product, the plastic throttle body, as background for the experiments detailed in the next chapter. The critical characteristics of the throttle body and information about the plastic material helps to round out the discussion of dimensional stability.

3.1 The Throttle Body

The first plastic products the Belfast Plant was preparing to launch into production were thermoplastic throttle bodies for a range of engine programs. Throttle body housings had traditionally been made from cast aluminum that was later trimmed, shot blast and machined to precision tolerances. Tight dimensional control is necessary because the throttle body orifice regulates the amount of air going into the engine. The throttle body assembly is a critical component because it directly impacts the performance of the vehicle.

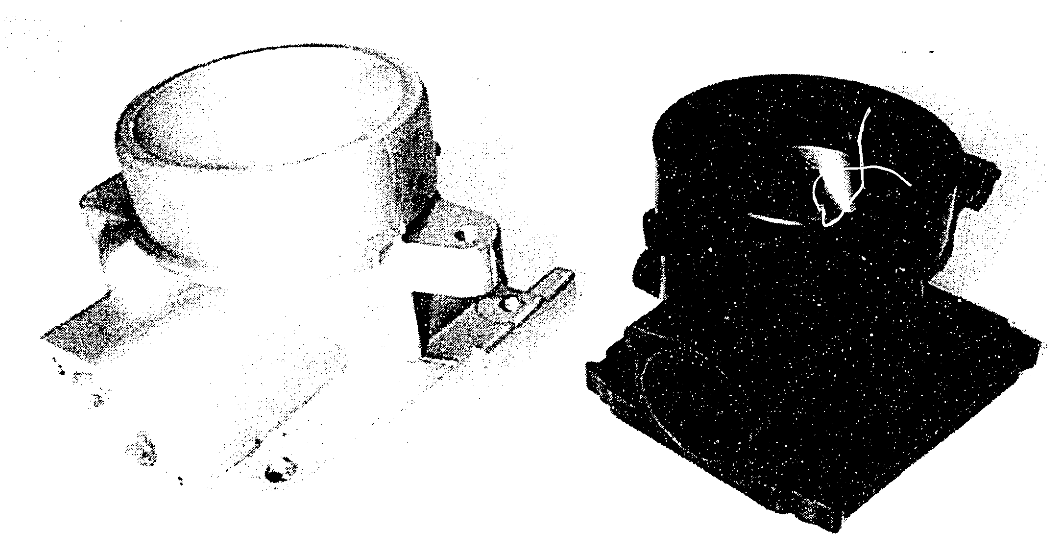

Figure 3-1. Plastic and Aluminum Throttle Bodies.

The photograph in Figure 3-1 shows the aluminum and plastic throttle bodies side by side. The glass fiber reinforced polybutyl terephthalate (PBT) plastic throttle body offers a weight savings of over 50 percent. The change also provides a significant cost savings due to lower material cost and the elimination of the need for post processing of the component since it is released from the injection mold cavity in a net shape condition.

The glass fiber reinforcement enhances the mechanical properties of the thermoplastic, however the orientation of the fibers within the part is dependent on the direction of the flow of the plastic as it fills the mold cavity. The physical properties of the reinforced PBT are dependent on the orientation of the fibers, known as anisotropy. Variation in shrinkage due to the anisotropy adds to the difficulty in maintaining the critical dimensions of the part.

The injection molded plastic component is used in a throttle body assembly. There are several operations that put additional stress on the molded component. Inserts, bearings and clips are pressed into the respective ports. A shaft is installed through the bearings and the bore, and a plate is placed through the slot in the shaft and aligned. Screws are used to hold the plate firmly into position. A bracket, spring and throttle positioning system (tps) are also attached. A throttle body assembly is shown in Figure 3-2 below.

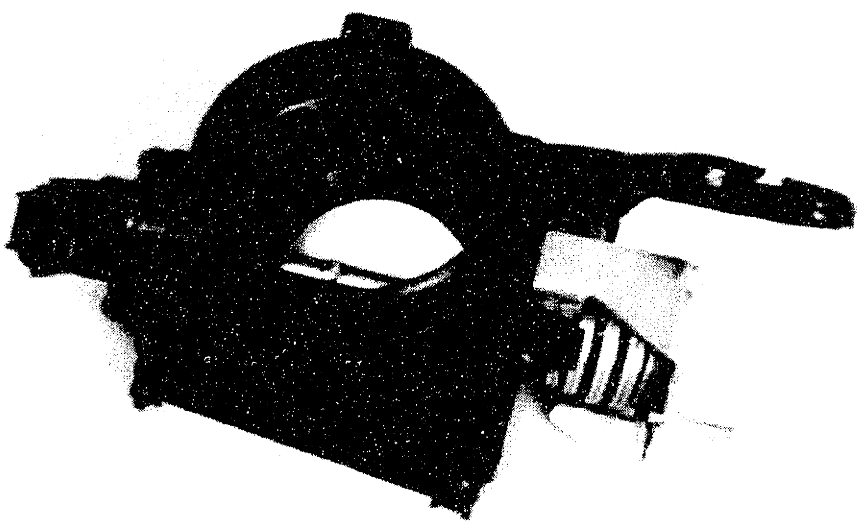

Figure 3-2. Plastic Throttle Body Assemby.

The final step of the process is the application of an adhesive paint that seals the remaining gap between the bore and the plate. The paint is sprayed in the bore area, allowed to cure, and then the seal is broken so the plate can move freely. The broken paint surface is intended to provide a prefect match between the plate and bore, however some of the paint typically flakes away when the seal is broken. The size of the gap is critical to the paint application process because a gap that is too large allows the wet adhesive paint to run through the gap. This may cause leaks or leave excessive material to shear when the seal is broken at the next station.

The stability of the bore and plate diameter is important to the function of the part. An assembly may pass an air flow test as it comes off the production line, but the gap may change slightly over time due to viscoelastic creep of the plastic. Significant changes in the orifice area will affect the air intake at idle or may cause the plate to bind, a phenomena known as stiction. The deformation of the material may also cause the adhesive paint to crack and chip.

The relief of the residual stresses in the material will occur over time or can be accelerated by the thermal cycle test. The thermal cycle test defined in the European engineering specification for the throttle body assembly includes ten cycles of four hours at 90°C minimum followed by four hours of -30°C minimum.

3.2 Thermoplastics

Thermoplastics are resins that repeatedly soften when heated and harden when cooled. Because they do not go through a chemical change, as thermoset plastics do when molecular chains become cross-linked, thermoplastics are ideal for recycling. The molecular chains of the polymer can be thought of as independent, intertwined strings that slip when heated, but bond firmly when cooled. However, there are limitations to the number of times a thermoplastic can be reused without significant degradation.

3.3 Semi-crystalline versus Amorphous Plastic

Thermoplastics are classified as semi-crystalline or amorphous depending on their molecular structure. Crystallization refers to the volumetric reduction that takes place when a plastic material is cooled and forms an organized, bonded molecular structure. Amorphous plastics have a completely random structure and thus the volumetric reduction is more uniform. Figure 3-3 shows a two dimensional representation of the amorphous and semi-crystalline structure.

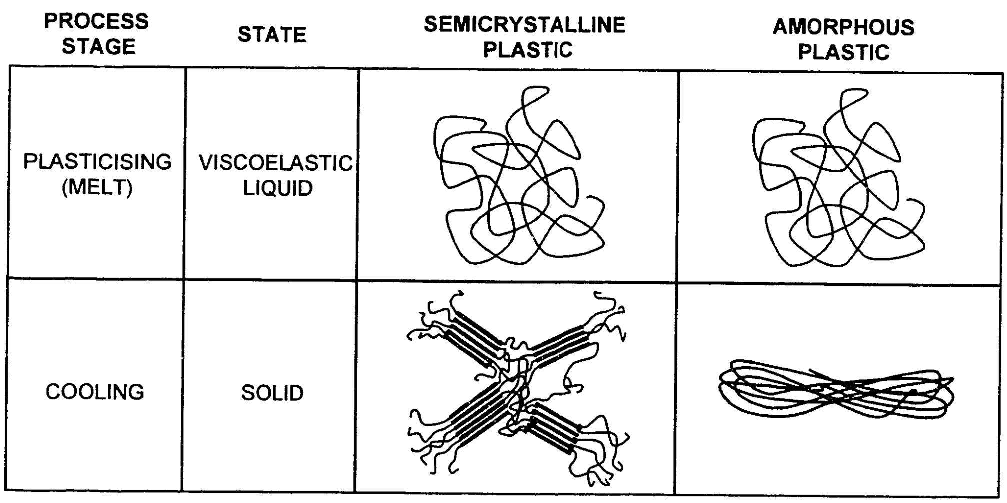

Figure 3-3. Two Dimensional Representation of Semi-crystalline and Amorphous Structure.

(Reference: Hoechst Celanese 10)

Crystallinity has substantial local effects that are dependent on the geometry of the part. The molten semi-crystalline plastic flowing in the mold contacts the wall and solidifies into a virtually amorphous state, but the material throughout the thickness of the wall shrinks more than the outer layer. The orientation of the molecules and reinforcing fibers also contribute to the variation in the amount of shrinkage that occurs.

Many differences in the thermoplastics can be attributed to the structure. A general comparison of the two plastics is shown in Table 3-1.

Table 3-1. General Comparison of Semi-crystalline and Amorphous Polymer Properties.

(*Reference: Hoechst Celanese 10*)

PROPERTY	SEMI-CRYSTALLINE	AMORPHOUS
STRUCTURE	ORDERED (with some random)	RANDOM
SPECIFIC GRAVITY	HIGHER	LOWER
TENSILE STRENGTH	HIGHER	LOWER
DUCTILITY	LOWER	HIGHER
RESISTANCE TO CREEP	HIGHER	LOWER
MAX USAGE TEMP.	HIGHER	LOWER
SHRINKAGE AND WARPAGE	HIGHER	LOWER
CHEMICAL RESISTANCE	HIGHER	LOWER

Semi-crystalline and amorphous thermoplastics also behave differently as they approach their melt temperatures. A semi-crystalline material will remain firm until it reaches its melt point and turns into liquid, similar to ice turning into water. The amorphous material softens with the escalating temperature until the material breaks down into a liquid state at the melt point.

The primary disadvantage of the amorphous plastic at the time of the material selection for the plastic throttle body was the price. The resins of the amorphous thermoplastic polyetherimide were over three times the cost of the reinforced polybutyl terephthalate (PBT). The price of amorphous plastic has declined somewhat over time as the suppliers have increased their production capacity, however there is still a significant cost difference that justifies the use of PBT.

4.0 The Injection Molding Process

The process of injection molding thermoplastics basically consists of softening the resin to a fluid state in a heated cylinder then injecting the molten polymer into the mold cavity of a defined shape where the material is packed under pressure until it cools and solidifies. There are eight basic stages to the continuous cycle that are outlined in Figure 4-1. The following sections describe each of these stages and where the process occurs in the injection molding equipment. Figure 4-2 is a schematic of a typical injection molding machine to assist in understanding the process.

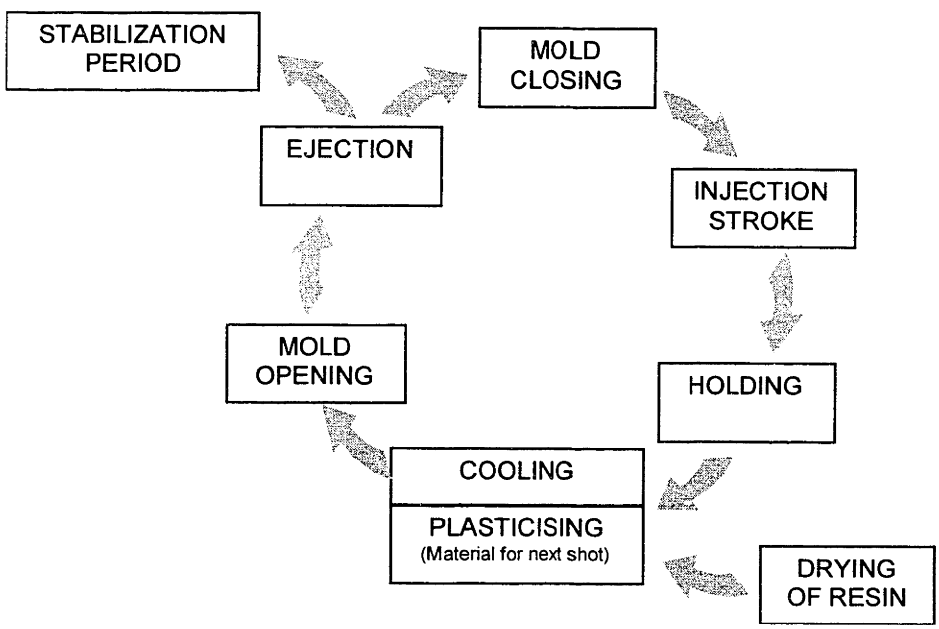

Figure 4-1. The Injection Molding Continuous Cycle

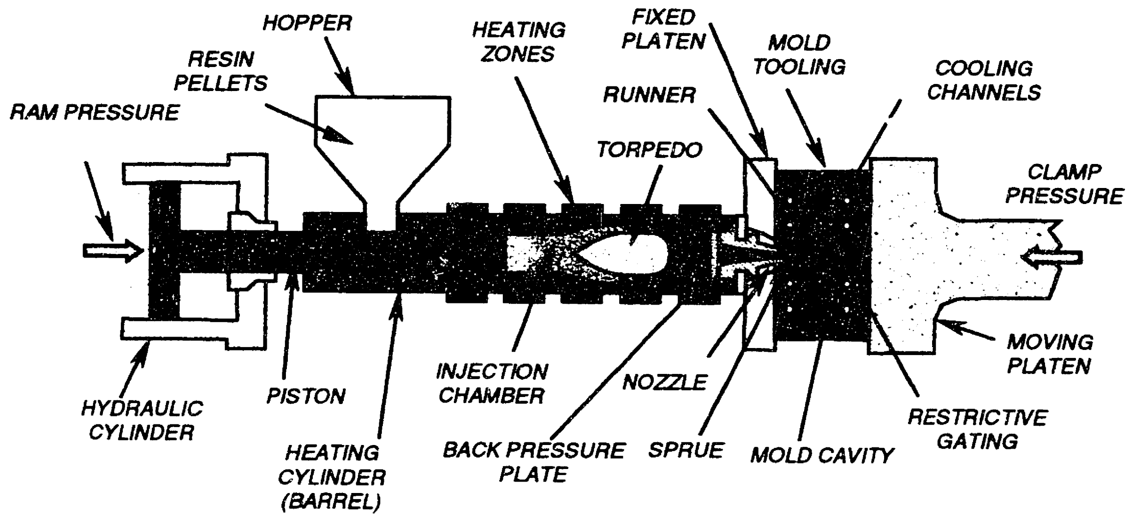

Figure 4-2. Cross–section of Typical Injection Molding Equipment.
(Reference: Chanda and Roy 5)

4.1 Drying of Resin

The resin granules will absorb a small amount of moisture from the environment during shipping and storage. The material must be properly dried, prior to processing, to minimize the possibility of degradation. Moisture in the material will convert to steam during the plasticising stage and will cause voids and porosity in the final product. Material suppliers specify moisture levels for the various types of material (typically below 0.02%), and drying columns are used to expose the granulated material to the necessary environment to drive off moisture. A photograph of the drying columns used at the Visteon facility is included in Appendix A.

