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A Practical Guideline for Establishing Non-Return Valve Specification and Performance Criteria

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A PRACTICAL GUIDELINE FOR ESTABLISHING NON-RETURN VALVE SPECIFICATION AND PERFORMANCE CRITERIA

by

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A PRACTICAL GUIDELINE FOR ESTABLISHING NON-RETURN VALVE SPECIFICATION AND PERFORMANCE CRITERIA

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The non-return valve has been a standard piece of equipment in the injection molding industry since the reciprocating screw was developed. Most molders understand the role of the non-return valve in the molding process. But few understand the functional problems of the non-return valve. Because of this, the non-return valve has been considered a nuisance item for injection molders.

Wear of the non-return valve is another problem that molders are faced with. The factors contributing toward wear are not entirely understood. Material, temperatures, hours and machine size, etc., all effect the life of a valve. Consequently, most worn valves are not discovered until there is a problem during molding. The molder must either adjust the process or shut the machine down for unscheduled maintenance. Therefore, a methodology for establishing predictive maintenance guidelines would be beneficial.

This methodology will give the molder a practical guide for specifying, evaluating, and maintaining non-return valves.

TABLE OF CONTENTS

Table of Contents-Continued

CHAPTER

Table of Contents-Continued

CHAPTER

Table of Contents-Continued

CHAPTER

Table of Contents-Continued

CHAPTER

Table of Contents-Continued

CHAPTER

Table of Contents-Continued

CHAPTER

LIST OF TABLES

LIST OF FIGURES

List of Figures-Continued

CHAPTER I

INTRODUCTION

Background

The injection molding industry has continuously evolved since the development of the early plunger machines. At the heart of this evolution is the injection molding machine. The injection molding machine has undergone many iterations in order to take advantage of today's level of technology.

Early machine improvements were driven by molders' need for basic functions on the machine such as fill clocks and accurate temperature controls. This was made possible through the use of solid state circuitry (Chabot, 1992). Later improvements came at the demand for more consistent, higher quality parts. Machine manufacturers were consequently pushed to build more robust machines that had better resolution and control over their functions. These technological advances also allowed machine manufacturers to implement control methods that allowed the molder to have a much better interface with the machine with the use of computers.

These improvements encompassed the entire machine by including the mechanical, hydraulic, and electrical systems. As technology became available, each of these systems has undergone major re-engineering, contributing to the overall improvement of machine performance and repeatability. While machine manufacturers have made much progress, there are components that have changed little during the evolution of the injection molding machine. The non-return valve, or check valve, is one of these components.

The introduction of the reciprocating screw in the early 1950's was made possible with a non-return valve (Dubois, 1972; Rees, 1994). The reciprocating screw is significant because it produces a uniform melt quality that had previously been lacking. Up to this point in time, material (resin) was melted and injected using a heated plunger assembly. Temperature of the material is a direct function of residence time and the temperature of the barrel. Since there is no mixing of the material as it moves through the barrel, the material closest to the barrel wall is the hottest with the material in the center being the coolest. This effect is further compounded as the size of the barrel increases in diameter, especially since polymers are an excellent insulator (Society of the Plastics Industry, 2001). This type of system resulted in poor melt quality due to the temperature stratification of the material and often resulted in numerous defects such as short shots, flash, burn marks, discoloration, etc. Many attempts were made to minimize this effect, such as placing a heated "torpedo" in the center of the melt stream, but to marginal success.

Screws were in use in the extrusion industry during this time and were proven to provide a uniform melt quality. The early attempts to integrate the screw into the molding process were accompanied by an inability to adequately transmit plastic pressure into the mold cavity during the injection process. This was due to the molten material flowing back along the flights of the screw since there was no mechanical method to prevent two-way flow. Attaching a non-return valve to the end of the screw solved this by adding the function of a plunger to a melting screw (Rees, 1994). A typical three-piece non-return valve is shown in figure 1. The valve's primary function is that of a one-way check valve. The check valve allows the melted polymer to flow through the valve during the plastication process (Lokensgard, 2004).

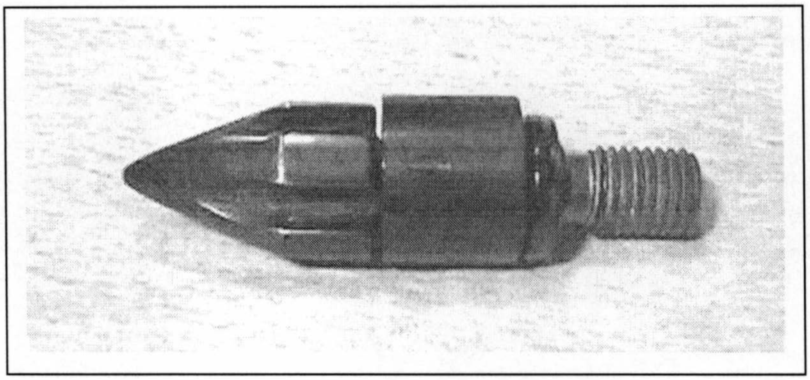


Figure 1. EMI Three-Piece Non-Return Valve.

The valve then closes, allowing the screw and valve to function together as a piston, and molten plastic is injected into the mold (Figure 2). The secondary function of the non-return valve is that of a governor. The passages and geometry of the valve create a restriction through the valve that affects the plastication process (Isayev et al., 1995). This restriction increases the pressure required for the polymer melt to flow through the valve. This is known as the pressure loss through the valve. Proper restriction is essential for many polymers, especially crystalline or shear sensitive polymers, to be properly melted.

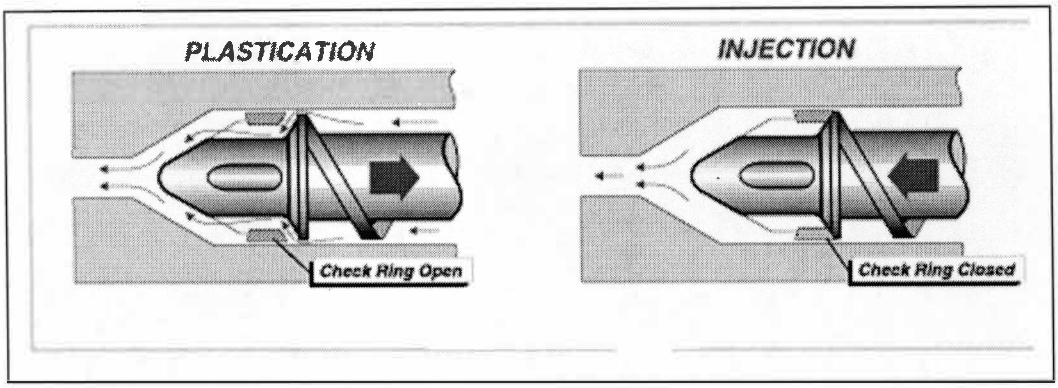


Figure 2. Typical Ring-Style Non-Return Valve in Open and Closed Position (www.ticona.com, 2006).

Problem Statement

Non-return valve specification has predominately been left to machine manufacturers and valve suppliers. Unfortunately, few valve suppliers understand their own product as shown by the lack of performance data to support their claims. Valve performance is affected by many things including: machine component wear, resin viscosity and molding process variables. The magnitude of these effects are not clearly understood, and consequently, there is not much published on the subject.

There is little uniformity in the industry as to certain qualifications of valve features as well. Terms such as "free flow" are used loosely to describe a valve with less restriction. However, the criteria for free-flow designs vary widely between manufacturers.

The availability of many valve choices on the market makes it difficult for molders to decide which valve will best suit their needs. Molders cannot afford to interrupt production in order to test valve performance. There is little published in terms of standardized testing for non-return valves. Without the data to make sound valve specification and evaluation decisions, molders will continue to struggle with this element of process variation.

Molders also have a difficult time interpreting valve wear. As a valve wears, it is not clearly known how the process is affected. This is exhibited by the practice of changing valves, whether it is needed or not, at predetermined time intervals. However, most molders only question the condition of the non-return valve when signs of failure become a nuisance.

Finally, valve performance impacts the bottom line of the company. How does the performance of the non-return valve relate to the cost of quality? All of these issues have been investigated, to some extent, by leading manufacturers. However, there is little published data to share and build on.

PCIM Consortium

The Premier Class Injection Molding (PCIM) Consortium was founded in 1991 in order research, develop, and implement technology into the injection molding process. The members that comprised PCIM at the time of the study include: ADAC Plastics, Cascade Engineering, Prince Corporation, and Wright Plastic Products.

Previous research was carried out by Ferris State University and Western

Michigan University (WMU) and based on industry needs. Research activities were performed at universities and member's molding facilities. The end goal was to provide the member companies with practical tools and information to be used by technical personnel at the plants.

PCIM has initiated a number of projects to help answer questions about certain technologies as well as developing guidelines for implementation. The most ambitious project was the shot-to-shot repeatability experiments. The project was initiated in 1992 and completed in early 1996. The purpose of these experiments was to understand the effects (magnitude and variation) that process variables had on product weight and dimensions. The experimentation was performed using both amorphous and crystalline resins that were in common use among the consortium members. This project provided insight in the mechanisms that control process variation when switching between machines or different grades of materials.

The shot-to-shot study helped to answer many questions held by the consortium members. However, there was a large degree of product variation that remained unanswered. Discussions for identifying the next phase of research led to the topic of the non-return valve. It was agreed there was a lack of knowledge pertaining to this key piece of equipment and its effect on the injection molding process. Therefore, a study was proposed to explore the variables that affect the performance of the non-return valve.

Expected Results

This research produced information and methodology that give the molder tools to use for specifying, evaluating, and maintaining non-return valves which best meet the molders needs. Initial goals included:

- Investigation of both amorphous and crystalline materials and process variables that affect the performance of the non-return valve.
- Develop specific procedures to quantify the performance of the non-return valve as part of the injection unit.
- Understand the effect that wear has on the performance of the non-return valve and how to compensate for it.
- Understand the economic conditions that will help the molder justify the cost of valve replacement.

CHAPTER II

REVIEW OF RELATED LITERATURE

With all of the advances in machine control and technology, the demands on the injection molding industry to produce quality parts has not subsided. Quality levels are being achieved in manufacturing today that were recently unattainable. Many companies are requesting that quality levels be met to a minimum of +/- six sigma (σ) or better. These quality targets are migrating into the injection molding industry. Molders are consequently looking for further ways to reduce product variation. The non-return valve is one of the items suspected of contributing variation to the process (Rosato & Rosato, 1990).

The non-return valve has been a standard piece of equipment in the injection molding industry since the reciprocating screw was developed (Dubois, 1972). Most molders understand the function the non-return valve plays in the molding process, yet few understand the nature of the non-return valve. The improvements in machine monitoring and control have helped shift the industry's perception of injection molding from a black art towards a scientific process. However, the proper operation of the non-return valve remains unclear for many injection molders. Because of this, the non-return valve has been considered a nuisance item for injection molders.

Types of Non-Return Valves

There are three predominate styles of non-return valves, with a minimum of ten design classifications, available to the injection molder (Martin, 1993; Heat Tech Systems, 2007). The ball check and ring styles have been around since the early days of the reciprocating screw. Today's designs have not changed substantially from the original designs. The basic designs include the ring-type style, ball valve and poppet or piston types.

The ring-type is the predominate valve used in the industry followed by the ball type. The piston or poppet style are the least used. Each of these styles has many different design variations, such as mixing or free-flow, in an attempt to enhance valve performance and maintenance.

Ring-Type Valves

The ring-type valve is the most widely used valve in the industry today (Galli, 1993; Rosato et al., 2000; Heat Tech Systems, 2007). Ring-type valves can be processed with a wide range of polymers. They tend to work better with the higher viscosity resins than ball-type valves (Wormer & Durina, 1994). There are three, four, and five-piece valve designs. Each of these iterations stems from the previous design in order to reduce the cost of both manufacturing and maintenance. The three-piece valve consists of a body, ring and rear seat as shown in Figure 3. The tip and front seat are integral to the body. The rear seat and ring are designed to be replaced as they wear.

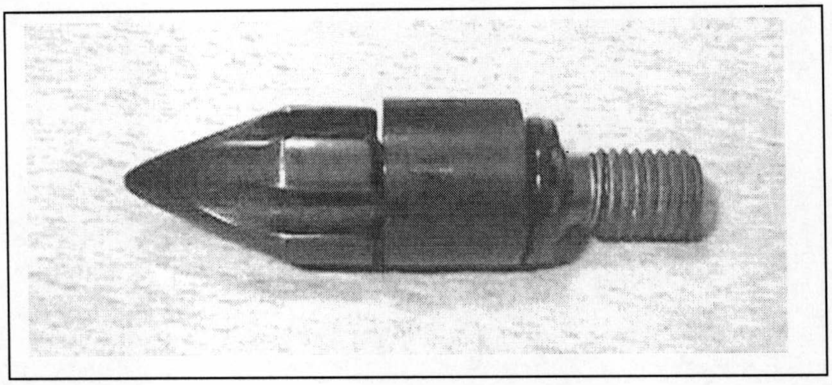


Figure 3. EMI Three-Piece Free-Flow Ring-Type Valve.

The four-piece valve is identical to the three-piece valve in geometry, except that it has a replaceable front seat as shown in Figure 4. Both the ring and front seat can be high wear items under certain processing conditions (www.zeigerindustries.com, 2007). Therefore, they were designed as replaceable

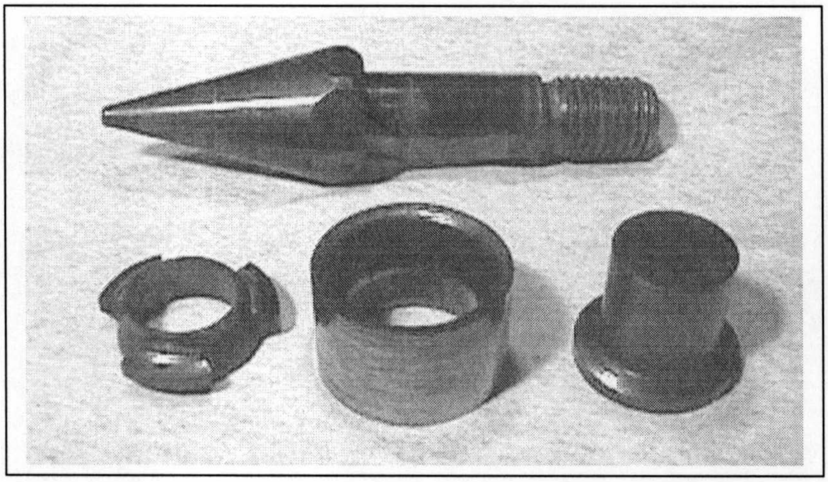


Figure 4. Four-Piece Ring-Type Valve. (Counter-clockwise from top) Tip, Front Seat, Ring, and Rear Seat.

components. The five-piece valve has a separated rear seat and spacer that is normally one piece in both the three and four-piece designs. There are also variants, such as Zeiger Industries Zpringlok® valve, which uses a spring to close the valve instead of valve movement (Zeiger Industries, 2007).

Free-Flow Valves

There are also valves classified as "free-flow" that have fewer restrictions and dead spots than traditional designs. These valves are designed to use with shear sensitive or highly filled materials (Olmsted & Davis, 2001). There is typically a larger than normal cross-sectional area between the ring and the body of the valve. The flow-path through the tip also has a more direct route to travel with fewer restrictions as shown in Figure 5.

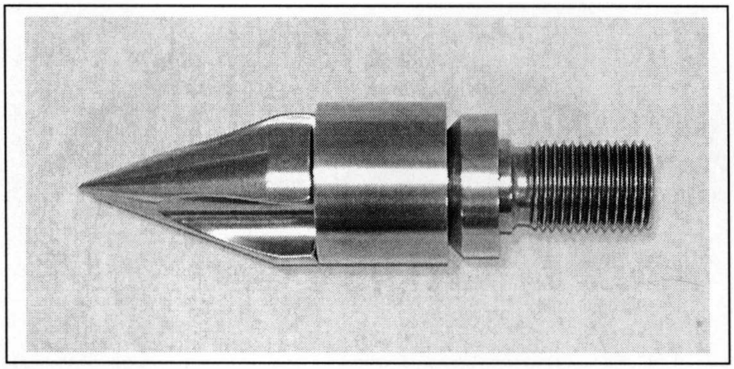


Figure 5. Three-Piece Free-Flow Valve. Notice the Unrestricted Flow Passages Through the Tip.

These modifications have helped reduce the shear rate through the valve. There is currently no industry standard for the design or performance requirements of a free-flow valve (Galli, 1993).

A descriptive term was devised to describe the degree of "free-flow" that a valve exhibits. This is called the Free-Flow Index. The index is the relationship of the cross-sectional of the area through the valve body compared to the cross-sectional area at the metering section of the screw as shown in Figure 6. The index will give the molder a starting point for determining whether or not a valve meets the molder's needs.

This is an important consideration for shear sensitive materials and highly crystalline materials. If the index value is too low, shear sensitive materials may be affected. If the index value is too high, then highly crystalline materials, such as nylon, may not melt properly. The screw may freeze to the barrel, prohibiting turning. In the worst case, the screw may even break.

It was during this portion of investigation that it was realized that screws have a pre-determined diameter at the screw face regardless of the depth specified at the metering section of the screw. This diameter matches up to the dimension of the retainer, or rear seat, of the non-return valve. For example, a 35 mm Van Dorn screw has a 30 mm mating diameter between the end of the screw and non-return valve. This dimension does not seem to have a basis for its origin. That is, the dimensions are clean whole numbers that do not translate into a certain percentage of diameters or areas. A 60 mm Toshiba screw has a 50 mm mating diameter.

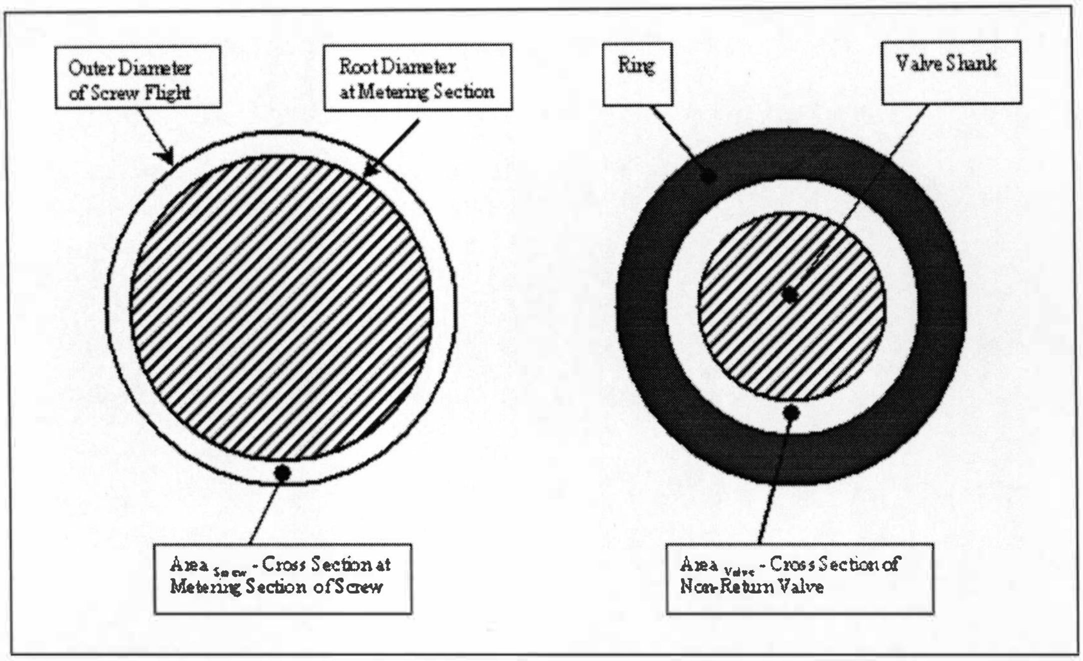


Figure 6. Picture of Free Flow Cross Section.

$$\text{Free-Flow Index} = \text{Area}_{\text{Valve}} / \text{Area}_{\text{Screw}}$$

If the free-flow index > 1, then the valve is less restrictive than the screw.

If the free-flow index < 1, then the valve is more restrictive than the screw.

In every case that was observed, there was a localized area between the screw and valve that was more restrictive than the metering section of the screw. This feature was incorporated into either the end of the screw or the rear seat of the valve. The land length of this area is relatively small and in most cases tapered down to the root diameter. This may become important when specifying a valve to have a less restrictive, or free-flow, design for shear sensitive materials.

In talking with several screw suppliers, it was revealed that some screw manufacturers have a second, smaller, diameter at the screw face for screws specified with a low compression ratio. This means that the advantage of the deeper metering section is not compromised. These screw manufacturers also supply non-return valves with rear seats to match the smaller screw face diameter.

Ball-Check Valve

The ball-check valve is typically recommended for materials that are not shear sensitive due to the restrictive flow path for the resin. They are recommended for use with low viscosity and unfilled resins. The ball-check closes quickly and repeatedly for these materials and is the primary market for these valves (Wormer et al., 1994). There are two main styles of ball-check styles available. The original front-discharge type and the side-discharge type.

The side-discharge type was developed to have fewer restrictions acting on the melt by allowing material to exit out the sides of the valve (Colby et al., 2006). A typical side-discharge type is shown in Figure 7. The ball can be replaced in both types of valves as it wears.

There are also valve designs of this type that have been designed with a replaceable rear seat. Wear of the ball or rear seat will effect the ability of the valve to shut-off consistently.

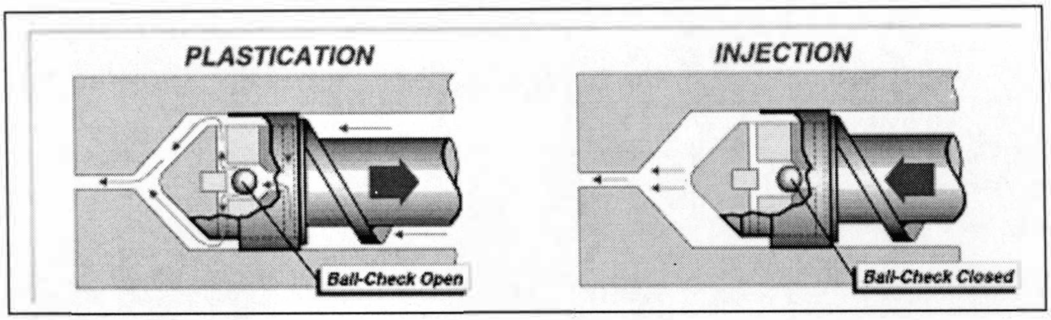


Figure 7. Typical Ball-Check Valve in Open and Closed Position (www.ticona.com, 2006).

Piston-Type Valves

Both ball and ring valve designs rely on forward screw movement to close the valve. As the screw moves forward, the ball or ring remains stationary until contacted by the rear seat. The problem with these valve styles is that resin viscosity affects valve shut-off. Higher viscosity resins add more resistance to valve closure. Both forward movement of the screw and high resin viscosity contribute to performance related variability of the non-return valve (Galli, 1993). The piston valve was designed to lessen the impact of these two factors, and thus, reduce the variation between shots over conventional valves.

The piston design isolates the closure mechanism from screw movement. This design reduces the effect material viscosity has on the valve's performance. In addition, the shut-off mechanism is not exposed to the same type of wear conditions as ball and ring-type valves. Therefore, valve shut-off performance should not deteriorate over time (Dray, 1994).

Piston-type valves have a piston internal to the valve body. Initial piston valves relied on forward movement to close the valve. Later piston type valves relied on a spring to pull the pin back after screw recovery in order to close the valve. While these valves functioned well in many cases, initially there were problems with these types of valves. The melt channel through the valve body tended to be too restrictive for certain materials, causing excessive shear in the material due to the restrictive flow path. Early versions of the spring valve had problems with the piston mechanism failing. The springs had poor life expectancy due to the constant heat load and harsh environment (Dray, 1994). Finally, filled materials still present a problem by wearing both the piston and the passage that seals the piston. This wear occurs as the valve closes if the fillers are small enough to fit, or wedge, between the sealing surfaces. Recent design innovations, however, have been made to reduce or eliminate these issues.

One of the latest styles of piston valves on the market is the Repeater® as shown in Figure 8. This valve relies on melt pressure to shut the valve instead of a

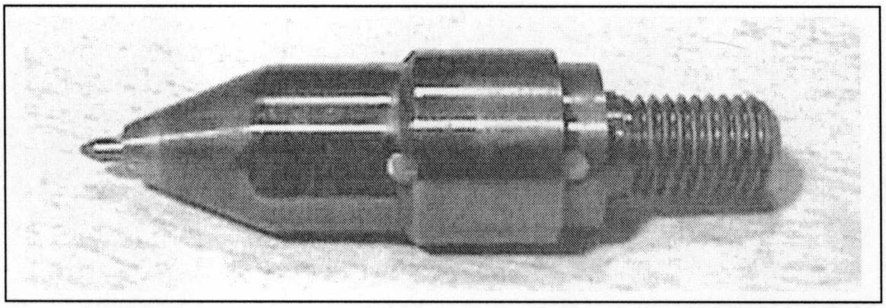


Figure 8. Repeater® Piston-Type Valve.

spring (www.usvalves.com, 2007). The area of the piston exposed to melt pressure is larger in the front than in the back. Therefore, the differentially higher melt pressure in front of the valve tip forces the piston closed. Research has shown this valve to reduce shot weight variation compared to a ring type valve when processing certain high viscosity resins (Dray, Stroup & Gregory, 1992; Lai & Sanghvi, 1993; Engelmann & Vander Kooi, 1995).

Design Optimization

With all of the different design options available to the processor, the ability to make a good decision on which valve to use is a guess at best without data to back up performance. This is why most processors end up using the standard OEM valve. This process is further compounded by the fact that each machine manufacturer has a preferred geometry for their injection unit, which influences the overall valve length and tip angle. One group of researchers tried to shed some light on this by conducting a study investigating how design geometry of the non-return valve affects the performance of the valve (Tseng & Lai, 2001). A designed experiment was conducted that looked at the effects of tip angle, flow passage ratio, ring stroke, and ring to barrel clearance as they relate to part weight. Two materials were processed: Polypropylene and ABS. In all, there were 18 unique combinations of valve geometry and resin. The data showed that the valve flow area compared to the discharge area of the screw was significant with both materials. The results were interesting; however, clear design guidelines could not be established.