4.2 Plasticising

The plasticising process begins when the dry granular resin material falls from the hopper into the injection chamber when the piston is drawn back from the cavity. The heater bands along the cylinder heat the material as the piston pushes the residual material from the previous shot around the torpedo and into the mold cavity. The thermal energy causes the polymer chains to move freely. Two major transitions in the state occur during the transition from solid to liquid. As the material reaches the glass transition temperature it softens and becomes ductile like rubber. At this stage, molecular motion increases and is reflected in dramatic changes in properties such as specific volume, heat capacity, stiffness and hardness (*Chanda and Roy,5*). As the temperature continues to increase, the material reaches the melt temperature when it becomes a viscous liquid. Shear forces within plastic also contribute to the heating of the material. Hot runners can also be used to continue to supply heat to the molten polymer until it enters the gates. The amount of heat transferred to the plastic determines the viscosity of the molten polymer which effects the consistency of the injection of the material into the mold cavity.

4.3 Mold Closing

Guides and location pins align to mate the sections of the mold tooling to form the enclosed cavity. Sufficient clamp force is applied to keep the tool tightly closed as the cavity is pressurized during the injection and holding processes. The maximum force the equipment can supply will limit the holding pressure and the size of the part that can be formed. The appendix includes some pictures of the tooling.

4.4 Injection

As the piston strokes it pushes the plasticised material past the heating elements and through the nozzle, which is sealed against the mold tooling. The material flows through the sprue (main opening in the tooling), into the runners (the channels that lead from the sprue to the mold cavity), past the restrictive gates, and into the mold cavity. The control of this process varies with the equipment design. The machines used at the Belfast plant control the injection speed profile of the piston. The internal pressure and flow rate of the material were dictated by the piston speed and viscosity of the material, but a maximum pressure limit was also set for safety reasons. Excess air inside the mold escapes through small vents in the mold tooling. As the material flows, the shear forces between the polymer chains increase the material temperature. Care must be taken to prevent excessive shear heat that will degrade the material. The speed at which this operation is performed, the size and position of the gating system, the geometry of the mold cavity and the viscosity of the material impact the flow of the material into the mold cavity. Inconsistencies in the material flow will effect the variation in the final product. The injection molding machines in the Belfast plant are equipped with a monitoring system that establishes a flow number for each process cycle. The flow number is basically a number associated with the flow energy during the injection phase. Limits are set for the flow number, and the machines are capable of automatic quality control based on the conformance of this measurement. The flow number is defined in more detail in Appendix C.

4.5 Holding

Pressure packs the molten polymer into all the contours of the mold cavity until the material at the restrictive gates hardens or "freezes off". Once the gates freeze off the pressure from the system is no longer effective. The holding pressure should be sufficiently high to force out the pockets of air, but excessive pressures may lead to over-packing or flash.

4.6 Cooling

The thermoplastic cools and crystallizes inside the mold cavity until it reaches a solid state. The temperature of the mold is controlled by fluid that circulates through the cooling channels of the mold. Uniform heat transfer between the tooling and the thermoplastic material is essential for consistent part production. The necessary cooling time is dependent on the thickness of the part and the efficiency of the cooling system. Uneven temperatures on the mold surface and low mold temperatures will contribute to the shrinkage and warpage of the molded part. Cooling time in the mold is typically the dominant factor in the total molding cycle time.

4.7 Mold Opening

After the part has cooled sufficiently in the cavity the mold will open. As the tooling pulls away it must overcome the forces of adhesion between the mold and the plastic. Plastic parts are designed with tapered surfaces to reduce the loads needed to remove the tooling. As the tool opens the mold cavity surface loses heat to the atmosphere through convection. The amount of time that the tool is open and the consistency of the time duration will effect the temperature of the mold cavity which can effect the variation of the end product.

4.8 Ejection

The packing of the material and the adhesion forces will cause the molded part to remain in the mold cavity until a knockout force ejects it. The part is typically ejected mechanically by knock out pins and/or compressed air in the mold tooling. Although the part is in the solid state it is still at an elevated temperature and may not be fully crystallized so care must be taken not to deform the part during knockout and handling.

4.9 Stabilization Period

After the molded part is ejected from the cavity it continues to crystallize and stabilize dimensionally. Parts should be held for an adequate stabilization period prior to inspection and delivery to the next process level. The most significant dimensional change typically occurs as the part cools to room temperature.

5.0 Design of Experiments

5.1 Purpose of DOE

Design of experiments (DOE) is a powerful statistical tool for learning about a process. The purpose of designed experiments is to provide a practical means of studying the effects of input parameters on a process response within an experimental design space. Engineers can efficiently analyze the effects of process parameters on a process (or design parameters on a product) by using orthogonal array experiments that only require a fraction of the tests needed in a full factorial test series. The combinations of factors are balanced so that no one factor is given unequal weight with respect to the other factors of the experiment. The test series also defines the interactions between process parameters that are often overlooked when each parameter is evaluated independently.

Ford Motor Company provides training on the methods to apply designed experiments, but there continues to be some hesitation to applying DOE within the Belfast plant. Despite the training on the process, many of the manufacturing engineers are reluctant to conduct a DOE test series. The following paragraphs list some potential reasons for their resistance.

Lack of time to properly plan and execute the experiments - The proper planning and execution of designed experiments can take considerable time and resources. During rapid product development and production launch when time is a premium, engineers often prefer to make decisions quickly based on past experience, fundamental knowledge, or intuition.

Concern for the stability of the process - In the early stages of product and process development many of the inputs into the process have not stabilized. The product design may still be changing. It is typical for a manufacturing engineer to want the design and process inputs to be stable before embarking on a series of experiments. Significant changes may invalidate the results of the experiment. On the other hand, the test results may highlight the necessity for a design or process change.

Lack if experience with the DOE process and statistical analysis – Although any competent engineer could learn what is necessary to perform the testing and statistical analysis, there is resistance to applying DOE methods due to lack of confidence in one's analytical abilities. With practice and experience a manufacturing engineer will become more comfortable with the process, and it will be easier to recognize situations that warrant a DOE test series.

Preference for theoretical knowledge – Many scientists and engineers focus on understanding the fundamentals of the technology over the practical application of designed experiments. There is some concern that DOE testing will become a substitute rather than a compliment for process knowledge. DOE test results should never be blindly accepted. Conclusions from the testing should always be backed up with scientific reasoning and further validation.

The Visteon Belfast plant is not unique in its hesitation to adopt DOE test methods. Many organizations have had difficulty in making decisions as to when and when not to use designed experiments. However, many firms, including Ford Motor Company, have been successful at optimizing a process or design through these quality techniques. In recent years Genichi Taguchi, Japanese quality master, has also been advocating the use of his methods in the early process technology stages in order to evaluate capabilities. (*Ashley 1.*)

Another DOE specialist, Madhav Phadke, explains the conflict with many development styles, "Certain aspects of technology development, and even research, are amenable to Taguchi's techniques [of designed experiments], because decisions affecting quality are being made, even at those early stages. Typically, however, when someone thinks of a new phenomena or mechanism, it is natural to want to demonstrate its viability to management in the most favorable way, so the engineer does experiments in relatively benign conditions that allow the technology to look good." (*Ashley 1*). The same effect can occur within a manufacturing department that is interested in pleasing upper management with positive results in new process development.

In summary, the method of DOE is recognized as a powerful tool for product development, technology development and process optimization. It can reveal characteristics of the design or process that may not be readily apparent to the researcher, engineer or operator. However, it is important for the organization to accept the methodology, determine the appropriate timing and application for its use, and validate the results with scientific theory for real learning.

5.2 DOE Planning Process

The flowchart outlined in Figure 5-1 outlines a process followed in planning and conducting a design of experiments test series. This process is typical of the procedures used in setting up a DOE, and the various stages can be separated into categories relating to the total quality management process for continuous improvement, the PDCA cycle, Plan-Do-Check-Act (*Shiba 24*) Each step of the process is important to the success of the design of experiments. Designed experiments using fractional factorial test matrices lead to an economy of experimentation that speeds the development process, however tests conducted without sufficient planning will lead to incorrect results and a waste of time and resources.

5.2.1 Define the Purpose of the Experiment

This initial step will set the scope for the entire experiment. A clear definition of the problem and the objective will help to determine if a DOE is necessary. The problem may be resolved by using another problem solving technique or method of analysis. Also it is important to determine whether the objective is to improve quality, reduce manufacturing costs, or minimize variability. According to many quality experts each of these will ultimately have an impact on cost (*Phadke 18, DeVor 6*), but understanding the objective of the experiment will help to focus the effort.

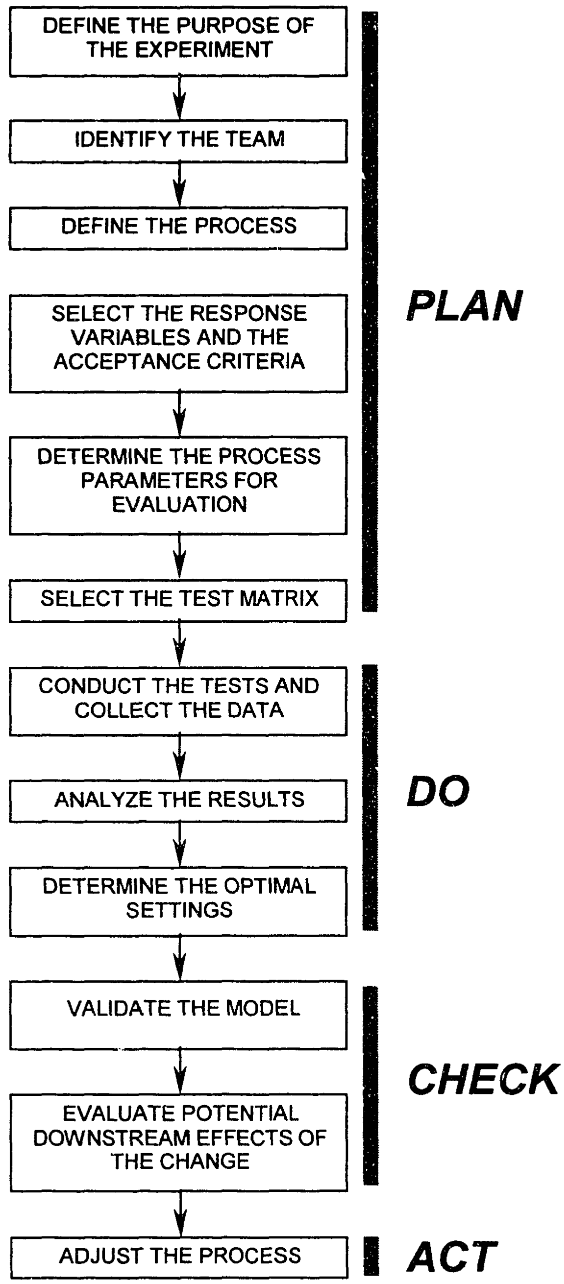

Figure 5-1. The Process for Design of Experiments.

For the one of the DOEs performed in the Visteon Belfast Plant the main objectives were outlined to be:

1. To characterize the amount of deformation and it's dependence on the injection molding process settings.

2. To optimize the injection molding machine parameters to minimize dimensional instability of bore diameter that occurs during to thermal cycling.

3. To evaluate the difference in deformation as a result of exposure to three and ten thermal cycles.

5.2.2 Identify the Team

Although it is possible to complete a design of experiments independently, it is recommended that a team be formed to plan the experiment and evaluate the results. Cross-functional teams are usually more successful in the planning and execution of designed experiments because of the various perspective each person brings to the team. Representatives from manufacturing, design, and quality are recommended. Material suppliers and next level customers should also be considered. Even if they are not actively involved on the team they should, as a minimum, be informed of the plan for the DOE so the potential impact of the testing on their organization can be evaluated. All the members of the throttle body launch team participated in various sections of the designed experiments. The material supplier and the manufacturing engineers of the throttle body assembly were also made aware of the testing.

5.2.3 Define the Process

The process under investigation should be clearly outlined. This step requires a good understanding of the product and process as well as the end customer's requirements. The inputs and the potential sources of noise in the process should be identified. It is also important for the process to have some level of stability. Large sources of noise may mask the effects of the variations in process parameters. For example, in order to minimize the noise for the plastic throttle body experiment care was taken to evaluate the injection molding process for a particular throttle body design, with a particular tool, using the same batch of material and the same machine. Additional testing would have to be conducted to determine the effects of these sources of noise on the process.

5.2.4 Select the Response Variables and Acceptance Criteria

The critical features of the process output should be understood at the beginning of the experiment. When there are several responses to be evaluated their importance will need to be rated in order to determine the optimal settings. Phadke recommends the following guidelines when selecting the response variables (*Phadke 18*):

- The quality characteristic should directly effect the part function or assembly methods specified by the customer.

- When possible, choose continuous variables rather than discrete variables.

- Try to select characteristics that are easily measured. Measurement devices should be readily available and capable of providing reliable results.

- Ensure selection is complete and covers all the requirements for the part.

For the throttle body DOE the deformation of the inside bore profile was determined to be the most critical feature. Our main interest was in determining how this profile was changing as a result of the thermal cycle testing. The critical features selected for analysis are defined in Table 5-1 and Figure 5-2. These dimensions were measured three times during the experiment; before thermal cycling, after three thermal cycles and after ten thermal cycles.

Table 5-1. Data Collection for Throttle Bodies.

FEATURE	COMMENTS / DESCRIPTION
BORE PROFILE (EVERY 3°)	- MOST CRITICAL FEATURE OF THROTTLE BODY - MAIN FOCUS FOR THE ANALYSIS OF THE TEST RESULTS.
BORE ROUNDNESS	- MEASURED AS DIFFERENCE BETWEEN HIGHEST AND LOWEST POINTS ON THE RADIUS PROFILE.
FLANGE FLATNESS	- IMPORTANT FOR SEALING OF THE GASKET WHEN THE ASSEMBLY IS ATTACHED TO THE ENGINE. – - MEASUREMENT DOES NOT DEFINE WHETHER FLANGE IS CONCAVE OR CONVEX
BEARING DIAMETER AT LEVER	- SEALING DIAMETER FOR A BEARING THAT SUPPORTS THE SHAFT THAT HOLDS THE PLATE THAT SITS INSIDE THE BORE DIAMETER.
BEARING DIAMETER AT TPS	- SEALING DIAMETER FOR THE BEARING AT THE OTHER END OF THE SHAFT.
FLOW NUMBER (Process Parameter)	- MEASURED TO EVALUATE PROCESS CONTROL AND CONSISTENCY OF THE MATERIAL FLOW - (SEE APPENDIX C FOR EXPLANATION OF THIS PARAMETER)
WEIGHT	- MEASURED TO EVALUATE PROCESS CONTROL AND CONSISTENCY - NOT A DESIGN REQUIREMENT

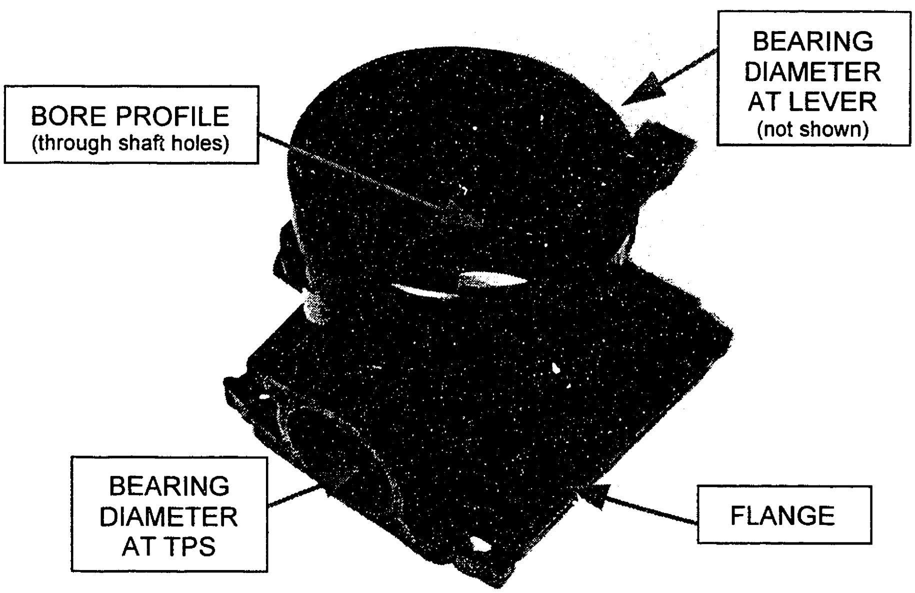

Figure 5-2. Throttle Body Critical Features.

It was important to note that the bore profile was measured every three degrees. The radius measurements were plotted with respect to the angle of measurement. Often in this type of analysis a circular feature is defined as mean radius and roundness. Since we were interested in understanding how the bore deforms we needed to focus on the amount of deformation that occurred at various angular increments, not just the difference between the mean and run-out before and after thermal cycling. Comparing only the generalized data would not give us an accurate indication as to where the growth or shrinkage occurred.

5.2.5 Determine the Process Parameters for Evaluation

The team should prepare a list of all the parameters that can impact the response variable. Based on experience and engineering judgement the parameters with the greatest potential to influence the response variables are then selected form the list. All other variables shall be held constant in an effort to minimize the noise in the experiment.

In the throttle body experiment the team selected five process parameters for the injection molding process; cooling time, melt temperature, injection speed, hold pressure, and mold heater setting (temperature of the oil entering the cooling channels of the mold tooling.) The parameters and the levels selected are shown in Table 5-2. Again engineering judgment should be used to set the limits narrow enough to focus on the area of interest, yet wide enough so the results will be significant. The parameters chosen were identical to a previous DOE performed at another Visteon facility in Rawsonville, Michigan with a similar product and equipment.

Table 5-2. Control Parameters and Test Levels.

Process Parameter	Low Level	Midpoint	High Level
Cooling Time (s)	10	20	30
Injection Speed Profile (mm/s)	~35	~50	~65
Hold Press. Profile (bar)	40	55	70
Melt Temperature (°C)	~230	~255	~270 7
Oil Temp. Setting (°C)	90	100	110

Note: The data shown in this table is for illustrative purposes only and does not reflect the actual values used in the experiment.

5.2.6 Select the Test Matrix

Once the process parameters for evaluation have been selected the potential for interactions should be estimated based on engineering judgement. Good estimations of the effects the process parameters will have on the response will aid in the selection of a test array. If interactions are expected then care can be taken in assigning the factors in order to minimize the confounding of two significant effects. The complication of performing the experiment may also influence the choice of the test array. If the test is easy to duplicate the team may begin with a smaller matrix and expand the testing as necessary based on the results of the initial test series. There are many references to aid in the selection of a test array. For further information regarding this topic, *Design and Analysis of Experiments* by Douglas C. Montgomery (*Montgomery 17*) is a useful resource.

In the plastic throttle body DOE an L_{16} (2^{5-1}) test array was selected. The alias structure is defined on the following page in Table 5-3 shows all main effects to be isolated from the two-way interactions.

Table 5-3. Alias Structure of an L_{16} (2^{5-1}) Test Array.

Design Generators: E = ABCD	Alias Structure:	I + ABCDE	
			AC + BDE
		Blk = AB +	AD + BCE
		CDE	AE + BCD
			BC + ADE
		A + BCDE	BD + ACE
		B + ACDE	BE + ACD
		C + ABDE	CD + ABE
		D + ABCE	CE + ABD
		E + ABCD	DE + ABC

A full factorial with five parameters would require 32 runs. In our test series we used a half factorial L_{16} (2^{5-1}) so only 16 runs were needed. . The test matrix used is shown below in Table 5-4. In order to compare the data against the baseline and to get a sense of the linearity of the effect, the experiment also included five runs at the midpoint. It is desirable to have a completely random test order, however for practical purposes the test was structured to reduce the number of times the mold heater setting had to be adjusted because the process took over forty minutes to stabilize after making a 10°C adjustment.

Table 5-4 defines the test series used in the experiment and the settings for each of the runs. The five midpoints were interspersed within the runs. The replicates will give an indication of the reproducibility of the process.

Table 5-4. L_{16} (2^{5-1}) DOE Test Series for the Injection Molding Process.

Run Order	Std Order	Cool Time (s)	Average Injection Speed (mm/s)	Holding Pressure (bar)	Melt Temperature (°C)	Mold Temperature Setting (°C)
1	1	+	-	-	-	-
2	2	-	+	-	-	-
3	7	+	-	+	+	-
4	8	-	+	+	+	-
5	5	+	-	-	-	+
6	6	-	+	-	-	+
7	3	+	-	+	+	+
8	4	-	+	+	+	+
9	13	+	-	-	-	-
10	14	-	+	-	-	-
11	11	+	-	+	+	-
12	12	-	+	+	+	-
13	9	+	-	-	-	+
14	10	-	+	-	-	+
15	15	+	-	+	+	+
16	16	-	+	+	+	+

5.2.7 Conduct the Tests and Collect Data

The data collection and the analysis of the results are the two most important stages in determining the success of the test series. Up-front planning will make the testing and data collection easier. Tables and spreadsheets prepared in advance can provide a check list to make sure all the data has been collected. The Visteon Belfast Plant had the advantage of the experience gained from the similar DOE performed in Rawsonville.

One of the objectives of the plastic throttle body DOE was to compare the effects of three and ten thermal cycles. The interest in this evaluation stems from the differences in the U.S. and European specifications. As a result there were several stages to the data collection process that are outlined in Figure 5-3. A summary of the data collected can be found in the appendix.

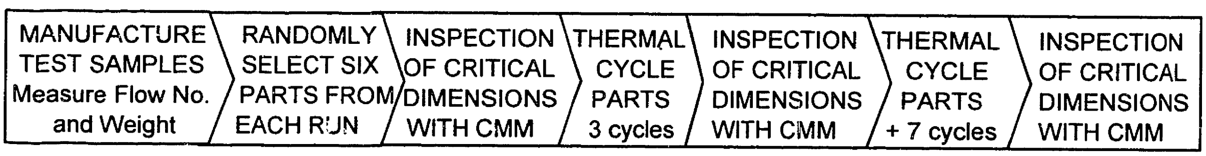

Figure 5-3 Test and Data Collection Process for the Plastic Throttle Body DOE.

5.2.8 Analyze the Results

As mentioned above the analysis of the data is another critical step in the success of a DOE. First the data must be reviewed carefully to identify trends or any suspicious data points. For example, in the DOE for the plastic throttle body the data for the bore radius was plotted to compare the measurements for components from a certain run. As seen in Figure 5-3 below, one data point at the 144 degree radial location on sample 3 is far out side the grouping of the other five data points. This sample was inspected and no physical reason for the reduced radius measurement was determined. The stray point was caused by noise from the measurement system. Several other suspicious points were found when the data was reviewed in more detail. To eliminate the influence of outlying data points the median of the six data points was used in the statistical analysis.

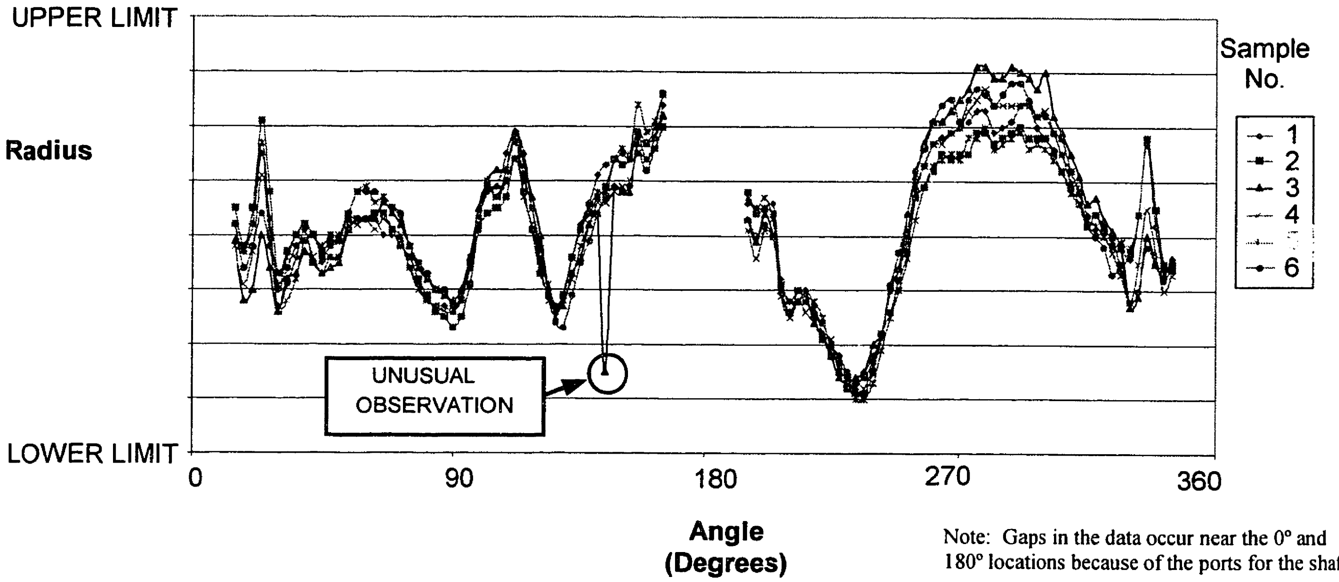

Figure 5-4. Bore Radius Profile for Six Samples from Run 7

The in process data was evaluated for its consistency and to determine if there were any unusual occurrences. There are no design requirements for these values. They are merely process aids that help determine the stability of the process. They can be used to monitor the process and determine when anomalies occur. The flow number and the weight were plotted with respect to the runs. The data was also evaluated to determine which process parameters influence the measurements. The data and graphs can be viewed in the appendix.