Valve Materials

Non-return valves are made from a variety of tool steels, depending on the intended use. H-13 is the most commonly used tool steel due to its low cost, toughness, and durability when hardened. D-2 steel is often used for the rear seat due to its good wear resistance. For corrosive applications stainless materials, such as Crucible Service's CPM420V are often used. For high-wear applications, carbide facing of tool steels is often used. However, CPM®-9V appears to be the new material of choice as more valve manufacturers are now offering this alloy. CPM®-9V has superior wear resistance as compared to H-13, resulting in longer life of components when running highly abrasive resins, especially in the front seat and ring interface. Valves made using CPM®-9V will often use either the same alloy, or D-2, for the rear seat component (Colby et al., 2006; Westland, 2006). Although a CPM®-9V valve is more expensive than one constructed of H-13, the service life is typically 2-3 times longer.

Valve Performance

Non-return valve performance is evaluated by both the ability to shut-off and the resulting melt quality. The ability of a valve to shut-off consistently affects the amount of material injected into the mold cavity before switching from the filling phase to the packing phase (Isayev et al., 1995). Operation of the valve is crucial to injection molding performance. A valve that does not function properly may produce parts with inconsistent weight and dimensions, short shots or cosmetic defects. Short shots occur when insufficient material is injected into the cavity of the mold, thus forming an incomplete part.

Melt quality is affected by the governing function of the valve. The proper amount of restriction to the flow path may be important to melt quality. Too little restriction can result in poorly melted resin, or poorly mixed colorant. However, this is usually partly due to having an incorrect screw design for the material, such as using a "general purpose" screw when a mixing screw is required. There are non-return valves that are specifically designed to aid in material mixing, but tend to work best when combined with screws that were designed for mixing (Salamon et al., 2000).

Restrictive passages increase the shear rate on the polymer. This results in resin degradation as it travels through the valve during recovery. Degradation is observed as a loss of physical properties and / or cosmetic defects in the part. Degradation can also be the result of dead spots in the flow passages (Rosato et al., 2000). Dead spots are areas, not directly in the flow path, that allow material to become stagnate and degrade over time. This can cause streaking or black specs to occur in the parts and runner system (Morse, 1967; www.spirex.com, 2007).

Valve Failure Modes

Non-return valves fail both in respect to performance as well as catastrophically. Wear between components affects each of the performance modes of the valve. Failure occurs when valve performance deteriorates over time until unacceptable parts or process conditions are achieved. This can show up in the form of short shots, excessive variation in product dimensions or part weight, or degraded material (Harper, 2006). For the molder, it is often difficult to determine when valve wear has significantly affected the product or process. This is because valve wear occurs slowly, often over many months. Corresponding changes to the product or process are gradual as well.

Catastrophic failure occurs as the result of wear and fatigue. Valves in poor condition, which remain in production beyond the useful service life, often experience catastrophic failure (Morse, 1967). An example of this type of failure is a cracked ring. This is usually due to either fatigue related to the high cyclical pressures or due to foreign materials, such as scrap pieces of metal in regrind, entering the screw and barrel. A cracked ring results in the machines' inability to reach or maintain proper plastic pressure. In the worst cases, the ring actually breaks into pieces.

The Molding Cycle

The injection molding cycle is made up of several basic components. Figure 9 shows a graphical representation of a typical molding cycle. This discussion will concentrate on the portion of the cycle, affected by the non-return valve, as shown in green. We will begin with the plastication process, or screw recovery, since this is how material is readied for injection. In addition, the ring-type non-return valve is the most common

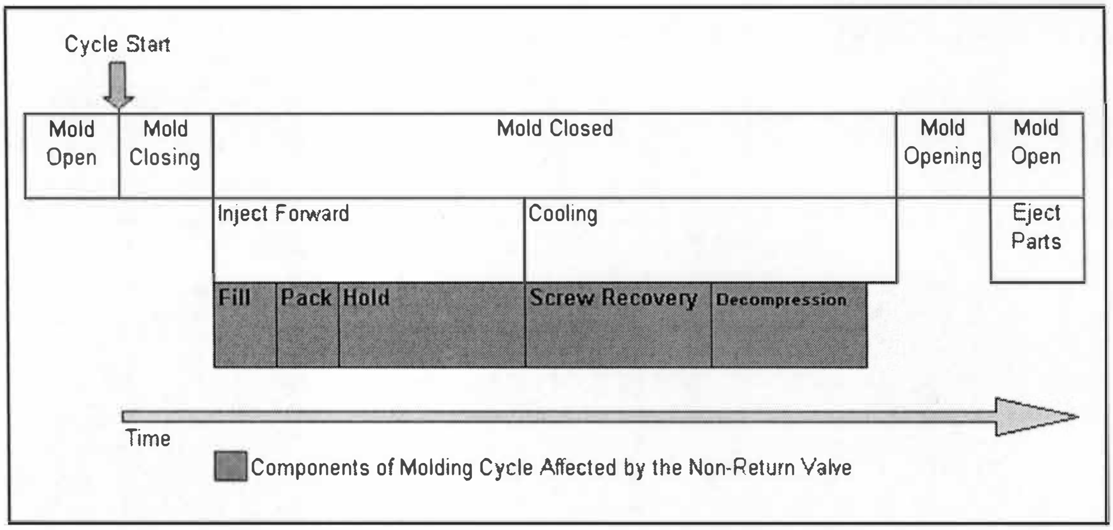


Figure 9. Typical Molding Cycle.

valve in use at the surveyed PCIM companies. Therefore, this is the primary valve type referred to throughout the discussion unless otherwise noted.

Plastication Process

Before the machine can produce a part, plastic resin needs to be melted through the process of plastication. This process is commonly referred to as "screw recovery". During the plastication process, the resin undergoes various stages of melting and pressure. Heat and friction are applied to the resin during screw rotation (recovery). Up to 90% of the energy needed to melt the resin is induced by the screw in the form of friction and compression (Harper, 2006; Muccio, 1994). The remaining energy comes from the heater bands surrounding the barrel. Figure 10 shows the sections of a typical three-zone injection molding screw.

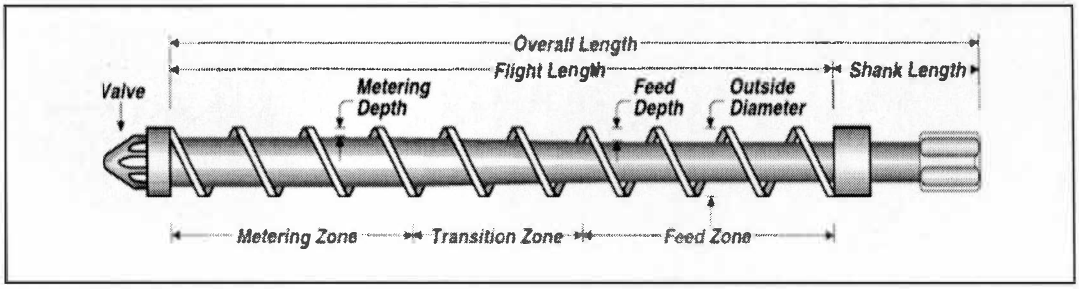


Figure 10. Typical Injection Molding Screw (www.ticona.com, 2006).

A typical "general purpose" screw is comprised of three zones: feed, transition and metering zones and occupy roughly 50%, 25% and 25% respectively (Westland, 2006). A common descriptor for the relative overall length of the screw is length to diameter ratio (L/D). L/D= Flight length of screw / Outer diameter of screw. This term is used to help classify the design of the screw.

Material enters the barrel at the feed section of the screw. As the screw rotates, material is conveyed down the flights of the feed section. Heat energy from the barrel and screw is transferred to the resin aiding in the melting process. The heat from the screw and barrel also help the resin to stick to the barrel so it can be conveyed down the screw flights (Colby et al., 2006). This section of the screw has a constant root diameter, and is predominately used for pre-heating the material. Gases, such as superficial moisture, are driven off in this region of the screw.

The material then enters the transition section of the screw. The transition section has a changing root diameter that increases from its smallest diameter at the feed section to its largest diameter at the metering section. The resin undergoes friction and compression as the screw rotates and conveys material forward. The ratio of depth at the feed section of the screw to the depth at the metering section of the screw is referred to as the compression ratio (Colby et al., 2006). This ratio is commonly used to help classify the ability of the screw to adequately process families of materials. The majority of melting is accomplished in this section of the screw.

The melted resin is then conveyed through the metering section of the screw. This section of the screw maintains temperature and consistency of the melt. Ideally, the resin is thoroughly melted at this point. Material that passes through the metering section is accumulated ahead of the screw to be used in the next molding cycle. The amount of material accumulated is referred to as the shot size.

Shot Size

During screw recovery, plastic pressure builds in the metering section of the screw. The pressure forces the non-return valve's shut-off device (ring, ball or pin) open so that material may flow through the valve. As the material accumulates ahead of the screw and non-return valve, pressure builds and eventually forces the screw back passages (Rosato et al., 2000). The screw stops rotating when it has traveled a certain distance. This amount is typically the linear distance back from screw bottom (in or mm). Some manufacturers and molders have converted the linear distance into volume (in^3 or mm^3).

The amount of material accumulated ahead of the valve is referred to as the shot size. The time required to accumulate the shot is referred to as recovery or rotate time. The amount of time it takes for material to travel from the feed throat to the nozzle of the machine is known as the residence time passages (Rosato et al., 2000).

Back Pressure

Back pressure is the resistance of the screw to move backwards as the shot accumulates ahead of the valve. The resistance is a combination of the frictional losses in the injection unit, the mass of the screw and injection drive system and the pressure being applied to the rear of the screw.

The resistance due to frictional losses and the mass of the screw and injection drive system is known as the "natural" back pressure of the system. Some degree of natural back pressure is inherent in all molding machines (Olmsted & Davis, 2001). Most resins typically require additional pressure to be added during plastication, in the form of pressure to the back of the screw ram, in order to assist melting, improve color mixing, or to produce a more consistent melt (Smith, 1995). This pressure can be controlled either hydraulically or electrically.

Pressure Loss Through the Valve – Governing Function

Pressure is also added to the melt due to the resistance created by the internal geometry of the non-return valve. This is also known as the "governing" feature of the valve since the restriction through the valve governs the flow. The degree of pressure loss depends on valve geometry and resin type being processed (Isayev et al., 1995; Martin, 1993). This pressure is difficult to account for since it is a small portion of the total system pressure. However, it is one of the variables that molders compensate for without directly realizing it. For instance, a molder processing a highly crystalline material such as nylon will have a process set up for his specific machine and mold conditions. If the non-return valve is replaced during maintenance with a different type of valve, the inherent back pressure of the system may change. If this pressure drops below a certain threshold, the molder may experience problems including poor melt consistency, solid pellets in the melt, or the screw may freeze (seize) in the barrel. Additional back pressure may then be required to properly melt the material.

Decompression

Decompression is applied after the screw has stopped rotating to relieve the melt pressure in the barrel ahead of the non-return valve. Decompression is achieved by retracting the screw and allowing material to decompress (expand) in the barrel (Dym, 1987). This is needed because the melted resin is under pressure. When the molding cycle is complete, the mold opens and the part is removed exposing a direct path to the melted resin. The material then tries to equalize to atmospheric pressure by decompressing through the nozzle (drooling) and into the mold sprue.

Insufficient decompression often results in a "cold slug" of material or freeze-off at the gates in the hot runner system. This cold material is the "drool" that has migrated through the hot runner gate and then freezing. Excessive decompression will draw air into either the nozzle of the machine or the drops in the hot runner and create splay on the parts (Harper, 2006). Machines with a mechanical shut-off device, either on the nozzle of the machine, or built into the hot runner system, do not have this problem.

Decompression is also referred to "setting the check ring" by veterans of the industry. This means the check ring has been forced against the front seat of the valve during decompression. There is not a satisfactory explanation as to why it is necessary to firmly "seat" the check ring against the front seat on the valve since this does not directly affect the shut-off mechanism of the valve. There is, however, a widely held belief that there is a correlation between the amount of decompression used, the speed / force of decompression, and the consistency with which the non-return valve shuts.

Decompression is used in a ring-type valve to help clear material from between the ring and rear seat. This allows the ring to close easier by having less material to force out of the way, and thus, less variation. Piston type valves do not require decompression since the pressure in the accumulated melt is used to close the valve. However, decompression may be required to prevent drool if excessive pressure remains in the melt after the valve is closed.

There is no established procedure for determining the amount of decompression to be used on a given valve. Consequently, the approach that molders have when setting the amount of decompression is that decompression is either "on" or "off". Fine tuning from this point is done by trial and error. For instance, if the nozzle is drooling, add more decompression. If air-induced splay occurs in the parts, then reduce the amount of decompression. Splay is a cosmetic defect that appears as a shiny, silver or white streak on the surface of the part. Splay can occur as a result of air being drawn into the nozzle during decompression (Bryce, 2001).