The analysis indicated that the hold pressure and the melt temperature had the predominant influence on the final weight of the component. This is logical because both of these parameters will effect the density of the material in the cavity. The injection speed and the melt temperature had the biggest impact on the flow number. Of the five control parameters these two were clearly the most likely to effect the injection energy.

The median of the six data points was plotted at each angular location for each of the runs of the test series. The same graphs were generated for the data after three and ten thermal cycles. All three graphs are aligned in Figure 5-5 so that the shift can be evaluated.

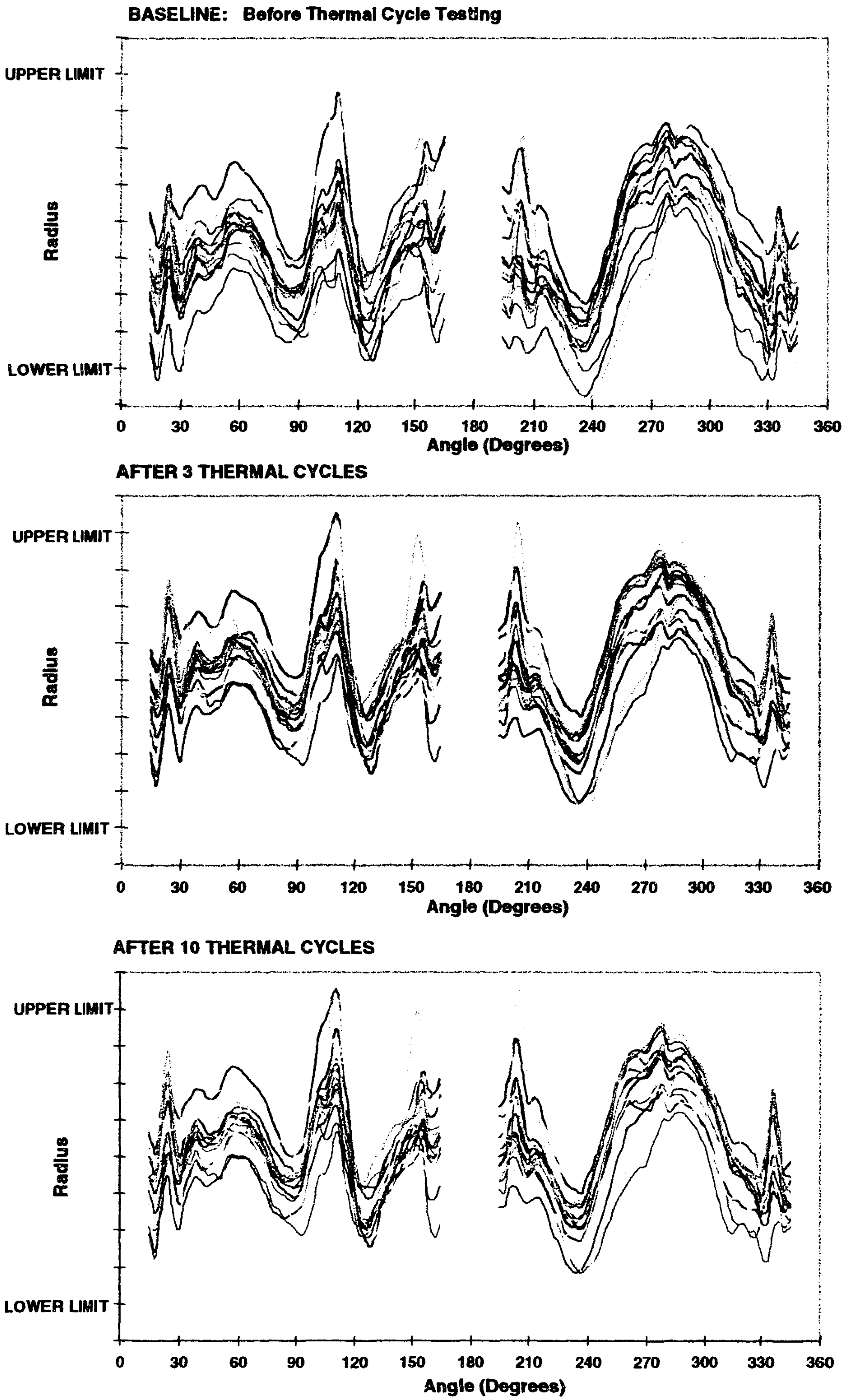

Figure 5-5. Comparison of Bore Radius Data for All DOE Runs.
(Baseline, After 3 Thermal Cycles and After 10 Thermal Cycles).

The comparison of the various graphs in Figure 5-5 shows some important trends as the parts were thermal cycled.

- There are consistent peaks and valleys within the various runs. This indicates that certain deviation from the target value is inherent in the tooling and the process.
- The bore radius tends to grow after thermal cycle testing for the ranges of the process parameters used in the experiment.
- The range between the various runs is less after the thermal cycle. As the residual stress relieves itself during the thermal cycling the plastic shifts towards a shape inborn in the part.
- There appears to be very little difference between three and ten thermal cycles.

To better evaluate the post thermal cycle shift, deformation for various runs versus the angular location was plotted in Figure 5-6. Only a select few runs were plotted to show the trend. The pattern, location of peaks and valleys, for the shift in radius is consistent regardless of the process parameters used and is related to the geometry of the mold tooling. The valleys are in alignment with the gating system, and the peaks coincide with the probable locations of the weld or knit lines, locations where two streams of the liquid plastic meet during the filling of the cavity. The anisotropic shrinkage occurs due to the orientation of the fibers in these areas.

The team identified the eight point of interest in the profile of the deformation that roughly correlate with these locations of the knit lines in the component. The average of these eight points was used as a single response to evaluate the effects of the five process parameters.

The statistical analysis of the data collected in the experiment was performed using Minitab Statistical Software, Release 12. There are several software packages capable of analyzing designed experiments. This particular software was selected because it is standard within Ford Motor Company. The graphs in Figure 5-7 show the statistically significant effects of the process parameters.

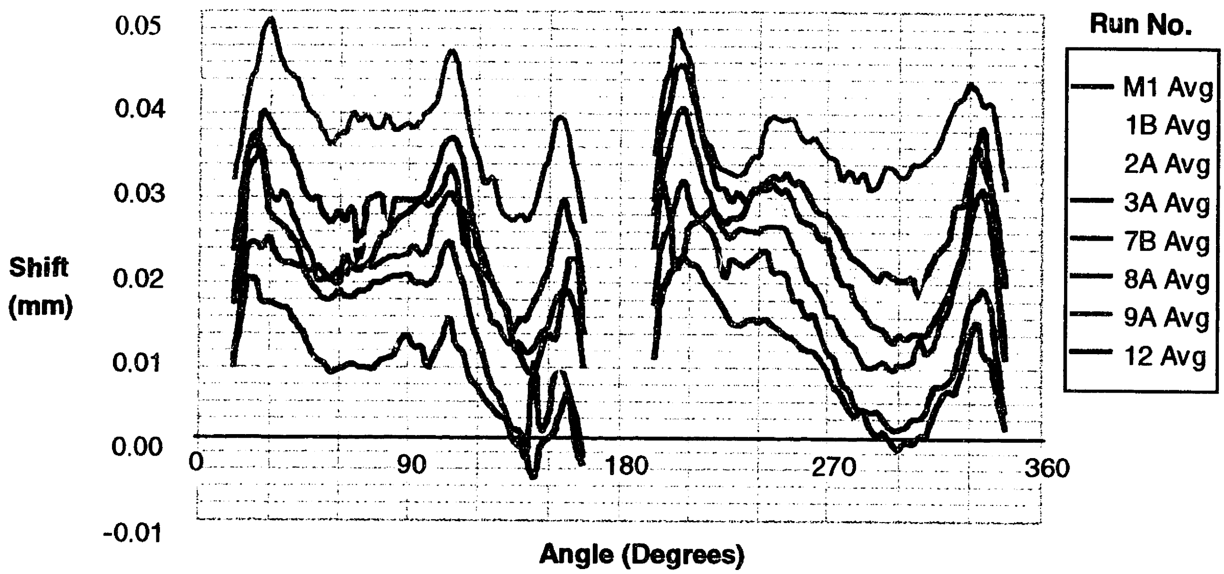

Figure 5-6. Shift in Radius After Exposure to Ten Thermal Cycles*

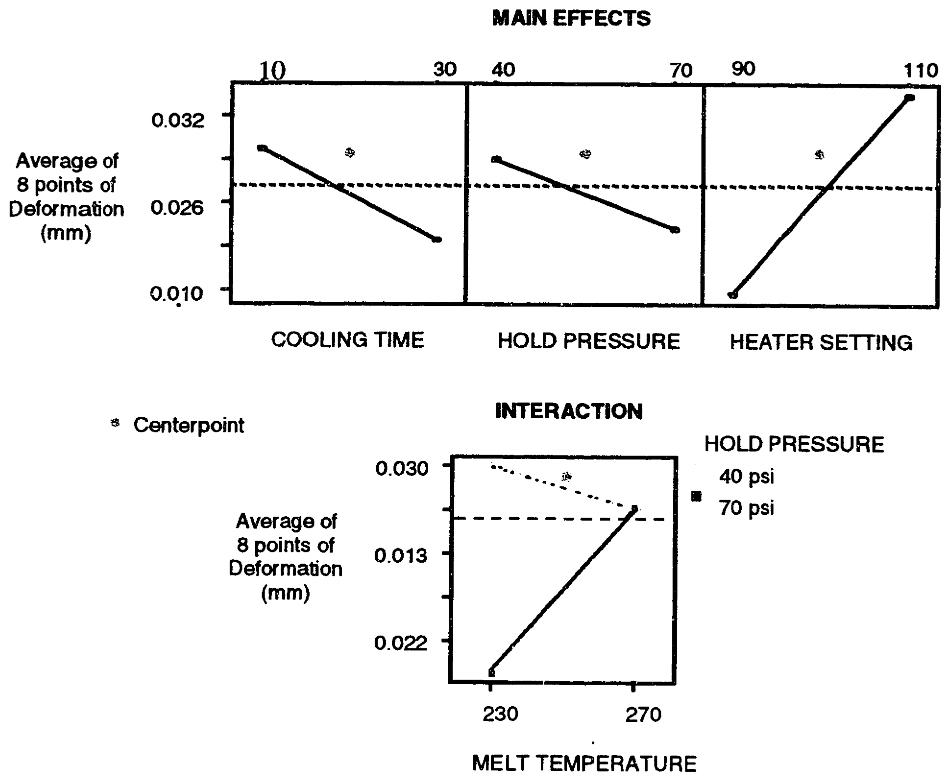

Figure 5-7. Main Effects and Interaction for Average of 8 Point Bore Deformation*

* The data shown in this table is for illustrative purpose only and does not reflect the actual values used in the experiment.

5.2.9 Determine the Optimal Settings

The next step in the DOE process is to generate the prediction equations and use them to better understand the dynamics of the process being evaluated. The ability to predict the effect of the various parameters on the responses has many benefits, such as:

Determining Optimal Settings – The prediction equations can be used to determine the optimal process settings needed to minimize or maximize a particular response. It also allows the team to understand the sensitivity of the response to variations in the parameters. In selection of the optimal process settings consideration should not only be given to the median or average value of the response, but an analysis should be conducted to determine the expected standard deviation.

Setting Tolerances - The prediction equations are a valuable tool in estimating the effect of various tolerances for the process parameters. This is a valuable tool for the process engineer in determining the process control capabilities for the equipment.

Trouble Shooting - During the project the prediction equation was used as a trouble shooting tool. The response had shifted over time and the equation was used to determine the possibility of the shift being attributed to a change in one of the studied process parameters. This is highly speculative because there could be other process changes outside of the experiment, such as material variation, that caused the change in response. Although it is by no means conclusive, it may give some direction for further investigation.

Extending Tool Life - The process parameters had an effect on the bore diameter before and after thermal cycle testing. Over time as the tool wears it might be possible to extend the life of the tool by operating at the extremes of the process limits. Care should be taken in using this approach since a change in the tool shape due to wear may have other effects on the product. Changes should be evaluated with additional thermal cycle testing prior to implementation.

The Minitab analysis was used to generate the coefficients of the prediction equations for the various responses for the bore radius before and after thermal cycling. An interactive spreadsheet was created to aid in the visualization of the shift in bore radius as a result of process changes. A copy of the spread sheet layout for the dimensional shift can be viewed in Appendix D.

Two approaches were used to model the bore radius profile of the plastic throttle body. The contour was modeled as an eighth harmonic Fourier series and as a set of eight discrete points at specified locations. The benefit of using the Fourier series is that the prediction equation can be used to predict the radius and deformation after temperature cycling at any angular location. This model is adequate for showing the general trends for the bore radius, however significant smoothing occurs at localized areas of high shrinkage, such as at the knit line locations. A comparison of the actual data collected during the experiment and the predicted bore radius using the Fourier model is shown in Figure 5-8. The evaluation of the bore radius at the eight discrete locations better characterizes the radius and shrinkage of interest with respect to our product.