There was study that investigated some of the causes for shot size variation in the molding process (Groleau & Groleau, 2000). One of the tests performed was to apply different levels of decompression against two injection rates. The graphed data appeared to show how much decompression was required for a particular combination of process parameters, material and valve. This study was performed after the work for this research and validates our findings. Their work supports the fact that there is a minimum threshold for decompression for which part weight stabilizes.

Valve suppliers and manufacturers do not have data or guidelines for determining decompression. Data is needed to strengthen the knowledge of both the users and suppliers of non-return valves.

Resin Degradation

Resin degradation can occur due to the restrictive passages that materials flow through, resulting in a localized increase in the shear rate. This may exhibit itself in the form of splay or streaking in the material or even a loss of properties.

Degradation can also occur due to material hanging up and "cooking" in dead spots. Dead spots are the result of changes in flow passage geometry in which the material becomes stagnant and does not flow. As the material degrades, small bits will eventually break away and show itself in the form of streaks or black specs in the part (Bryce, 2001).

Inject Forward – Shut-off Function

Once screw recovery is complete, the mold opens and parts are ejected. The next cycle begins by closing the mold and injecting the screw forward in order to fill the cavity with material. As the screw begins to move forward, the ring remains stationary relative to the barrel wall. The rear seat of the valve is pushed into the rear seat of the ring. This closes the valve, preventing material from flowing back through the valve and over the flights of the screw. This allows the screw and valve assembly to function together, as a piston, in order to inject material into the mold. The ability of the screw to move backwards during recovery and then move forward during injection is where the term "reciprocating screw" stems from.

The inherent problem with both ball and ring valve designs is that they allow material to flow back through the valve as it closes (Dray, 1994). The amount of material allowed to flow back through the valve is known as leakage. Leakage is inherent to the design of both these valve types. Therefore, it is important to understand the amount of leakage as well as the variability of the leakage the valve produces. If the valve leaks consistently, the amount of leakage becomes less important.

Filling the Cavity

Mold Fill

The leading method of mold filling widely used by industry is known as Decoupled Molding^{SM}, which is a service mark of RJG Inc. Decoupled molding means the fill, pack and hold phases are separated from each other by using distinct control methods. Decoupled II molding is the most commonly applied form of Decoupled molding and will be the basis of this discussion. This means that the mold fill phase is separated from the pack / hold phase by using two distinct control methods.

The objective is to fill the mold as fast as possible to take advantage of the non-Newtonian behavior of the polymer. The mold is filled 95% to 99% full, by weight, in a *velocity* controlled manor. The mold is then packed and the pressure held using *pressure* for control.

Filling the mold to 99% full allows for an almost immediate building of pressure in the part cavity during the pack phase. This helps to assure the overall dimensional stability of the part is optimized. Filling the final 1% to 5% of the mold is accomplished by relying on the inertia of the injection ram, so that by the time the cavity is 100% full, the machine has fully switched to its' hold pressure. Hold pressure is then used to keep material from flowing back out of the cavity. This compensates for material shrinkage during cooling and is usually applied until the gate has solidified, no longer allowing material to flow into or out of the part.

Most modern molding machines are equipped with separate pack and hold controls. However, there is usually no difference in the physical operation of each controls, only the naming. Regarding pack and hold as related to Decoupled Molding^{SM} terminology, the pack phase is performed in a velocity-controlled manor while the hold phase is performed using pressure.

For our discussion, we will regard this as a single *hold* phase since most molding machines are not equipped to perform Packing in a velocity-controlled manor.

Fill Rate

The advantage of a fast fill speed is represented by the apparent viscosity curve developed by Bozzelli and Groleau (1990). The curve graphs the apparent viscosity of the polymer versus the shear rate and illustrates the behavior of Non-

Newtonian Fluids (plastics) on a molding machine (Bozzelli, 1995). Apparent viscosity is also known as the dynamic viscosity of the resin as it is injected into the mold cavity (Morton-Jones, 1989). The procedure to produce this graph is conducted on a molding machine and is referred to as an "On Machine Rheology Curve" and is shown in figure 11.

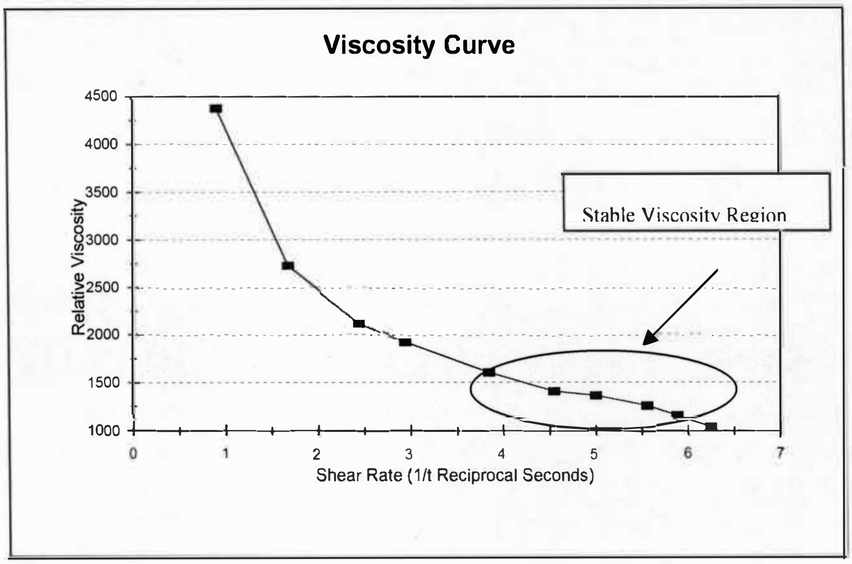


Figure 11. Machine Rheology Curve for Nylon 6/6.

Apparent viscosity is calculated by multiplying plastic pressure with fill time. This is plotted against the reciprocal of fill time (shear rate). As the shear rate on the plastic increases (faster fill), the resulting apparent viscosity drops at an increasing rate.

This means that at a low shear rate range, a small change in fill time results in a large change in apparent viscosity. Conversely, at the high end of the shear rate range, a change in fill time has little effect on shear rate. Injecting at a high shear rate will enable the machine to produce more consistent parts since any small change in the machine's velocity will result in little change to relative viscosity during fill.

The value for each viscosity curve is unique to the combination of material, molding machine, and mold geometry. However, the basic shape of each curve is similar.

Transfer Method

The point at which the machine switches from the fill phase to the hold phase is known as cut-off or transfer. There are four methods of achieving this: time, hydraulic pressure, screw position, and cavity pressure. It is widely accepted that both time and hydraulic pressure have been proven as unsuitable transfer methods for most molding situations.

Screw position is the most common transfer method used in industry. Therefore, it will be the primary method discussed throughout the paper. Transfer means as the screw travels forward, the control *transfers* from a *velocity* mode to a *pressure* mode at a certain position on the injection stroke. This position is adjusted until the mold is 95% to 99% full. If we assume that the machine is consistent, variation in the volume of plastic, in the cavity at the cut-off position, is directly related to the performance of the non-return valve. Any resulting variation of plastic in the cavity during the filling phase is then compensated for by the pack / hold phase (Dray et al., 1992).

Cavity pressure is also used as a switchover point from fill to packing. The cavity is filled to a certain plastic pressure before the machine transfers to pack mode. This can result in a more consistently filled mold during the fill stage. The consequent time to build pack pressure remains constant as well. There is debate whether or not this process yields the most dimensionally stable parts. Cavity pressure cut-off is not as widely used as position due to the extra hardware required and the lacking confidence and knowledge of the technology in the industry.

Intensification Ratio

Plastic pressure in the cavity is directly correlated to the pressure being applied to the ram at the rear of the screw. The ratio between the projected area of the ram and the projected area of the screw is called the intensification ratio (Bozzelli, Larsen, McDonnell, 1998). This allows the machine to achieve plastic pressures much higher than the machine is capable of delivering. For example, most hydraulic machines generate approximately 2000 PSI of hydraulic pressure. If the intensification ratio between the ram and the screw is 10:1, the resulting plastic pressure will be 20,000 PSI. Therefore, it is important to know the intensification ratio of the machine in order to prevent damage to the mold. It is also necessary to know the intensification ratio when duplicating a process from one machine to another, or to understand the pressure losses through the melt "system".

Pack / Hold Phase

Variation in the volume of plastic in the cavity during the fill phase is compensated for by the pack phase. Pack pressure masks the variation produced by the non-return valve by packing the cavity to a specified pressure. This pressure directly correlates to the plastic pressure in the cavity through the intensification ratio.

However, there is an increase in apparent viscosity that is a result of the decrease in the fill speed while changing from a velocity-controlled phase to a pressure-controlled phase. This affects the ability to pack the part. A resin's ability to transmit pack pressure is referred to as the packability of the resin. This occurs since the resin is no longer moving in a *dynamic* manner, but is in a *static* viscosity phase (Bozzelli, 1995).

This becomes significant when performing traditional de-coupled molding where the position method of transfer is used. If the amount of resin in the cavity varies at the transfer position, the machine will not be able to reach the desired pack pressure at a consistent time since the screw is traveling slowly during the hold phase. This means that if a resin is difficult to pack, then an inconsistent time to reach pack pressure will yield inconsistent parts (Bozzelli & Cardinal, 1995). In addition, as the screw applies pressure to the melt, the pressure loss through the plastic in the cavity is varied due to the varying volume of plastic in the cavity. This means that the pressure transmitted to the end-of-fill point in the cavity will vary as well.

Gas Assisted Molding

An inconsistent shot size is especially problematic in gas-assisted injection molding. Part quality and consistency rely heavily on shot weight consistency. Material is injected into the cavity until it is almost full. Inert gas is then injected into the material either through the runner or directly into the cavity. Gas pressure is used to pack the part instead of plastic pressure.

The absence of traditional pack / hold pressure means the part will show increased variation in part weight since no additional plastic material is used to finish filling the cavity. Assuming the machine is consistent, the resulting shot size variation is caused by the non-return valve. Variation of the amount of plastic in the cavity will effect the cooling and, thus, dimensions of the part.

Cushion

In order for the machine to transfer pressure from the plastic in the injection unit to the plastic in the cavity, plastic must remain ahead of the screw in the injection unit. This amount of plastic is called the cushion. Cushion is monitored using the position of the screw, and is the minimum forward screw position during the cycle.

Fluctuation in cushion position directly relates to the variation of the non-return valve closing (Bozzelli, Furches, Bujanowski & Little, 1991). The inability of a machine to maintain a cushion signals wear in the injection unit. This will also be revealed in the parts through dimensional variation, sink, or short shots (Hatch, 2006).

Sink is a result of plastic shrinking as it cools, creating a "sink", or, depression on the part. Excessive cushion can also lead to resin degradation and temperature stratification of the melt in the cushion area which in turn can lead to inconsistent or bad parts (Dray et al., 1992; Dray, 1994).

Valve Wear

Wear of the non-return valve is a problem molders are faced with. The factors contributing to wear are not entirely understood. Material (resin), filler type and content, process temperature and pressure, screw revolutions per minute (RPM), run hours and machine size all affect the life of a valve (Mennig, 1995). Consequently, most worn valves are not discovered until there is a problem during molding that can not be easily compensated for. The molder is then forced to react by either adjusting the process or shutting the machine down for unscheduled maintenance. Both of these remedies are problematic for the molder. Therefore, it would be beneficial to the industry to develop methodology for establishing predictive maintenance guidelines and procedures.

Wear of the non-return valve affects the consistency and ability of the valve to shut-off. The ability of the valve to seat without allowing material to flow either through or around the valve during injection is critical. This affects the consistency and magnitude of melt pressure that is transferred to the part cavity. This, in turn, is directly correlated to part performance dimensionally, physically and cosmetically.

Determining if components are worn has not been an easy task historically. Dimensional tolerances provided by the manufacturer may or may not correlate to the performance of the injection unit as a whole. There are countless instances of new screws and non-return valves that have been installed but did not meet performance expectations. Therefore, the degree of wear in the injection unit also must be evaluated from a practical point of view.

Standard Society of the Plastics Industry (SPI) wear tolerance guidelines for the screw, barrel and non-return valve may or may not be practical for the material being processed. For instance, a high viscosity polymer may be able to be processed effectively beyond typical recommended wear limits. On the other hand, a very low viscosity polymer may be sensitive to wear - especially the clearance between the non-return valve and barrel. This phenomenon may be most noticeable when the molder attempts to process a low viscosity resin when the machine normally runs higher viscosity resins. Although the machine processed the higher viscosity resin with no apparent problems, the lower viscosity resin in the press results in problems with repeatable shot size and / or the inability to hold a cushion.

Front Seat Wear

Wear of the front seat occurs during the recovery phase of the cycle. As the screw rotates in a typical 3-piece valve, the ring remains stationary while the valve body and front seat turn with the screw. In unfilled materials, the plastic material provides a film of lubricant between the ring and front seat. The addition of fillers, however, acts abrasively on the valve during recovery (Johannaber, 1985; Mennig, 1995). The resin acts as a lapping compound between the ring and front seat. Both the ring and front seat will experience abrasive wear over time.

The distance the valve has to travel in order to close increases as components wear. As a result, leakage increases and closure becomes erratic (Dray, 1994). As leakage increases, the amount of material remaining in front of the valve is also reduced. This results in a smaller net shot size, which results in a reduced cushion position.

In certain designs, wear in the tip will also affect the recovery time. Flow passages for the material are reduced as the tip wears. The increased pressure drop across the valve results in an increase in the shear rate being applied to the resin. An increase in valve restriction will show itself as an increase in recovery time. The passages will gradually become more restrictive as the valve wears, preventing material from flowing through the tip. The increased shear rate can also exhibit itself in the form of splay or degraded resin.

Extreme wear will result in the valve failing catastrophically. As the tip wears, the amount of material on the valve body retaining the ring is reduced to a minimum. In extreme cases, the tip is eroded to the point where it can no longer retain the ring and the ring is forced over the tip and off the valve. This can cause severe damage to the screw, barrel and end-cap assembly.

There is a strong correlation between screw RPM and the resulting wear rate of the ring and front seat. This is based on the relative surface speed between the components. Several valve suppliers have published wear data for their valves. A chart has been compiled from various sources and is shown in appendix A. These data do not take into account the variety of fillers and process conditions that are in use, but are a good guideline for establishing screw rpm limits.

Rear Seat Wear

Wear between the rear seat and ring occurs during the injection portion of the cycle. The ring and rear seat does not experience the same type of abrasive wear as do the ring and front seat. Instead, the ring and rear seat are pressed against each other during injection. There is no relative movement between the two components. Instead, plastic deformation occurs under compressive loading, as the ring and rear seat force a depression into each other over time.

During the injection phase, the pressure exerted on the ring and rear seat is extremely high. The pressures on other worn sample valves have been calculated to be as high as 75,000 PSI for a machine capable of 2000 PSI hydraulic pressure with a 10:1 intensification ratio. This pressure is directly related to the contact area between the ring and rear seat. Adhesive wear can also be observed under high forces. The ring and rear seat "are briefly welded together" when closed and, when pulled back apart during recovery, small particles are ripped from the opposite surface (Gornik, Bleier & Roth 2001). This type of wear will result in a loss of the valve's ability to maintain a cushion.

However, in a new valve, the pressures are even higher. The angle ground on the ring is less than the angle on the rear seat. This creates a pinch point between the ring and rear seat. This pinch point can be though of as a "circle" of contact. As the valve wears, the contact area between the components increases in width from a thin circular line until the contact is the complete overlapping area between the two surfaces. Wear between these two components will accelerate when processing filled resins.

It is not known how wear of this area affects the process, however, it is revealed later that there is increased process variation during this time and that the valve undergoes a break-in period.

Barrel Wear

The clearance between the ring, or valve body, and the barrel is also affected by wear. The majority of wear in the barrel is a result of abrasive material acting upon the screw and barrel during processing (Mennig, 1995). Wear can occur in any of the zones of the barrel: feed, transition or metering depending on the processing conditions. However, performance of the non-return valve is affected only by wear in the transition and metering sections since the valve can travel through these zones. The non-return valve does not travel through the feed zone.

The ring does not turn with the screw in most ring-type valves. Therefore, there is little wear in the barrel due to the ring and barrel interface. However, there are valves in which the ring rotates with the screw. These are known as locking ring valves. The ring for this type of valve, along with the body of ball and poppet style valves, rotate with the screw. This design was made to eliminate wear between the ring and front seat. However, barrel life is compromised instead (Mennig, 1995).

Ring Fatigue

Fatigue is another failure mechanism for these components. There is a large amount of pressure from the melt exerted on the valve and barrel walls during injection (20,000 PSI is common). Ring expansion during injection occurs at high pressures and fatigue eventually causes the ring to fail. The ring can crack and eventually break into multiple pieces. As mentioned previously, the majority of broken rings are usually accompanied by tramp metal that entered the machine. A cracked ring will exhibit itself, before catastrophic failure, through the inability of the machine to hold a cushion. A cracked ring can result in the same type of severe damage to the injection unit as mentioned for the front seat if the ring breaks into pieces.

Injection Unit Wear as a System

The non-return valve functions as part of a system. Therefore, any processing issue experienced needs to be evaluated with this in mind. Excessive wear in either the transition or metering zone of the barrel can allow plastic to back flow during recovery or injection, and can exhibit itself in the form of reduced cushion, short shots, degraded material or increased recovery time (Bryce, 2001). This is due to the ring not being able to maintain a tight seal between the barrel to keep material from flowing over the valve. This failure mode is commonly mistaken as valve seat failure when, in fact, the valve is in good condition.

Excessive back flow of resin can be observed on most molding machines by watching the screw during injection. The screw will often turn as a result of the plastic flowing back over the valve and down the flights of the screw (Rosato & Rosato, 1990). This effect is commonly referred to as "wind-milling". Degraded resin can occur, from the excessive shear history the material is exposed to, due to the back flow of the resin.

Recovery time is also affected by barrel and ring wear since the material is forced back over the valve's ring or body during recovery (Mennig, 1995). In cases where the barrel has worn beyond the limit for processing, it is common to have the screw "stall" during recovery, as material can not accumulate ahead of the screw in order to force it backwards. A common processing pitfall is to reduce the back pressure setting until recovery can be completed. This will most likely lead to other quality problems.

Wear in either the front or rear seat of the non-return valve will change the amount of stroke required to close the valve. This may also affect the amount of decompression required. It is not known how this may affect processing and there are no published data to support this.

This type of wear that results in either variation of closure or the inability to hold a cushion is one of the main nuisance variables molders face. In other words: how to compensate for wear of the injection unit as a system – screw, barrel, and non-return valve. A study was performed to simulate how this type of wear would affect processing (Nicolia & Roth, 2000). The goal of the simulation was to understand what the best method of processing would compensate for a wear condition. This was done by monitoring part weight, cushion position and transfer pressure versus the transfer methods used: position versus hydraulic pressure during the pack phase. Wear was simulated by removing material from the outer diameter of the ring, which allowed plastic to back flow over the ring during injection. The study concluded that position transfer showed more variation, than using hydraulic pressure (during pack phase) for transfer and confirmed that the worn condition would result in a reduction of hydraulic pressure and cushion position.

Another study was conducted to try to compensate for non-return valve leakage by increasing the pack time (real-time) so that part weight is maintained (Yang & Gao, 2005). The study correlated plastic pressure in the nozzle with part weight, and then correlated the change in part weight with a change in pack time. The study showed that it is feasible to maintain part weight by increasing pack time.

However, this was only tested on one set of process variables in the laboratory. This methodology appears to accomplish similar results as compared to packing to a cavity pressure, but with much more complication necessitated by the need to correlate an incremental change in part weight to an incremental change in pack time.

Determining Valve Replacement

Screw, barrel and non-return valve wear is an acknowledged maintenance item that should be accounted for using standard maintenance procedures. However, it is common for most molders to delay proper inspection of the screw and barrel if they are unsure about the problem. Even if components are known to be worn, replacement is usually delayed until the valve no longer functions or acceptable parts can no longer be molded. As it turns out, the difficulty with replacing the non-return valve is often due to the lack of available press or maintenance time. This syndrome is due to a combination of the "production" mode that some molders get trapped in and the uncertainty of how valve and injection unit wear affects the molding process. This is a result of lean manufacturing and inventory practices adopted by many molders. Replacing a typical non-return valve can take anywhere from a couple of hours to an entire shift depending on the size and design of the press. Proper inspection and measurement of all components can often take multiple shifts, as the components need to cool to room temperature.

There are four schools of thought regarding non-return valve replacement as determined from an informal survey. The first and most common is to replace the valve when it is thought to be worn out, or catastrophic failure occurs. This usually occurs after struggling with process problems in production. As discussed previously, there is little agreement in industry as to when the valve is actually worn out. Therefore, molders usually operate with worn valves until they are no longer able to make acceptable parts. Catastrophic failure occurs when either a component of the valve breaks due to physical failure or the valve fails to function (performance failure). The valve needs to be changed immediately before production can resume.

Screw and barrel inspection is another opportunity for valve replacement. Inspection is performed at predetermine intervals. The non-return valve is inspected for signs of damage or excessive wear. The valve is often replaced if it shows signs of wear. One drawback with this method is determining how much valve wear can be allowed before performance is affected. Correlating performance changes to normal valve wear has not been accounted for in industry. This type of inspection strategy can be useful for detecting potential physical problems with the valve, but may not correlate to processing issues. For example, there may be wear to the front seat of the ring, but recovery time or shut-off function may not be affected. The opposite can also happen with no visible signs of wear detected, yet there is an inability to hold a cushion.

A third method used for certain processors is to replace the non-return valve at pre-determined time intervals, usually during screw and barrel inspection, whether it is needed or not. These molders have decided that it is better to be proactive than to take the risk of producing bad parts. They consider the cost of the non-return valve to be negligible compared to the need for additional downtime if the valve were to fail unexpectedly. However, few processors are using this method.

Finally, a few molders are trying to develop predictive maintenance programs in order to determine when a component is about to fail. The difficulty with this approach is how to determine which variables to monitor, and how to correlate the variable response to specific machine components.

Optimizing Non-Return Valve Performance

The previously mentioned phases of the molding cycle, along with component wear, all contribute to, or are affected by, the function of the non-return valve. Variation of valve closure affects the quality and consistency of parts produced. During injection, material flows between the ring and rear seat as the screw begins to move forward. If the time for valve closure varies, then the amount of material remaining in front of the valve will vary as well. This directly affects the amount of material injected into the cavity. This also means that the screw has a different distance, and therefore time, to travel before building plastic pressure, although the position to transfer remains constant.

The variation in time to build pressure adversely affects the polymer due to its non-Newtonian behavior. This becomes problematic during the pack / hold phase.

At point of transfer, the material velocity approaches zero, and the static viscosity of the material increases rapidly. The rapid increase of material viscosity, combined with the varying amount of material, affects the packing of the part and thus the final product's dimensions as discussed in the Pack Phase section.

This variation exhibits itself, as displayed on the machine controller, as cushion variation. When using cavity pressure for the cut-off method, variation due to the non-return valve will correlate to a change in fill time. Non-return valve variation represents a portion of the total variation in a final product. The magnitude of this effect depends on many other variables including polymer type, processing conditions, part geometry, and mold construction.

The impact of process variables on non-return valve performance is not well understood. There is much conjecture regarding the effects process variables have upon the performance of the non-return valve. It is widely known in industry that, screw decompression affects non-return valve performance, but not how. It is also suspected that injection velocity affects the ability of the valve to shut-off. A primary goal of this research is to identify these variables using a series of designed experiments.

There are few published works directly relating to the process of optimizing the performance of the non-return valve. The studies cited in the preceding literature review have been centered around testing one valve against another, or valves that solve a certain problem, such as splay. Most work regarding process optimization of the non-return valve amounts to little more than a sales pitch for the latest valve on the market: "Our latest valve was compared to a generic valve, and had a lower standard deviation for part weight."

However, one study was performed that is worth mentioning. It investigated optimizing the closing distance of the non-return valve using a designed experiment (Gornik, Bleier & Roth 2001). This was accomplished using a 2-level, 3-factor design. Independent variables included: back pressure, decompression and injection speed. The results showed that a 10% reduction in closing distance could be achieved. While this test used decompression as a variable, there was no procedure for establishing the amount of decompression used.

CHAPTER III

METHODOLOGY

Research Strategy

Experimentation was divided into three phases: 1) Discovery Phase, 2) In-Plant Experimentation and Testing Development, and 3) an In-plant Wear Study. The discovery phase was conducted at Western Michigan University's plastic processing laboratory and was used to establish significant variable effects and the groundwork for how research would be conducted in the manufacturing plants. A strategy, using the information from the discovery phase, was then devised to take into the plants in order to test the theories following two parallel paths. The first goal was to develop procedures that could be used to optimize, or quantify, the performance of the non-return valve. The second was an in-plant wear study designed to observe the performance of the non-return valve as it wore in an aggressive production application.

Discovery Phase

The discovery phase consisted of developing the research plan based upon the needs of the consortium. Previous PCIM work had provided answers into the factors that influence dimensional shift and stability (variation). However, the factors influencing a large portion of variation were not understood. The results indicated that the non-return valve played an essential role in this variation. This was the driving factor in the research goal. The research team met with PCIM advisors in order to establish a starting point for the research. Further action items were the result of data gathered from these experiments.

It was first necessary to identify the types of valves in use at the PCIM member plants. A questionnaire was distributed in order to determine the types of valves in use at the facilities, along with failures associated with each type. Worn valves were also requested at this time in an attempt to understand the failure mechanism of non-return valves. This information was used to help determine the research plan for the long-term wear study.

It was also necessary to understand the effect the non-return valve had on the molding cycle, as well as, how the valve interacted with the injection unit. Since one of the roles of the non-return valve is to act as a governor, it was necessary to try to quantify that effect. Throughput tests were conducted in order to identify the effect the non-return valve had on the injection unit during the plastication process.

Finally, A series of statistically designed experiments (DOE's) were conducted in order to determine the process variables that significantly effected the response of the non-return valve. A matrix of all experiments performed is shown in Appendix D.

Questionnaire

A questionnaire was distributed to the PCIM member plants in order to determine the types of valves were in use at their facilities. Valve styles, types of materials processed with each valve, and information on the problems or failures associated with each valve type were also requested (Appendix B). This information was used by the research team at WMU to design the research plan to meet the needs of the consortium. Research performed in the discovery phase was limited to the materials and valve types used in common by the PCIM plants. These valves would then be procured for the laboratory molding machine.