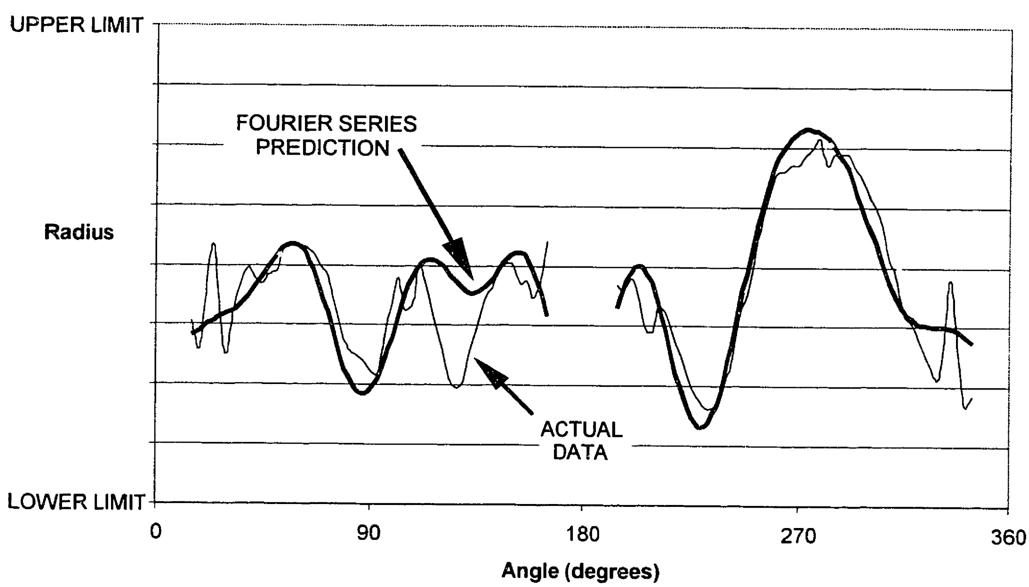

Figure 5-8. Actual Data versus Fourier Prediction Model

The difference between the dimensional shift of the eight critical locations of the bore radius profile after three and ten thermal cycles was small relative to the shift in dimension. The data can be compared in the tables in Appendix B. The differences were calculated to be comparable to the repeatability of the measurement system. The data indicates that in general, over 85 percent of the deformation occurred after the first three thermal cycles.

The following conclusions were made from the results and analysis of the DOE:

- The heater setting (temperature of the cooling fluid entering the mold cooling passages) has the most significant effect on the amount of deformation that occurs during thermal cycle. The results indicate that the temperature should be decreased to lower the amount of deformation. This seemed counter-intuitive to the team. Typically it is believed that a lower temperature mold cavity will cool the part quicker which would tend to increase the amount of residual stress in the part.
- Cooling time also has a significant effect on the stability of the bore radius dimension during thermal cycle. Increasing the time the part stays in the mold cavity lowers the amount of deformation. However, it is important to remember that the cooling time has a direct impact on the cycle time so there are limitations on setting this time.
- A higher hold pressure reduces the amount of deformation. This seems likely since a higher pressure will pack the material more tightly into the cavity.
- There is an interaction between melt temperature and hold pressure. If a high pressure is used then deformation of the bore radius will be less if a lower melt temperature is used.

- The data shows areas of localized deformation that roughly correlate to the positions of the gating system. This information would not be uncovered if only the mean radius and roundness dimensions were studied. There is significant smoothing that occurs when the radius profile is defined using a Fourier series. When dealing with precision tolerances it is best to focus on specific locations of concern and avoid generalizing the data.

- There is very little dimensional difference between the parts exposed to three and ten thermal cycles.

5.2.10 Validate the Model

Conclusions from the initial test series analysis should always be validated with additional testing. Verification runs at the proposed optimized settings should be performed to compare the results to the predictions. Points at the midpoint or previous test locations should also be included to determine if the response has shifted over time.

In our designed experiments for the plastic throttle body the data analysis indicated that the operating point to minimize the shrinkage of the bore diameter was outside of the boundaries of our testing. Several parameters were already at the process limits; the cooling time could not increase above 30 seconds due to capacity constraints, the holding pressure could not be increased because of machine design limits, and the melt temperature of the plastic should not drop below the manufacturers recommendations. The mold heater setting, the parameter that showed the most significant effect on shrinkage, was the only parameter varied during the second test series to travel down the steepest slope of descent defined in Figure 5-9.

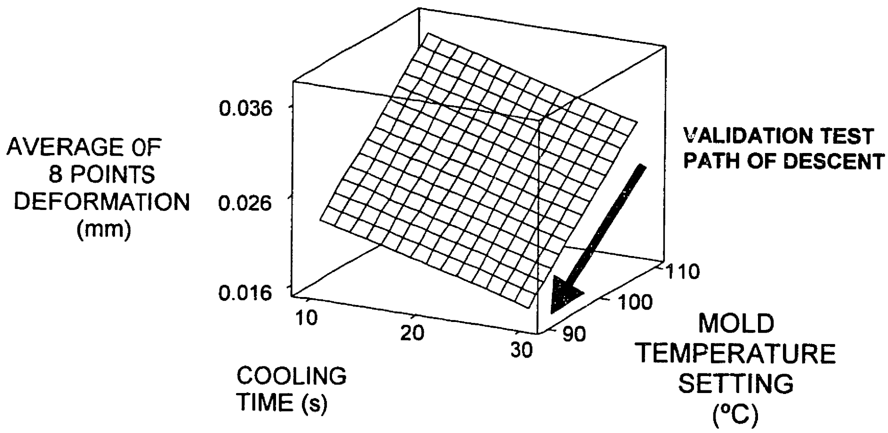

Figure 5-9. Mold Heater Setting Adjustment Down Steepest Slope of Descent*

The results of the second set of testing indicated that there had been a shift in the process response over time. Some variation is expected within the process due to noise from material and process variation. Despite the difference in the actual bore radius, the estimation of deformation due to thermal cycle testing was still accurate. The comparison of the graphs shown in Figure 5-10 shows similar trends to the previous test series. The bore radii from various temperature settings shifted over time to a profile that was inherent to the product.

* The data shown in this table is for illustrative purposes only and does not reflect the actual values of the experiment.

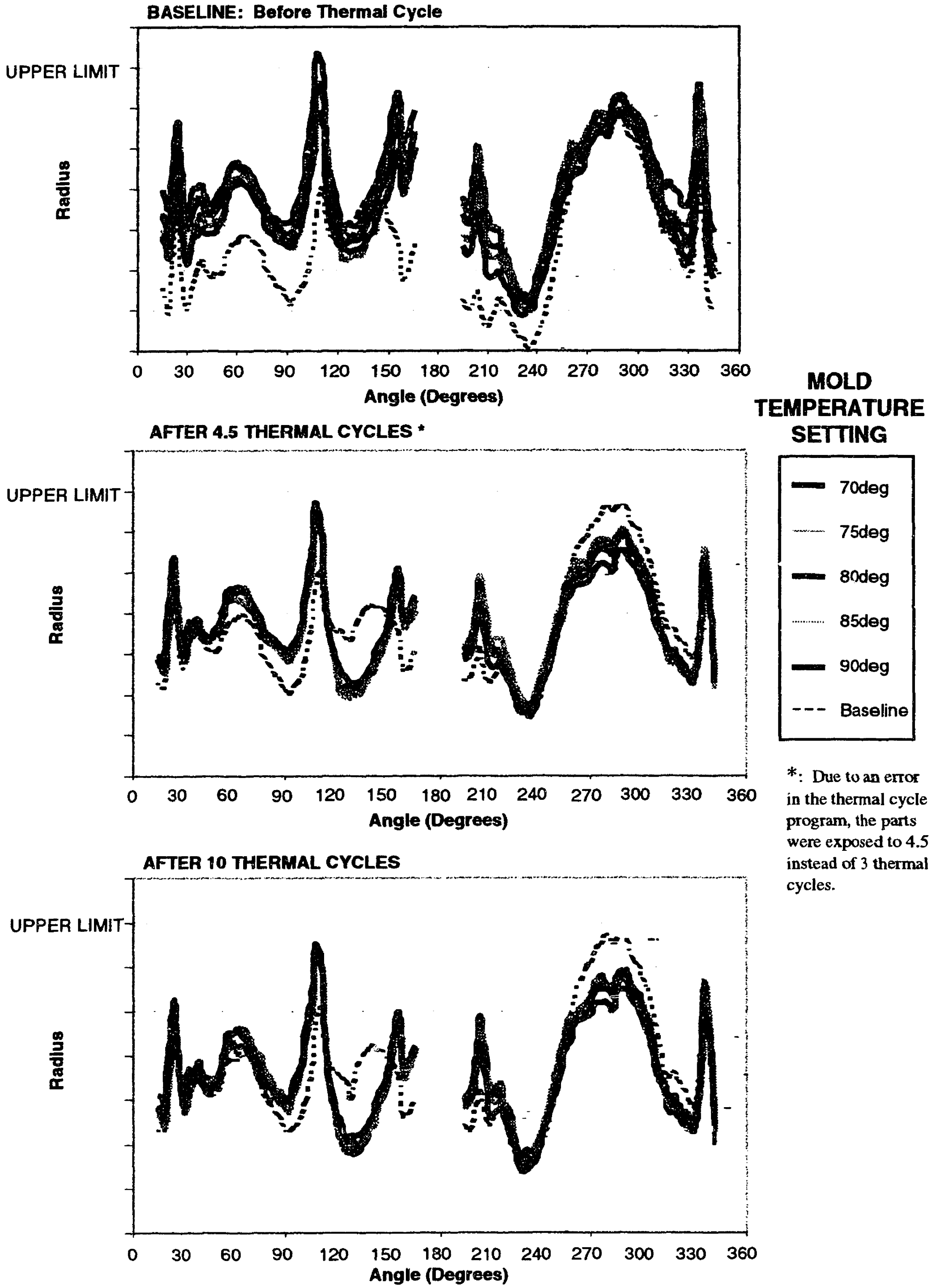

Figure 5-10. Verification Run Bore Radius Comparison.
(Baseline, After 4.5 Thermal Cycles, and After 10 Thermal Cycles)

At the lower mold temperature settings the bore radius actually contracted. A reduction in the throttle body bore radius could potentially cause an interference fit with the throttle plate. The target deformation is zero so the sum of the squares (SS) was plotted, as shown in Figure 5-11, to determine the optimal heater setting.

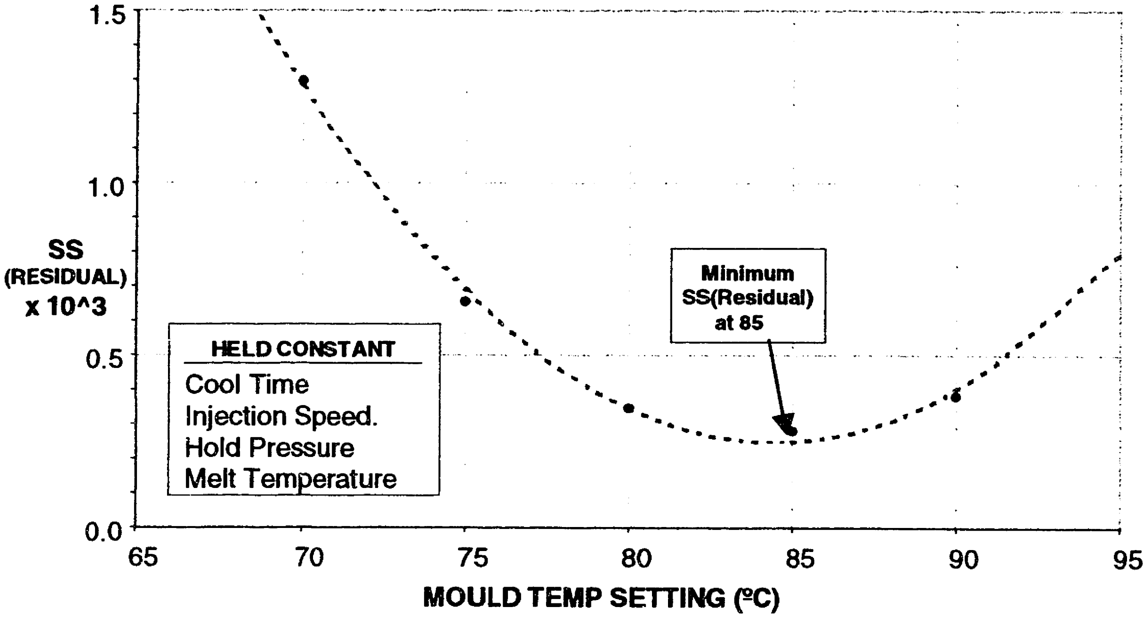

Figure 5-11. Sum of the Squares of the Residuals for the Validation Run

he graph above indicates that the shift in the bore radius is closest to zero at approximately 85° C. This is expected to be the optimal operating point in regards to the stability of the bore diameter, however, the adjustment to the mold temperature also had an effect on the size of the bore diameter. The bore is larger when the lower mold temperature is used.

Figure 5-12 shows a comparison of the deformation for the current and optimized process settings. The deformation profile with the proposed process settings decreases with an average reduction in deformation of over 50 percent, taking into account that shrinkage is still considered deformation.