Request for Used Valves

Along with the questionnaire, a request was made for used valves and sent to PCIM member plants in order to document the service life and failure modes of valves used in production (Appendix C). Attached to the request form were self-adhesive labels designed to be applied to the worn valves for identification purposes. The labels had provisions for information regarding the history of the valve including 1) Length of time the valve was in service, 2) Resins used, and 3) Reason for removing the valve. The valves were then forwarded to the research team at WMU for evaluation.

Determining Test Valves

Standard designs for both three and four-piece ring-type valves were common among all PCIM plants. These were represented in the laboratory study by the Van Dorn OEM three-piece valve since both valves were of the same basic design as far as function is concerned.

Another valve that was in frequent use was the three-piece EMI valve. This valve was unique because it had unfavorable comments in the questionnaire by ADAC. This was also the same valve currently in use by Prince Maplewood with good success. This valve was different than the standard three-piece valves referenced above in that it is a "free-flow" design. Therefore, it was desired to test this valve in order to find out why it produced acceptable results for one facility and not another.

These first two valves selected for testing were ring-type. It was desired to test a valve that operated using a different design. This would allow the research team to identify any common significant process variables between non-return valves using different shut-off mechanisms. A Dray piston-type valve was selected for testing. This valve was in limited use at PCIM member facilities. However, recently published data was intriguing and merited investigation.

Determining Test Materials

Results from earlier PCIM shot-to-shot research showed there were significant differences, between amorphous and crystalline materials, for both the magnitude and variability of part weight and dimensions (Engelmann, Dawkins, Monfore, & Vander Kooi, 1996). The experimentation was performed using both amorphous and crystalline resins that were in common use among the consortium members. It was decided to explore the variables that affect the performance of the non-return valve using these same material families. This would allow for continuity between research projects.

Materials to be tested included both amorphous (ABS and Polycarbonate) and crystalline resins (Nylon). These three resins are also the most commonly used resins in the PCIM facilities. These resins also happen represent a wide range of material viscosity, which was widely suspected to influence non-return valve variation. These materials were provided by the PCIM plants.

Equipment

All machine trials at Western Michigan University were conducted using a 1992 85 ton Van Dorn hydraulic toggle injection molding machine with an EL controller. The injection screw was a general purpose, 20:1 length to diameter (L/D) ratio, 35 mm (1 3/8 in.) diameter with a five ounce shot capacity. The intensification ratio of the machine was 10:1. The mold used was a standard stainless steel ASTM tensile bar mold. Mold water was regulated using a 1993 AEC mold temperature controller. Circuit water was monitored on all zones for flow rate, input and output temperatures, and pressure lost through the circuit. Resin was dried using a 1990 Una-Dyn UDC style dryer with an OMNI II-X controller and a digital dew point meter. Material loading was done using a 1993 AEC hopper loader and a 1997 Autoloader. Part weight was measured at press side using an Ohaus TS120 digital scale with 120 gram capacity and .001 gram resolution.

Data Acquisition and Analysis

Part weight data were directly entered at the press into Quattro® Pro spreadsheet software. The data were graphed real-time in order to observe any trend or variation in part weight. Further analysis was accomplished by exporting the data into Statistica® statistical software.

Results were analyzed to examine the effects on both mean part weight and part weight variance. Analysis of variance methods were used to analyze the factorial designed experiments. Pareto graphs were produced showing the ranking, by significance (*p*-value), of effects for the independent variables on mean part weight and weight variance. Mean part weight was calculated by summing the number of observations taken for a particular treatment group and then dividing by the number of observations. A treatment group was defined as the conditions, or set-points of the independent variables, applied to the process. Variables were considered significant at a 95% confidence level or $p <= .05$ unless otherwise noted. Variance is a measure of the variation in the response (part weight) at a given treatment group. Variance is computed as the sum of squared deviations (from the mean) divided by n-1, where n is the number of observations.

Graphical analysis was produced using Statistica® software. Curves were fitted to the XY coordinate data according to the distance-weighted least squares smoothing procedure. Post hoc comparisons were conducted using Tukey Honest Significant Difference (HSD) tests to check for significant differences between group means.

Experimental Protocol

All designed experiments were conducted using robust mold set-up procedures established in previous PCIM work (Vander Kooi, 1996).

On-Machine Rheology

On-machine rheology curves, or viscosity curves, as discussed in Chapter II, were produced for all materials tested in the laboratory. These data helped to establish the minimum and maximum injection velocities for each material tested.

Gate Seal

Gate seal studies were performed to determine the amount of time required to ensure the gate has sealed before hold pressure was released (Figure 12). Proper gate seal was essential for part consistency and stability. If hold pressure was released too soon, material was allowed to flow back out of the cavity through the gate, reducing

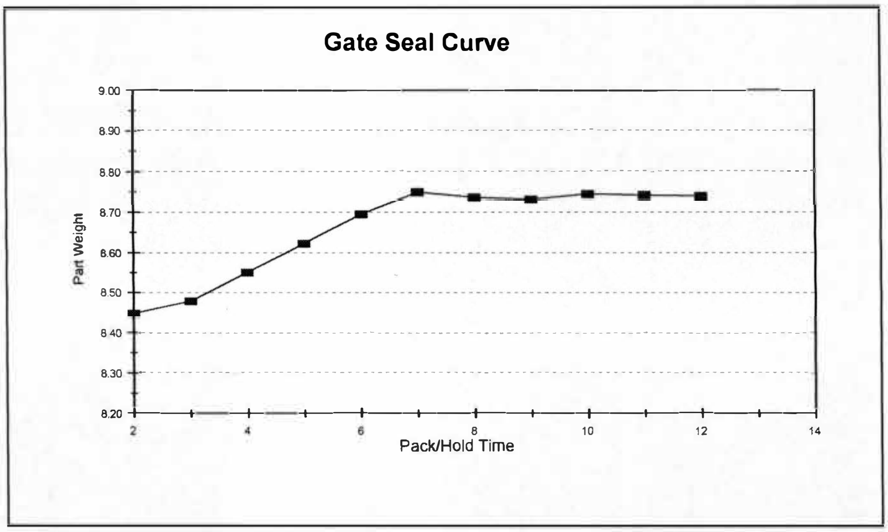


Figure 12. Gate Seal Curve for Nylon 6/6.

part weight. This can produce parts with inconsistent weights, and thus, inconsistent dimensions.

The gate seal procedure was performed by molding and weighing parts across a specific range of hold times. Hold time was gradually reduced while maintaining a consistent cycle time. The parts were then weighed and graphed against hold time. Gate seal time was determined when part weight began to drop as hold time decreased. In figure 11, it can be observed that part weight begins to drop when hold time is reduced below 7 seconds. 7 seconds is the minimum time required for gate seal, and therefore, part weight to remain stable.

Melt Temperature

Melt temperature was taken using an Omega hand-held pyrometer and "J" type immersion probe using the 30/30 method (Bozzelli, Groleau & Ward, 1992). This method of temperature measurement has been shown to be an accurate and repeatable method when using hand-held pyrometers. The melt probe was heated to within 30°F of the desired melt temperature and then inserted into a fresh purging from the machine for 30 seconds. Melt temperature was determined from taking the average of three readings. The peak temperature displayed by the pyrometer was the approximate melt temperature.

Machine Stabilization

The injection molding machine was allowed to stabilize during all experiments before data were gathered. The molding machine was allowed to stabilize for a period of time in order to allow set-point changes to take full effect. The length of time required for stabilization depends on the type of change made. Changes affecting the residence time of the material in the barrel or changes in the barrel temperature take longer to equalize compared to hydraulic pressure or screw position changes (shot size, cut-off position, etc.).

Stabilization was determined by observing variation in part weight, as shown in Figure 13. Part weight was measured at the press and entered into Quattro® Pro spreadsheet software. Part weight was graphed in a real-time mode. The process was declared stable when part weight data appeared to be random, with no apparent upward or downward trends. This meant that machine conditions had stabilized and the variation in part weight was normal for the given process conditions.

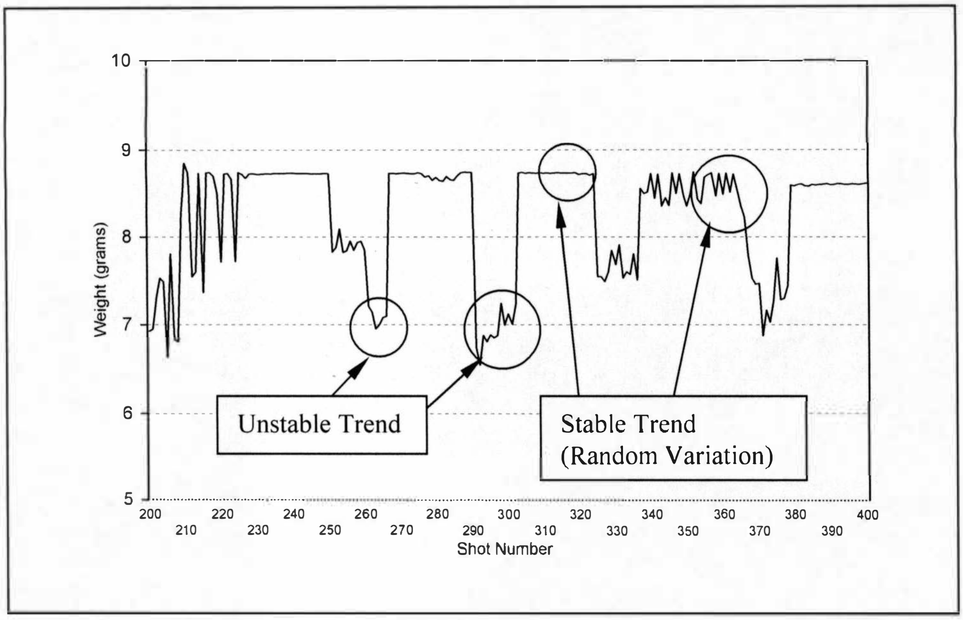


Figure 13. Graph of Real-Time Shot Weight Data Used to Determine Machine Stabilization.

Throughput Test

The non-return valve was previously determined to have two distinct functions: governor and shut-off device. The governing function is the effect that the valve has on the plastication process as discussed in Chapter II. It was hypothesized, that if a non-return valve with a given flow restriction, was placed in the system there would be an increase in the pressure required to turn the screw at a given RPM. Theoretically, this would be accompanied by a reduction in throughput and an increase in melt temperature. A test was developed to quantify the effect the valve has on the system by observing material throughput during recovery. Testing was performed both with and without a valve at Western Michigan University's plastics processing laboratories. The EMI three-piece valve was used for this study.

In order to accomplish this without a valve, a zero restriction round screw tip was made to install in place of the non-return valve as shown in Figure 14.

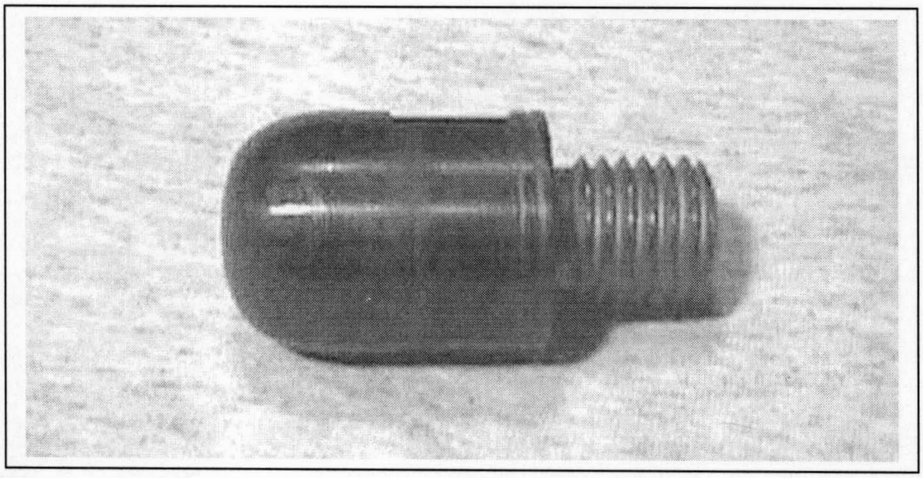


Figure 14. Zero-Restriction Round Screw Tip.

The overall diameter of the screw tip was made to match the final diameter of the plasticating screw. The orifice in the nozzle tip was also modified by enlarging the diameter of the flow channel to ½ inch in diameter so that any remaining restriction in the injection unit was minimized. The extruder was fixed in position to prevent the screw from retracting during recovery.

The material used for this test was polycarbonate (PC) resin (amorphous). Barrel temperatures were set at the material manufacturer's recommendations. Extruder throughput was then tested at four different RPM settings: These settings were determined by dividing the operating range of the extruder, % screw volume, into equal divisions; 20% (60 RPM), 40% (150 RPM), 60% (250 RPM) and 80% (350 RPM).

Throughput was monitored by taking six consecutive samples of extrudate from the nozzle tip at 30-second intervals. Samples were collected on paper plates. The paper plates were numbered and tared prior to sample collection. Each plate and extrudate was then weighed and recorded. Throughput, in lbs./hr, was then calculated by multiplying the weight by 120 (lb/30s * 3600s/hr). A seventh plate was used for melt temperature measurement. Melt temperature was taken using the 30/30 method. Hydraulic pressure was monitored at the screw drive motor to calculate the required torque at each RPM. The data were used to produce throughput graphs for evaluation across the different RPM settings.

The preparation of the machine and round screw tip was time consuming. In order to get the machine to function, the injection unit had to be fixed in position to prevent the screw from retracting during recovery. In addition, the restriction loss due to the removal of the non-return valve made it difficult to plasticate the polycarbonate resin. The test was repeated using nylon resin (crystalline).

Design of Experiments

A series of statistically designed experiments were conducted in Western Michigan University's plastics processing laboratory in order to determine the major process variables that significantly affect non-return valve performance as determined by part weight mean and variation. Initial experiments were screening in nature, meaning resolution was compromised in order to reduce the number of experimental runs. Data were analyzed using standard least squares analysis of variance (ANOVA) methods to quantify the effects for both mean part weight and part weight variance.

Polycarbonate (amorphous) resin was chosen to be the first material tested with the OEM three-piece ring valve. Potential independent process variables, that may have had an affect on non-return valve performance, were listed based upon past PCIM shot-to-shot research and experience relating to amorphous materials. The list of variables for the first experiment included: screw RPM (RPM), decompression (DECOMPRESSION), injection speed (INJECT SPEED) and back pressure (BACK PRESSURE). Each variable had two factor settings, high and low.

High and low settings for each variable were determined by the material manufacturer's recommendations as well as machine and mold limits. The combinations of these variables, forming the experimental runs, were referred to as treatment groups. A four-variable, two-factor, factional factorial, resolution IV screening design [2**(4-1)] was constructed consisting of eight unique treatments plus a replicate for a total of nine runs and is shown in table 1.

Table 1

Design: 2**(4-1) Fractional Factorial, Resolution IV - Screening Type.
OEM Three-Piece Ring Valve with Polycarbonate Resin

Variable / Run	Treatment	RPM	DECOMPRESSION (inches)	INJECT SPEED (inches/second)	BACK PRESSURE (psi)
1	1	High (80%)	High (0.50)	High (4.0)	High (200)
4	2	High (80%)	High (0.50)	Low (1.0)	Low (70)
5	3	High (80%)	Low (0.00)	High (4.0)	Low (70)
2	4	High (80%)	Low (0.00)	Low (1.0)	High (200)
7	5	Low (20%)	High (0.50)	High (4.0)	Low (70)
8	6	Low (20%)	High (0.50)	Low (1.0)	High (200)
3	7	Low (20%)	Low (0.00)	High (4.0)	High (200)
6	8	Low (20%)	Low (0.00)	Low (1.0)	Low (70)
9	1	High (80%)	High (0.50)	High (4.0)	High (200)

The order in which treatments were applied was randomized to help average any experimental drift. A replicate of treatment one (run nine) was also added to the experiment to measure the repeatability of the treatment effects. This replicate allowed for a comparison of data at the beginning versus the end of the experiment, providing an estimate of experimental error, or drift.

A second test was conducted using the same valve and experimental design using nylon resin. A third test was conducted using EMI's three-piece free-flow ring valve (Figure 3). Nylon, polycarbonate, and acrylonitrile-butadiene-styrene (ABS) comprised the materials for the third, forth and fifth tests, respectively, using the same valve.

ANOVA results from the first test showed that a large amount of variance remained unexplained for polycarbonate. Previous work had shown that melt temperature was a significant variable for amorphous resins (Engelmann, Dawkins, Monfore, & Vander Kooi, 1996). Therefore, barrel temperature was added as a variable to the experimental designs for tests three and four in order to try to resolve the unexplained variance. The resulting design was a five-variable, two-factor, factional factorial, resolution V screening design [2**(5-1)] consisting of 16 unique treatments.

The fifth test was conducted using ABS resin. Results had shown the four main factors effecting valve response were pack pressure, injection speed, barrel temperature and decompression. It was decided to drop the variables RPM and Back Pressure from the design matrix as they were not significant (p>.05). The resulting experimental matrix was a three-variable, two-factor, full resolution [2**(3-0)] design. Previous experiments had only given modest insight to the two-way interactions between the independent variables. The increased resolution of this design allowed estimation of the three-way interactions. This design was used for both the fifth and sixth tests.

The sixth test was performed using a piston-type valve, the Repeater ®, and ABS resin. This is the same valve shown previously in Figure 7. A matrix of all experiments performed is shown in Appendix D.

In-Plant Experimentation and Development

Findings from the discovery phase of the experiments aided in creating two procedures to test non-return valve performance in a production environment. The first procedure tested the ability of the injection unit to maintain pressure during the injection cycle. This was necessary since the non-return valve was frequently blamed for leaking during injection and hold phases, often resulting in the inability to maintain a cushion. The second test established a quantitative method for establishing the amount of decompression applied to a valve.

Injection Unit Pressure Test

A practical test was developed to test for combined wear in the injection unit. The test accounted for wear in both the shutoff functions of the valve as well as the clearance between the barrel and non-return valve. This test indicated if the system was capable of delivering the melt at a determined pressure.

The injection unit pressure test was initially developed at Western Michigan University's plastics processing laboratory to determine if the OEM 3-piece non-return valve on the 85-ton Van Dorn injection molding machine was worn in the seating area. This valve was the original valve supplied with the press and had been in use since 1992. During this time, the press had been used for instruction purposes in the laboratory and for conducting many research experiments. However, the total number of hours on the machine was very low as compared to a production machine over the same period. A typical production press was scheduled for 5184 hours in a year (240 production day at 24 hours / day at 90% load capacity). In contrast, press usage in the laboratory was only several hundred hours per year. In addition, materials processed were also predominately non-reinforced, which usually are the least abrasive.

The injection unit test involved limiting the available injection pressure and injecting on-cycle while material flow was blocked to the cavity. The maximum available hydraulic injection pressure was limited to a percentage of the maximum available. Pack and hold pressures were set to "zero", so that only the "fill" portion of the controller would be used during the test. Under these conditions, the machine would attempt to inject until the inject-forward timer expired. The maximum available hydraulic injection pressure set-point was then increased, and the procedure repeated, until the maximum machine pressure was reached. The resulting cushion was a combination of material leakage and compressibility of the melt. This data was plotted to show the cushion versus available hydraulic injection pressure. A written procedure for the injection unit pressure test is shown in Appendix E.

The injection unit pressure test was designed to be performed with the press in production using both the mold and material in question. If the mold had a cold runner configuration, or a simple hot sprue into a runner, then the sprue would be used to block material flow into the mold. If the mold had a hot-runner manifold, a nozzle cap needed to be constructed for the nozzle of the machine since there was not an easy method to shut off the flow of material through the manifold. A sketch of the nozzle cap constructed is shown in Appendix E. Presses equipped with a shut-off type nozzle were ideally suited to this test, since the nozzle shutoff isolated the injection unit from the mold.

Decompression Test

As mentioned in Chapter II, there was no established procedure for determining the amount of decompression used on a given valve. Decompression was either "on" or "off", and fine-tuning was done by trial and error. There was little published for determining how much decompression to use.

There also was no published data to show how varying the amount of decompression affected the performance of the non-return valve. Therefore, it was decided to try to optimize the process of determining the amount of decompression to use for a given combination of material and valve.

The molding machine was set up to mold short, or incomplete, shots. The resulting short shots show the variation in part weight, and thus the variation in the valve's ability to close repeatedly. In order to accomplish this, pack and hold pressures were set to zero. Beginning with a decompression value at zero, shot weights were recorded to quantify variation. Decompression was then increased incrementally, and the test repeated until a maximum value was reached. The maximum value was not that of the machine, but rather, the point at which decompression was no longer suitable due to either splay, or no added benefit to variance.

The amount of decompression used was dependent on the screw diameter and valve being used. For small screw diameters, decompression should be increased in small increments. Larger increments should be used for larger screw diameters. For example, based on typical practice, a 65mm screw would typically have decompression set between 3 and 10 mm. Therefore, the initial test would be performed by starting at a setting of 1.0mm and increasing decompression in increments of 1.0 mm until a setting of 15mm is reached. The data were graphed to show the corresponding shot weight and variation at each set-point. A written procedure is shown in Appendix F.

Many newer machines are equipped with decompression velocity as a machine setting. Little published information was found to describe how decompression velocity affected part weight. Therefore, a test was designed to test decompression at two levels of decompression rate.

In-Plant Wear Study

Long term wear testing was performed at Cascade Engineering to measure the effect of wear on non-return valve performance over time. An extensive wear study was conducted concurrently with the discovery phase. The wear study was designed to observe the effect that valve wear had on valve response variables over time. Little published work was found showing how valve wear affects processing conditions other than known failure modes. Therefore, it was necessary to study dependent variable response against valve wear.

The production machine used was a 700 ton Cincinnati Milacron press, with a 114 mm diameter screw. The non-return valve is nitrided H-13 with a D-2 rear seat. This machine was ideal for the test because of the dedicated production part, which was a sound-deadening component used under the hood in an automotive application. The material was a highly filled (66%) thermoplastic elastomer. The filler was a proprietary mineral blend that was considered highly abrasive for an injection molding resin.

The data were collected using two different methods. The first involved a series of designed experiments in order to determine how valve response changed with valve wear. The second involved monitoring machine performance and evaluating whether changes in performance correlated to valve wear over time.

Experimental Timeline

The wear study was conducted over a period of nine months, at which time it was determined the valve was physically worn out. Testing was performed using two valves; a control valve and a production valve. The control valve was used to establish a baseline of performance at the beginning of the experiment. After the initial baseline was performed with the control valve, the production valve was installed. Since the machine was fully utilized for this product, it ran continuously during the week with the exception of periodic testing and inspection of the valve. The control valve was re-installed at the end of the experiment in order to check for changes in experimental conditions.

It was not known how long the test would be conducted at the onset of the experiment, therefore, the valve was evaluated frequently at the beginning of the test. As the wear rate became apparent, the testing frequency was modified to improve the efficiency of the experiment. The valve was tested one week after installation to check for wear. The test was repeated again after the second week. Physical inspections, along with machine monitoring, helped to determine the frequency of testing and inspection. The matrix of testing is shown in Appendix D.

Determining Valve Wear

Previous production experience had shown the front seat of the valve was the first and most extensive area to wear. Front seat wear was observed by taking physical measurements and component weight. The rear seat tended to wear much slower than the front. It was also more difficult to measure wear in this area. In order to quantify valve wear, three solid circles, of different depths, were etched into the center of the shut-off contact area in the rear seat. The etchings were .0005, .0010, and .0015 inches deep, respectively. A sketch of the rear seat with the etchings is shown in Figure 15. The different depth etchings were used to help monitor the progress of rear seat wear during the experiment.

Machine variables were tracked in order to provide a correlation with valve wear. The valve was determined to be worn out when either the process variables monitored showed significant change, the deepest etching of .0015 in. had eroded away, or the time allotted for the experiment ran out.

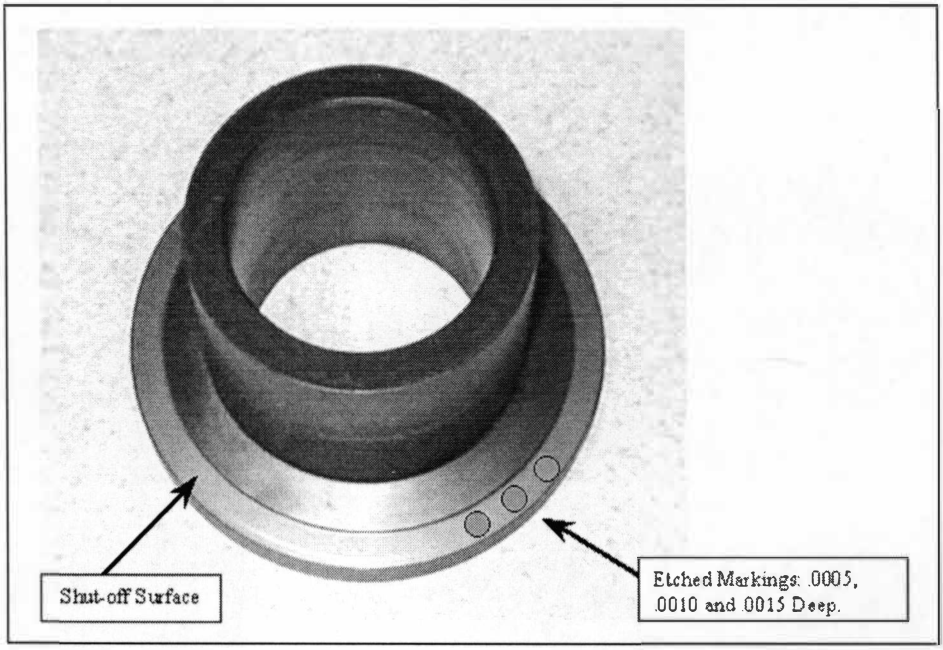


Figure 15. Sketch of Rear Seat With Etched Circles Used to Determine Wear.

Designed Experiments

Chapter II discussed some of the effects in published literature that are the result of a worn injection unit. A series of designed experiments were devised to evaluate the non-return valve under specific test conditions during long-term production. The plan was to repeat the experiment periodically until it was determined that the valve had physically wore out or failed to perform. This would allow the research team to observe any effect on the response variables over time as the valve wore.