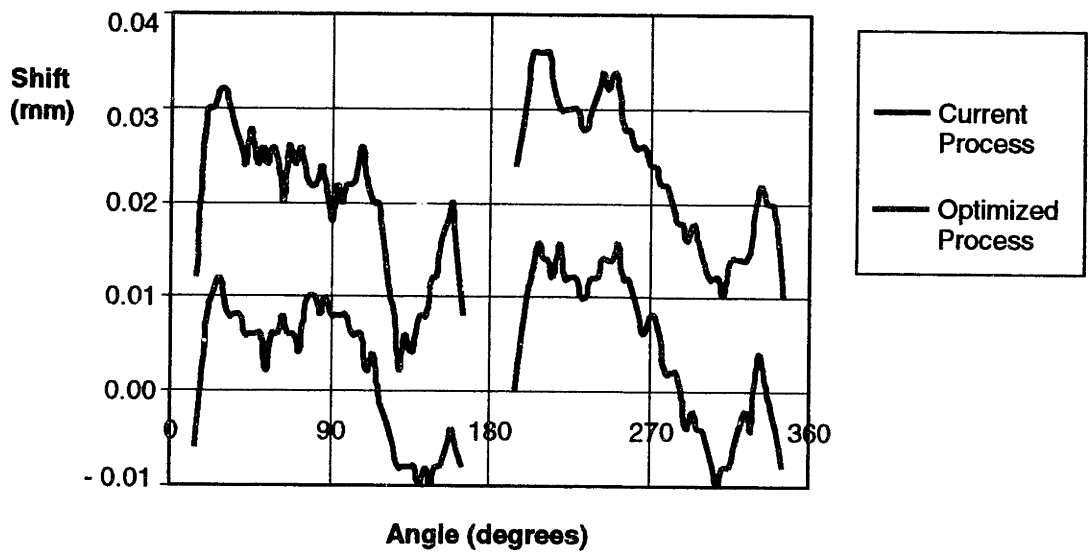

Figure 5-12. Current and Optimized Process Deformation after Ten Thermal Cycles*

5.2.11 Evaluate Potential Downstream Effects

Although the designed experiments indicate certain process changes should be implemented, it is important view the entire system to see what effects the change may have outside the test area. The material suppliers and downstream customers should be notified of the results. Changes at the component level may alter the assembly process.

In the plastic throttle body experiment the deformation results in some shrinkage of the bore diameter. The effect of this change would have to be evaluated. Deformation at the 90 and 270 degree locations are more likely to present a problem with stiction, interference between the bore diameter and the mating part, because these locations are furthest from the centerline of the shaft and would produce the largest moment.

An additional consideration is that a reduction in the mold temperature results in a larger bore diameter. The larger diameter may cause the assembly to have an unacceptable gap between the body and plate that cannot be filled by the adhesive paint.

* The data shown in this table is for illustrative purposes only and does not reflect the actual values of the experiment.

Additional testing was initiated at Visteon to determine the effect of the larger diameter on the production line and in regards to the performance of the throttle body assembly.

Since changes to the process and the tooling both effect the final shape and stability of critical dimensions, it is important that the two be developed in unison. Strong linkages between the processes reinforce the importance of the team approach. Separation of responsibilities and functional roles lead to independent optimizations. When working with precision components it is important for the plastics engineer, the design engineer, the manufacturing engineer and the tool maker to work closely together. Often slight changes effect the entire system and cannot be decoupled.

5.2.12 Adjust the Process

Once the results of the test are understood and proven, the next step is to take action. Sometimes the action is to make adjustments to the process parameters. If the program is in the initial development stages then there will be fewer barriers to the change. Adjustments to a customer validated process may require additional testing at the upper assembly level. Every organization has there own method of implementing engineering changes. The test reports generated during the DOE test series should support the proposed change.

In other situations the team may determine that the best action is to perform additional testing. In the throttle body test series the second set of tests revealed a shift in the bore diameter. Further investigation into the cause of the shift may uncover other process inputs or parameters for additional testing.

Design of experiments is a valuable learning tool. As the organization gains experience with setting up and conducting the DOE tests and analysis they will recognize the benefits of tuning the process during the development stage.

6.0 Predictive Methods

Another potential means of optimizing the process and the tooling is by analytical means. Computer Aided Engineering (CAE) flow analysis software for modeling the plastic injection molding process initiated in the 1970s and has been evolving rapidly along with the advancement in computing capabilities (*Moldflow 16*). Today there are various software packages to determine the flow rates and paths, assess the heat transfer efficiency, evaluate the stress, and predict shrinkage, warpage and fiber orientation.

The analysis tools allow the product and tool designers to evaluate their products before expensive tooling is manufactured. This can save considerable time and money, however many companies are not confident in the analyses methods so in most cases conservative measures are taken when designing and fabricating molds to allow for rework as necessary for fine-tuning.

Analysis programs are often used as troubleshooting tools to determine why a mold does not produce the desired part. Considerable capital is tied up in injection mold dies, and some companies only deem the analysis necessary as a means of salvaging existing tooling. As the capability of the software improves and the product and mold designs become increasingly complex, the trend is to invest in up front analysis to avoid costly errors.

A survey of companies in the plastic injection molding industry that have used CAE technology indicates that a small portion of companies feel they have benefited from using the software despite the fact that most felt the technology was valid. The companies that felt the software was a useful tool typically performed the analysis in the early stages of product development felt it served as a communication aid between the design, manufacturing and tooling departments. The software facilitated the concurrent efforts in the product and tooling design that was the most beneficial. (*Austin 2*)

The capabilities of injection molding analysis software are continuously increasing, and companies are relying on them more heavily in product and tooling design. However, the analysis is only as good as the model and the assumptions used, so all the work must be reviewed carefully to determine whether the results are credible. They are tools for the development team, not a substitute for knowledge of the injection molding process.

6.1 Visteon's Use of CAE Software

The Visteon Belfast Plant used CAE tools in the development of the plastic throttle body design. Their material suppliers, General Electric Polymer Group and Hoechst Technical Polymers Division, have performed several analyses using Moldflow® software to evaluate the fill pattern and to predict shrinkage and warpage (*Brounné 3*). The model of the component was constructed as mid-planes, meaning each section of the part was estimated as a shell of a certain thickness linked with adjacent shells. The mid-plane model provides adequate approximation for simple shapes, but the error of the analysis increases as the part geometry becomes more complex. The plastics engineer worked closely with technician performing the analysis. In some cases the analysis required several iterations before he was satisfied with the results.

It is important to back up the analysis with verification once the tooling has been fabricated and parts have been made. The feedback is an essential part of the learning process. In many cases parameters or assumptions can be adjusted so as to provide more accurate results for future analyses. This feedback is often overlooked if the parts are fabricated as expected. Only when the deviations are extreme does it seem to warrant further investment in the analysis. In other cases it becomes a matter of prioritizing the workload and placing a higher importance on the feedback communication.

Some of the analyses that were performed for the plastic throttle body design were validated through testing. For example, the prediction of the mold flow patterns was verified by conducting a series of progressive short-shots. This is when the amount of material injected into the cavity is undersized so that it does not completely fill the volume. The amount of injected material is progressively adjusted so the fill pattern for the material can be observed. A photograph of these samples is shown in Figure 6-1 below. The results of the analysis were compatible with the evidence from this experiment.

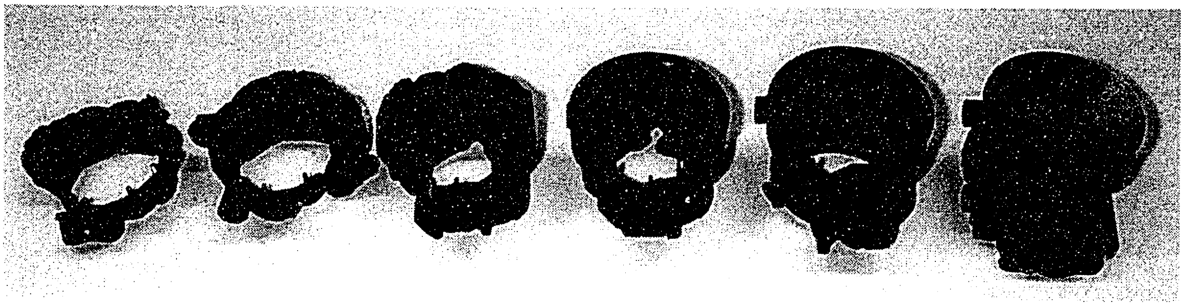

Figure 6-1. Samples from the Throttle Body Fill Pattern Evaluation.

The use of CAE techniques is common at Ford Motor Company, and they have the plastics process modeling capability at their technical research centers. These centers are often overloaded with requests for analysis as the number of plastic automotive components is rapidly increasing. As a result many new project areas within Ford, such as the Visteon plant in Belfast, have gone to outside sources for assistance with CAE analysis. There are documented success stories of CAE analysis, including a report on the Moldflow's website about Ford's success in solving shrinkage and warpage problems of trim panel components. Part of their solution involved the adjustment of the pressure profile to provide uniform transmission of the packing pressure across the part. (*Moldflow 16*)

The results from the design of experiments indicated that the mold temperature had the most significant effect on the amount of shift in the bore radius profile during thermal cycle testing. This conclusion is also supported by tests conducted at another Visteon plant that produces a similar product. Since this has been shown to be an important characteristic of the process it may warrant further investigation. Currently the patterns for the fluid within the tool and the temperature control system have been designed using engineering judgement. An analysis on the heat transfer efficiency of the mold tool may provide some additional information to support the test results indicating the mold temperature should be lowered.

6.2 CAE Tools

According to a representative from the Moldflow Company, one of the leading software companies in injection molding analysis, the software to predict the fill characteristics of an injection mold tool is the most commonly used in the product design and tooling development stages (*Longwell 12*). Precision injection houses have come to rely on this software to optimize the mold cavity design based on predictions the flow rates, shear rates, weld line locations, and fiber orientation. Predictions of shrinkage and warpage have improved dramatically over the past few years, however variations between analysis assumptions and actual conditions make it difficult to predict these with parameters with a high level of confidence.

The state of the art CAE tools are incorporating mesh elements for three dimensional analysis as opposed to the two dimensional mid-plane models used in most of the previous generations. Injection molding software designers are continuing to develop tools that are compatible with solid modeling computer aided design (CAD) software. This will save time because models for the analysis will not have to be reconstructed. They are also designing more user-friendly interfaces.

Most analysis software requires the designer to optimize the design by reacting to the results of the analysis. Cray Research has developed software to enhance the productivity of the industry standard plastic molding simulation software by incorporating design of experiments. The software allows the development team to evaluate the sensitivity of the mold parameters to the process prior to fabrication of the tool. (*Sgi 23*)

7.0 Conclusions

This thesis demonstrates the feasibility of using designed experiments as a structured approach to process evaluation. Plastics engineers typically set the process parameters based on experience, supplier recommendations, and a method of trial and error. This may be adequate for establishing initial parameters, but the complexity of the process and the interactions between various parameters may make it difficult to optimize using this method. By mapping out the effects of the process parameters within a certain window. The following conclusions were made based on the experiments:

- Design of Experiments is a viable method of optimizing the process parameters to minimize residual stress, and thus reduce the dimensional instability of critical features. The results clearly showed an operating point at which the bore profile of the throttle body is most stable.

- The selection of the response data is critical to the determination of the optimal process. In our experiment we were trying to optimize the stability of a circular shape. Determination of the results based on the mean diameter and the run-out would not be sufficient.

- The temperature of the cooling fluid has been demonstrated to have the biggest effect on the dimensional stability of the part. The efficiency of the cooling system has a significant effect on the amount of residual stress found in a part. For precision components the design of the cooling system of the tool is critical to the quality of the part.

- Process optimization to minimize residual stress should be performed in conjunction with the tooling evaluation. Changes to the process effect the pre- and post-thermal cycle dimensions. The tool should be fine tuned using the optimized process settings.

- A team approach is critical to the success of an in-depth analysis of the process. Up front discussions and planning are needed to address the issues of the experiments and evaluation. Theoretical and practical validation of the results will lead to team learning.

The DOE method of process analysis was successful in finding the relationship between the dimensional stability of a critical feature and five process parameters; cooling time, injection speed, melt temperature, holding pressure and cooling fluid temperature. The tests demonstrate the benefits of a structured approach to investigating the effects of the injection molding process parameters on the dimensional stability of the molded component.

7.1 Future Work

Based on the results of the evaluation of the injection molding process, Visteon should consider additional evaluation in the following areas:

- The results indicate that the process settings should be adjusted to reduce the temperature of the cooling fluid. Visteon must evaluate the throttle bodies and assemblies using the proposed process and determine if the change is acceptable. If additional criteria exist, then the response parameters must be established so that they can be evaluated with respect to the process settings. For example, it may be determined that although these parameters optimize the residual stress of the bore profile, they increase the stress at some other location of the part. This difference could be caused by the temperature distribution in the tool. In this case, the additional responses must be identified and quantified so that they can be included in the evaluation.

- Visteon should consider using simulation software in the development of the tool cooling passages for new projects. Mold temperature has shown to be the most significant process parameter in controlling the quality of the component. Establishing capabilities in efficient mold cooling will enhance their competence in precision injection molding.

- This method of evaluation may be used to determine the optimal process settings to minimize the dimensional instability of the other throttle body sizes and the plastic plates that mate with the critical interface.

- The method of evaluation may be used in other areas of the process. For example, the incoming material effects the quality of the part. Visteon should consider working with its suppliers to determine which characteristics of the material have the biggest impact on the quality of the end product. This would be valuable information to both companies.

- The team problem solving approach should be encouraged. Barriers to team learning are not easy to overcome. Visteon's management should take advantage of the opportunity presented in establishing a new process area of the plant. This is an opportunity to cultivate a cooperative work culture. It is important to grow this area of the organization as an integrated team rather than allow the group to become departmental in its decision making.

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Appendices

Appendix A

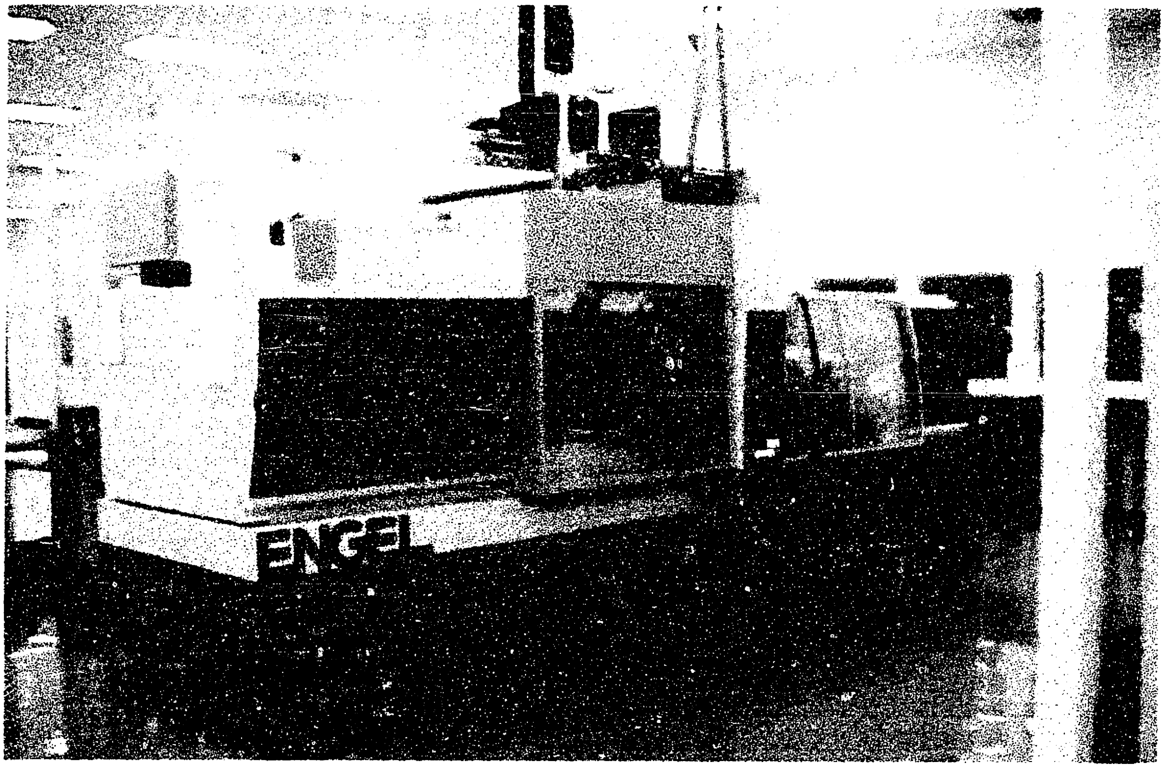


Figure A-1. Engel Automated Plastic Injection Molding Equipment.

Figure A-2. Shop Floor and Expansion Area.

Figure A-3. Injection Mold Tooling (Closed)

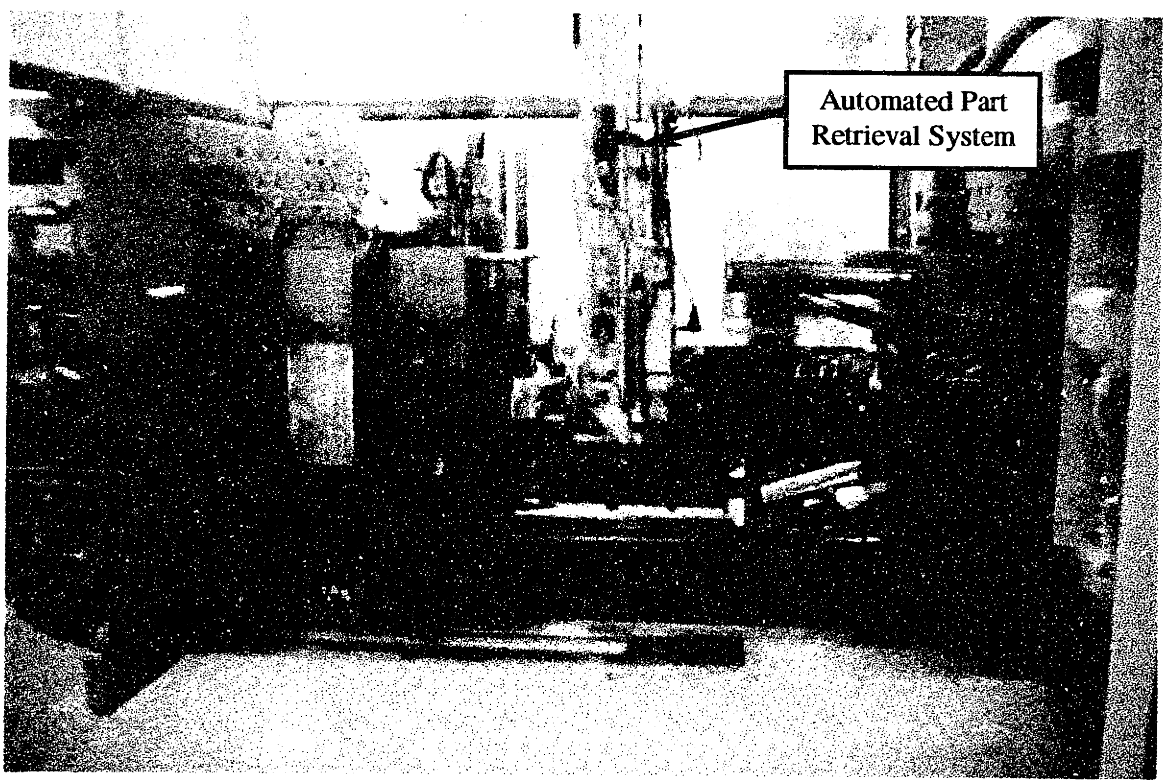


Figure A-4. Injection Mold Tooling (Open)

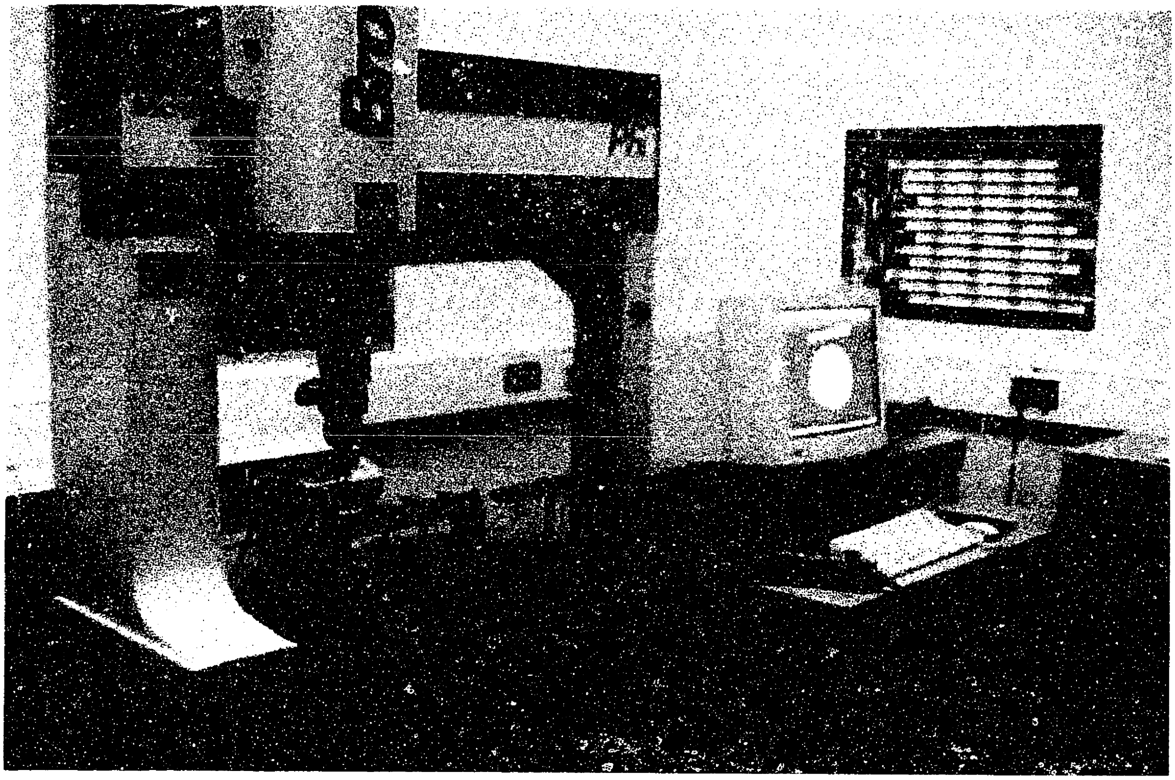


Figure A-5. Coordinate Measurement Machine (CMM) Inspection Equipment.

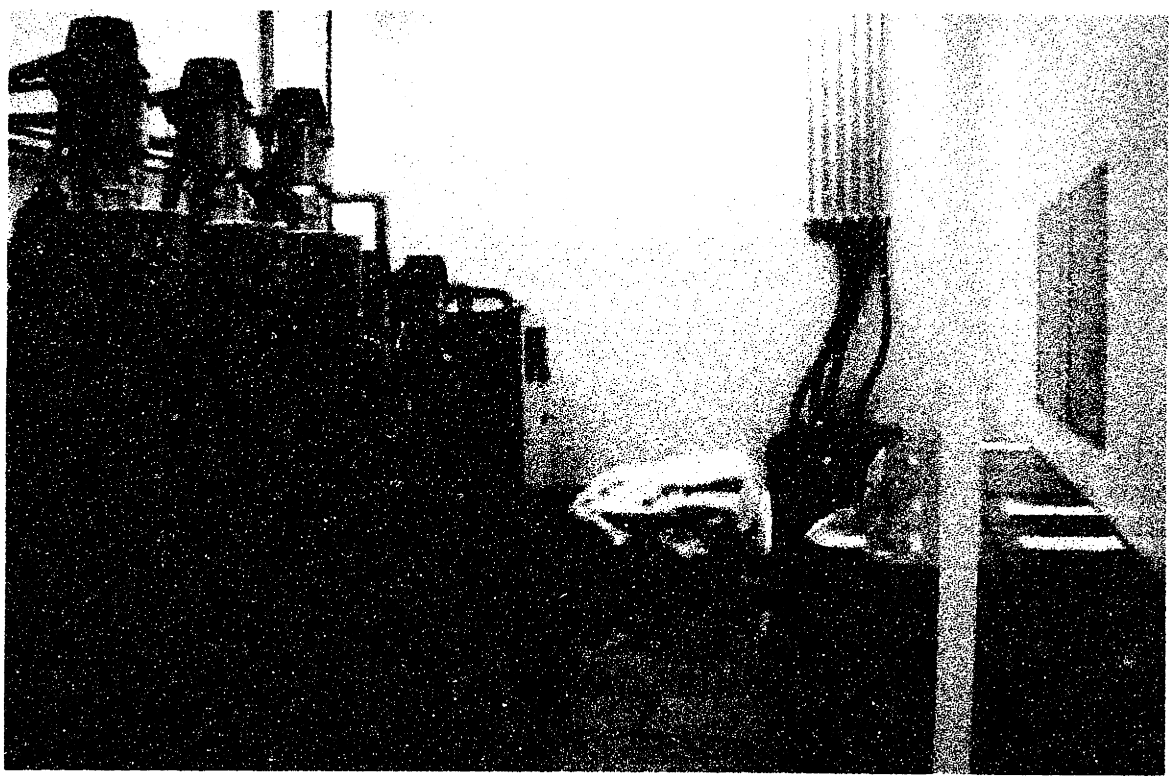


Figure A-6. Drying Columns, Vacuum Transfer Lines and Resin Granule Storage Bins.

Appendix B

DATA SUMMARY FOR DIMENSIONAL SHIFT

Note: The data presented is for illustrative purposes and has been altered from the actual experimental results.

Replicates of the baseline and half the runs are designated with a "B" or "M" with numeric value.

Feature:	8 PT BORE RADIUS AVERAGE				FLANGE FLATNESS			
	DIMENSIONAL SHIFT AFTER				DIMENSIONAL SHIFT AFTER			
	3 THERMAL CYCLES		10 THERMAL CYCLES		3 THERMAL CYCLES		10 THERMAL CYCLES	
Group	MEDIAN	STD DEV	MEDIAN	STD DEV	MEDIAN	STD DEV	MEDIAN	STD DEV
1A	0.018	0.006	0.017	0.005	0.002	0.006	0.005	0.005
1B	0.014	0.006	0.011	0.006	0.005	0.010	0.014	0.003
2A	0.026	0.008	0.026	0.008	-0.017	0.013	-0.003	0.016
3A	0.022	0.007	0.025	0.008	0.014	0.015	0.009	0.020
3B	0.017	0.006	0.018	0.007	0.012	0.011	0.013	0.011
4A	0.020	0.006	0.021	0.007	0.001	0.017	-0.008	0.017
5A	0.031	0.009	0.032	0.010	0.016	0.007	0.016	0.005
5B	0.029	0.010	0.031	0.010	0.019	0.004	0.019	0.007
6A	0.033	0.011	0.035	0.011	-0.002	0.017	-0.004	0.013
7A	0.018	0.006	0.015	0.005	0.001	0.007	0.003	0.011
7B	0.015	0.005	0.014	0.005	-0.001	0.009	0.001	0.005
8A	0.021	0.007	0.022	0.007	-0.019	0.014	-0.013	0.019
9A	0.035	0.011	0.039	0.012	0.032	0.010	0.031	0.016
9B	0.035	0.011	0.039	0.012	0.035	0.012	0.027	0.009
10A	0.032	0.010	0.035	0.011	0.007	0.011	-0.004	0.018
11A	0.022	0.007	0.022	0.007	-0.001	0.010	-0.001	0.010
11B	0.023	0.007	0.021	0.007	0.006	0.004	-0.009	0.018
12A	0.013	0.004	0.011	0.003	-0.013	0.009	-0.021	0.017
13A	0.022	0.008	0.023	0.008	0.016	0.005	0.015	0.012
13B	0.027	0.008	0.027	0.008	0.014	0.004	0.012	0.005
14A	0.014	0.005	0.011	0.004	-0.004	0.012	-0.007	0.012
15A	0.033	0.010	0.037	0.012	0.003	0.013	0.007	0.012
15B	0.033	0.010	0.036	0.012	0.012	0.016	0.009	0.011
16A	0.026	0.009	0.031	0.010	0.001	0.027	-0.001	0.018
M1	0.029	0.009	0.032	0.010	0.011	0.011	0.012	0.010
M2	0.025	0.008	0.027	0.009	-0.012	0.011	0.005	0.012
M3	0.022	0.007	0.023	0.007	0.001	0.003	0.001	0.003
M4	0.029	0.010	0.032	0.010	0.014	0.008	0.010	0.009
M5	0.029	0.009	0.031	0.010	0.006	0.017	0.008	0.015

DATA SUMMARY FOR DIMENSIONAL SHIFT

Note: The data presented is for illustrative purposes and has been altered from the actual experimental results.

Replicates of the baseline and half the runs are designated with a "B" or "M" with numeric value.

Feature: BEARING DIAMETER AT LEVER / BEARING DIAMETER AT TPS

		BEARING DIAMETER AT LEVER				BEARING DIAMETER AT TPS			
		DIMENSIONAL SHIFT AFTER				DIMENSIONAL SHIFT AFTER			
		3 THERMAL CYCLES		10 THERMAL CYCLES		3 THERMAL CYCLES		10 THERMAL CYCLES	
Group		MEDIAN	STD DEV	MEDIAN	STD DEV	MEDIAN	STD DEV	MEDIAN	STD DEV
1A		-0.003	0.002	-0.003	0.001	0.000	0.001	0.000	0.001
1B		-0.002	0.000	-0.003	0.000	0.000	0.000	0.000	0.001
2A		-0.004	0.001	-0.002	0.000	0.000	0.002	0.001	0.001
3A		-0.002	0.000	0.000	0.006	0.001	0.001	0.004	0.003
3B		-0.002	0.000	-0.003	0.001	0.000	0.001	0.002	0.001
4A		-0.002	0.000	0.000	0.006	0.001	0.001	0.004	0.003
5A		-0.002	0.000	-0.002	0.001	0.002	0.000	0.004	0.001
5B		-0.002	0.001	-0.002	0.000	0.003	0.000	0.004	0.001
6A		-0.001	0.000	-0.001	0.001	0.002	0.000	0.005	0.001
7A		-0.003	0.004	-0.005	0.003	0.002	0.000	0.001	0.000
7B		-0.001	0.000	-0.003	0.001	0.001	0.001	0.001	0.001
8A		-0.004	0.000	-0.002	0.002	-0.001	0.000	0.002	0.000
9A		-0.001	0.001	-0.003	0.002	0.002	0.001	0.002	0.001
9B		-0.001	0.001	-0.002	0.001	0.003	0.001	0.003	0.001
10A		-0.001	0.000	-0.003	0.001	0.003	0.001	0.005	0.003
11A		-0.002	0.000	-0.002	0.001	0.002	0.001	0.003	0.001
11B		-0.003	0.000	-0.001	0.006	0.002	0.001	0.002	0.002
12A		-0.003	0.000	-0.004	0.000	0.002	0.000	0.001	0.001
13A		-0.002	0.000	-0.002	0.001	0.000	0.001	0.002	0.001
13B		-0.002	0.000	-0.003	0.000	0.002	0.000	0.004	0.001
14A		-0.003	0.000	-0.003	0.001	0.000	0.000	0.001	0.000
15A		-0.002	0.000	-0.004	0.001	0.002	0.002	0.004	0.000
15B		-0.001	0.000	-0.003	0.001	0.003	0.002	0.004	0.001
16A		-0.001	0.001	-0.002	0.002	0.003	0.001	0.004	0.000
M1		-0.001	0.001	-0.001	0.000	0.002	0.000	0.002	0.001
M2		-0.002	0.005	0.000	0.005	-0.001	0.000	0.002	0.000
M3		-0.003	0.000	-0.003	0.000	-0.001	0.001	0.002	0.001
M4		-0.002	0.000	-0.003	0.000	0.002	0.000	0.003	0.000
M5		-0.002	0.001	-0.002	0.001	0.001	0.000	0.004	0.001

DATA SUMMARY FOR DIMENSIONAL SHIFT (Continued)

Note: The data presented is for illustrative purposes and has been altered from the actual experimental results.

Replicates of the baseline and half the runs are designated with a "B" or "M" with numeric value.

Feature: BORE DIAMETER MEAN OF RADIUS | BORE DIAMETER ROUNDNESS

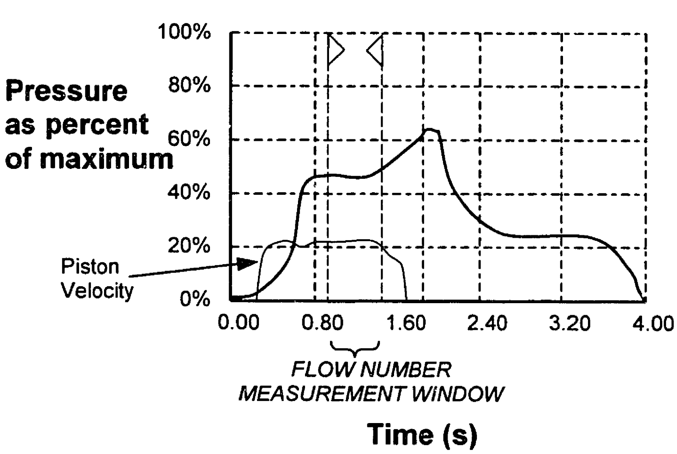
	BORE DIAMETER MEAN OF RADIUS — DIMENSIONAL SHIFT AFTER				BORE DIAMETER ROUNDNESS — DIMENSIONAL SHIFT AFTER			
	3 THERMAL CYCLES		10 THERMAL CYCLES		3 THERMAL CYCLES		10 THERMAL CYCLES	
Group	MEDIAN	STD DEV	MEDIAN	STD DEV	MEDIAN	STD DEV	MEDIAN	STD DEV
1A	0.010	0.001	0.009	0.001	0.002	0.001	0.003	0.001
1B	0.011	0.001	0.010	0.002	0.002	0.002	0.003	0.002
2A	0.013	0.001	0.014	0.002	-0.003	0.009	0.002	0.003
3A	0.012	0.001	0.013	0.001	0.003	0.002	-0.002	0.011
3B	0.010	0.001	0.011	0.000	0.002	0.001	0.002	0.002
4A	0.011	0.001	0.012	0.001	0.000	0.004	-0.002	0.007
5A	0.016	0.001	0.018	0.001	0.002	0.001	0.003	0.002
5B	0.016	0.001	0.017	0.000	0.004	0.002	0.003	0.001
6A	0.018	0.001	0.019	0.001	-0.001	0.002	-0.003	0.001
7A	0.009	0.001	0.008	0.001	-0.003	0.001	-0.004	0.001
7B	0.009	0.000	0.008	0.000	-0.003	0.002	-0.004	0.002
8A	0.011	0.001	0.012	0.001	-0.002	0.001	-0.004	0.001
9A	0.020	0.000	0.022	0.001	-0.001	0.003	-0.001	0.003
9B	0.020	0.000	0.022	0.000	-0.002	0.002	-0.001	0.002
10A	0.018	0.001	0.019	0.002	0.001	0.003	-0.006	0.016
11A	0.012	0.001	0.012	0.001	0.000	0.002	0.000	0.003
11B	0.012	0.001	0.012	0.001	0.001	0.002	-0.003	0.012
12A	0.007	0.000	0.005	0.001	0.000	0.003	0.000	0.004
13A	0.013	0.002	0.013	0.002	-0.001	0.002	0.000	0.002
13B	0.015	0.000	0.014	0.000	0.000	0.002	0.000	0.001
14A	0.007	0.001	0.006	0.000	0.000	0.001	0.001	0.002
15A	0.017	0.001	0.020	0.001	-0.004	0.001	-0.005	0.001
15B	0.018	0.001	0.020	0.001	-0.003	0.001	-0.004	0.001
16A	0.015	0.001	0.017	0.001	-0.003	0.001	-0.004	0.002
M1	0.016	0.000	0.016	0.001	-0.004	0.001	-0.003	0.001
M2	0.014	0.000	0.015	0.001	-0.002	0.000	-0.003	0.000
M3	0.011	0.001	0.013	0.001	-0.002	0.001	-0.002	0.001
M4	0.017	0.001	0.017	0.000	-0.001	0.002	-0.001	0.002
M5	0.015	0.001	0.017	0.001	0.002	0.007	0.001	0.003

Appendix C

Description of Flow Number

The injection molding machines at the Visteon facility in Belfast were manufactured by Engel. The equipment has in-process monitoring capabilities for the injection phase through the Microplast and Microflow programs. These programs calculate a "flow number" based on the injection energy as measured by the machine control system and built-in hydraulic pressure sensors in the injection cylinder. The flow number can be used to determine the stability of the injection process. Process limits for the flow number can also be set to detect anomalies.

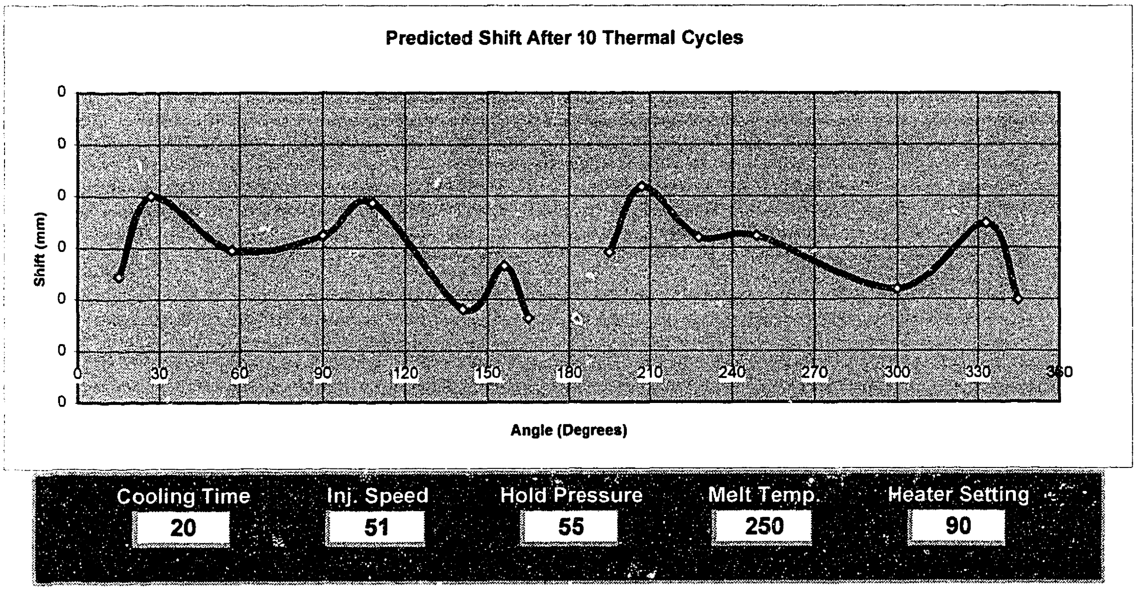
The required injection pressure for a given type of plastic and mold design depends on the viscosity and temperature of the material as well as the injection speed. If the melt temperature and the injection speed profile are consistent from shot to shot then the material viscosity can be inferred from a hydraulic pressure measurement taken during the injection phase. The graph below shows the measurement window that must be set in order to eliminate the variation that occurs during the initial acceleration of the piston and during the final compression of the material. This measurement gives an indication of the flowability of the material that may be effected by variations in viscosity due to variations in the material, changes in the fiber content, moisture or contamination.



Appendix D

Prediction Model

Microsoft Excel Spreadsheet:
Interactive Graph of Dimensional Shift



Coefficients used in Prediction Model

Coefficients	15	27 *	57 *	90	108 *	141	156 *	165
Constant	0.009125	0.016500	0.010063	0.012437	0.016063	0.005875	0.011375	0.005813
A: Cooling Time	-0.001500	-0.002125	-0.001187	-0.001187	-0.001687	-0.001875	-0.002250	-0.002187
B: Inj. Speed					-0.001063			
C: Holding Press.			-0.001063		-0.001188	-0.001375	-0.001250	
D: Melt Temp.					0.000938	0.000625		
E: Heater Setting	0.003375	0.003625	0.002188	0.002438	0.003813	0.003875	0.005375	0.004812
AB: Cool Time*Inj. Speed			0.000687			0.000875	0.001250	
AE: Cool Time*Heater Setting			0.000687		0.001063	0.000625		
CD: Holding Pres.* Melt Temp.		0.001625	0.001563		0.001687	0.000875		
CE: Holding Pres.*Heater Set.						-0.000625		

Coefficients	195	207 *	228	249 *	300 *	333 *	345	8pt Avg
Constant	0.011813	0.018250	0.012375	0.013063	0.006750	0.014625	0.007313	0.013313
A: Cooling Time	-0.001437	-0.001750			-0.001375	-0.002125	-0.001812	-0.001562
B: Inj. Speed								
C: Holding Press.			-0.001125	-0.001562	-0.001625	-0.001625	-0.000938	-0.001187
D: Melt Temp.		0.001375				0.000875		
E: Heater Setting	0.003688	0.003125	0.001375	0.001938	0.003125	0.004625	0.004188	0.003438
AB: Cool Time*Inj. Speed						0.000875	0.000812	
AE: Cool Time*Heater Setting					0.001000	0.000875		
CD: Holding Pres.* Melt Temp.		0.001500	0.001375		0.001375	0.000875	0.000937	0.001187
CE: Holding Pres.*Heater Set.								

* : Location considered in 8 point average.

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