Independent variables selected for the wear study were: injection speed, decompression, back pressure, screw rpm and barrel temperature. Part weight was selected as the dependent variable. The design used was a five-variable, two-factor, factional factorial, resolution III screening design consisting of eight unique treatments (Table 2).

A center-point treatment was added to check for curvature and a replicate treatment was added to check for any drift during the experiment for a total of ten runs. Pack pressure was added as a blocking variable since its absence was thought to cause increased part weight variation. This means that high and low pack pressure settings were applied to each treatment group. This basic design was used throughout the wear study.

Table 2

Design: 2**(5-2) Fractional Factorial, Resolution III - Screening Type.
Cascade Engineering Wear Study. Four-Piece Ring Valve

Variable / Run	Treatment	BARREL TEMPERATURE (°F)	INJECT SPEED (inches/second)	BACK PRESSURE (PSI)	RPM	DECOMPRESSION (inches)
1	5	Low (420)	High (4.0)	High (100)	Low (35)	Low (.00)
2	8	Low (420)	Low (1.0)	Low (0)	High (80)	High (.30)
3	7 *	Low (420)	Low (1.0)	High (100)	High (80)	Low (.00)
4	6	Low (420)	High (4.0)	Low (0)	Low (35)	High (.30)
5	9	Mid (460)	Mid (2.5)	Mid (50)	Mid (57.5)	Mid (15)
6	3	High (500)	Low (1.0)	High (100)	Low (35)	High (.30)
7	1 *	High (500)	High (4.0)	High (100)	High (80)	High (.30)
8	2	High (500)	High (4.0)	Low (0)	High (80)	Low (.00)
9	4 *	High (500)	Low (1.0)	Low (0)	Low (35)	Low (.00)
10	5	Low (420)	High (4.0)	High (100)	Low (35)	Low (.00)

* Treatments 1,4 and 7 were used for the periodic abbreviated testing.

The average cycle time during the experiment was 60 seconds with an average shot weight of 1150 grams. This potentially made conducting a large experiment costly in terms of both machine time and material usage. It took approximately 16 hours to complete the 10 runs, using approximately 115 kg (253 lbs.) of material. Since the process would need to be tested repeatedly over the course of the wear study, it was decided to conduct abbreviated experiments, during the course of production, to keep the impact to production to a minimum. Three treatment groups

(1, 4 and 7) were randomly picked from the above design. The same three treatments were also used to test the control valve. One of the treatment groups was replicated as a check for experimental drift, within each sub study, resulting in a total of four runs performed during each abbreviated experiment. This modification allowed the periodic testing to be completed in less than five hours.

Machine Monitoring

The second method of collecting the wear data was by monitoring machine variables over time during everyday production. Recovery time, fill time, cushion, cycle time and cavity pressure at transfer were recorded.

These variables were easily read from the controller of the machine. Data recording was performed manually. The raw data were collected on a form as shown in Appendix G. Data from ten consecutive shots was collected during every eight hour shift of production. The data from the study were entered into a Quattro Pro® spreadsheet for later analysis. The data was then imported into Statistica® and scatterplots were produced to illustrate the change in the mean and variation of the response variables.

Cost Justification of Non-Return Valve Replacement

Factors involving the costs to replace a non-return valve were investigated in order to give the molder justification of non-return valve replacement. Informal discussions with molders were during PCIM plant visits to determine the factors associated with the costs of valve replacement, as well as the evaluation process used to determine when a machine goes down for maintenance. These responses were used to help establish guidelines for justification of valve replacement.

CHAPTER IV

RESULTS

As detailed in Chapter III, experimentation was divided into three phases. The first phase was the discovery phase. The discovery phase was used to determine the role of the non-return valve and the variables that effect valve performance. The second phase was test development and in-plant experimentation. Two test procedures, the injection unit pressure test and the decompression test, were developed at Western Michigan University's plastics processing laboratory. These procedures were validated and refined in the PCIM member plants. The third phase was the in-plant wear study. This study tracked the life of a non-return valve, in a production environment, in order to establish a correlation between valve life and process variables.

Discovery Phase

Throughput Test

The first throughput test conducted used Polycarbonate (PC) resin, with both the EMI valve and the zero-restriction screw tip. It can be seen, in Figure 16, that throughput was numerically higher at all RPM settings with the non-return valve than it was without the valve. There were not enough data to determine statistical significance, therefore, all results for throughput are numerical observations only.

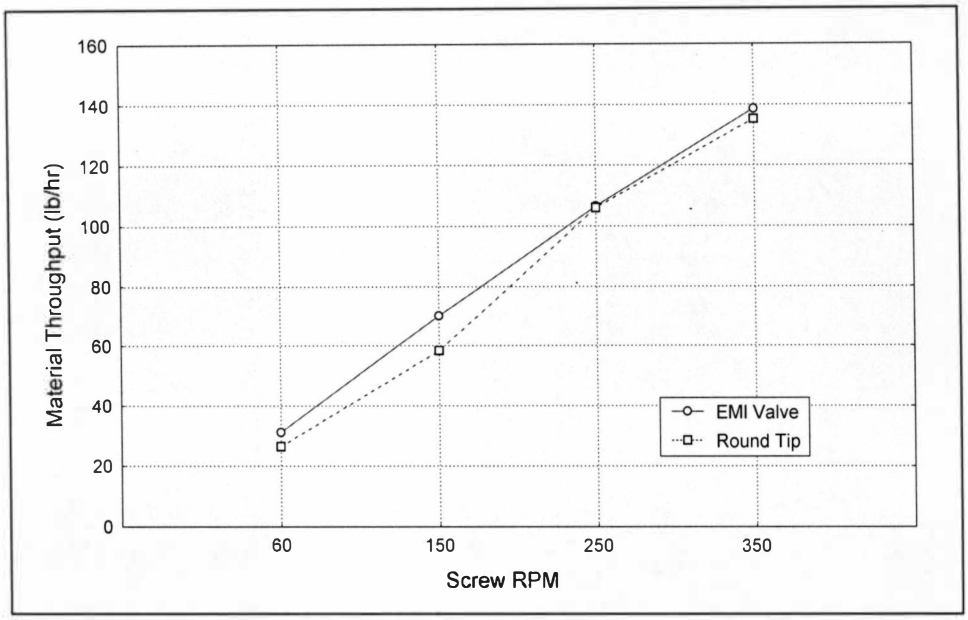


Figure 16. Screw RPM Versus Material Throughput.

It was hypothesized, that if a non-return valve with a given flow restriction, was placed in the system there would be an increase in the pressure required to turn the screw at a given RPM. This should also be accompanied by a reduction in throughput and an increase in melt temperature. As shown in the graph, the results are opposite the hypothesis. Melt temperature with the non-return valve was shown numerically greater at all RPM settings than without the non-return valve as shown in Figure 17.

Figure 18 shows the hydraulic pressure required to rotate the screw at a desired RPM. Hydraulic pressure was numerically higher for the screw with the non-return valve installed.

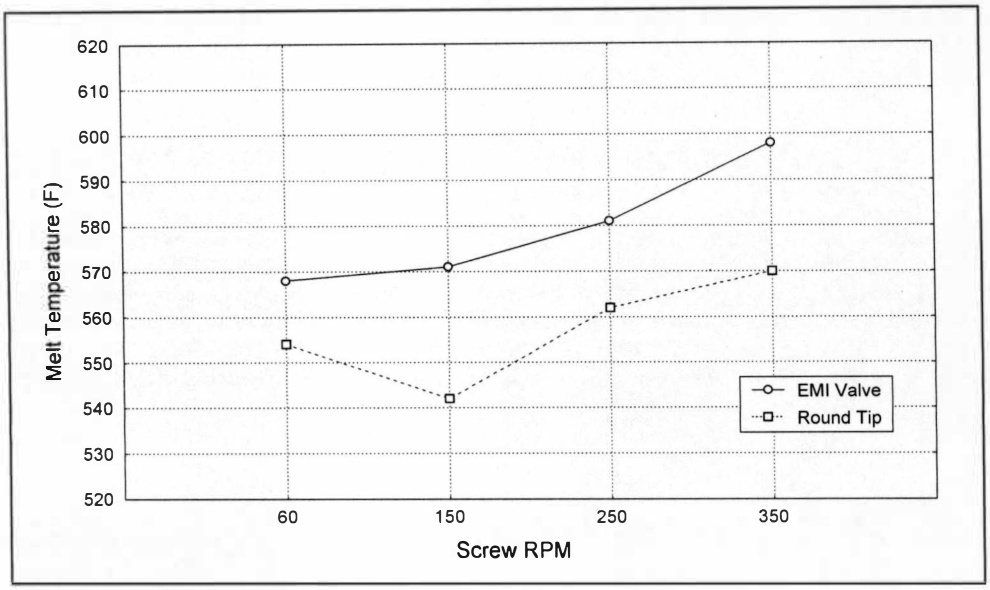


Figure 17. Screw RPM Versus Melt Temperature.

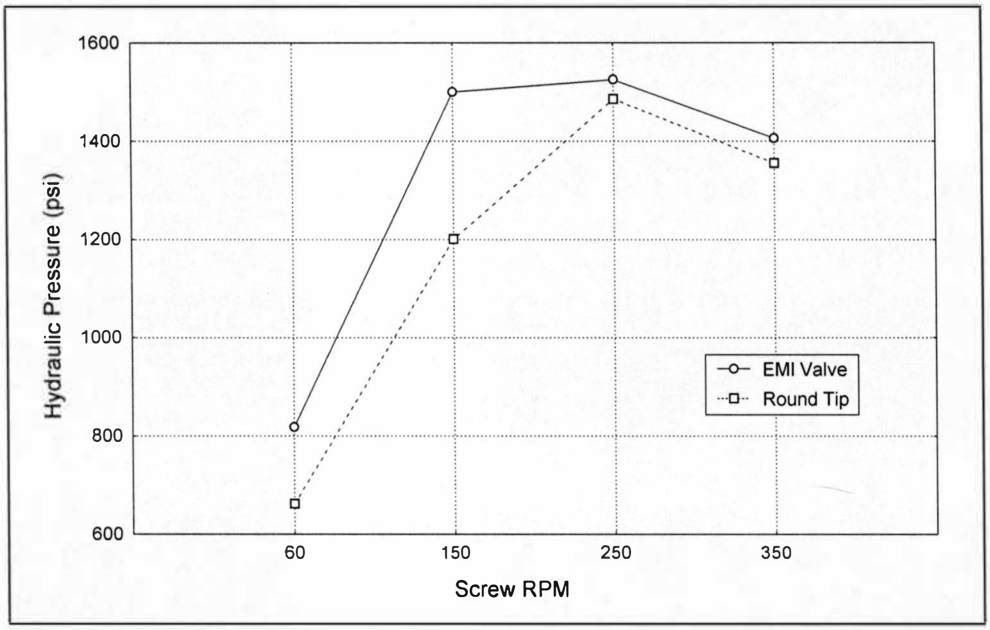


Figure 18. RPM Versus Hydraulic Pressure.

Melt temperature and required hydraulic pressure were expected to increase numerically with the addition of the restriction provided by the non-return valve. However, it was not expected that throughput would increase with the additional restriction of the non-return valve in the system.

An attempt was made to perform a second test using nylon resin. The procedure could not be performed due to the melting requirements of the resin. There was not enough friction in the system to melt the resin, due to the high degree of crystallinity, and consequently the screw seized inside the barrel. It should also be noted, that the inability of the screw to melt the nylon resin, without the restriction of the non-return valve, is an indication that the screw is not optimally designed for this type of material. Therefore, while the throughput test yielded useful data, this procedure was best used in a laboratory setting.

Design of Experiments – Discovery Phase

Designed experiments were conducted at Western Michigan University's plastics processing laboratory in order to determine the process variables that significantly affect non-return valve performance. Data were analyzed using standard least squares analysis of variance (ANOVA) methods. The data reviewed effects for both mean part weight and part weight variance. There were a total of six experiments conducted in similar fashion. Two experiments, showing diverse results, are explained in detail below. The results for all experiments are summarized in table form at the end of this discussion.

OEM Three Piece Ring Valve - Polycarbonate Resin

The first experiment investigated the OEM three-piece ring valve using a Polycarbonate resin. The results of the ANOVA were summarized in Pareto graph form. This allowed for a visual representation of the magnitude of the effects ranked from highest to lowest. The numerical value for the effect magnitude of each independent variable is located on the right hand side of the bars.

Part Weight Mean. Mean part weight was calculated by summing the number of observations taken for a particular treatment group and then dividing by the number of observations. Figure 19 showed independent variables pack pressure, inject speed, and decompression were significant ($p<.05$).

It was determined that pack pressure had the largest effect on mean part weight. The effect was positive. That is, as the pack pressure set-point was increased, the response for mean part weight also increased. Injection speed was the next most significant variable, followed by decompression. Both also had a positive effect on mean part weight. For injection speed, this means that as it increased, mean part weight increased. For decompression, an increase also resulted in an increase in mean part weight.

The interactions of injection speed by pack pressure (3 by 5) and RPM by back pressure (1 by 4) were also significant ($p<.05$). Both interaction effects were negative.

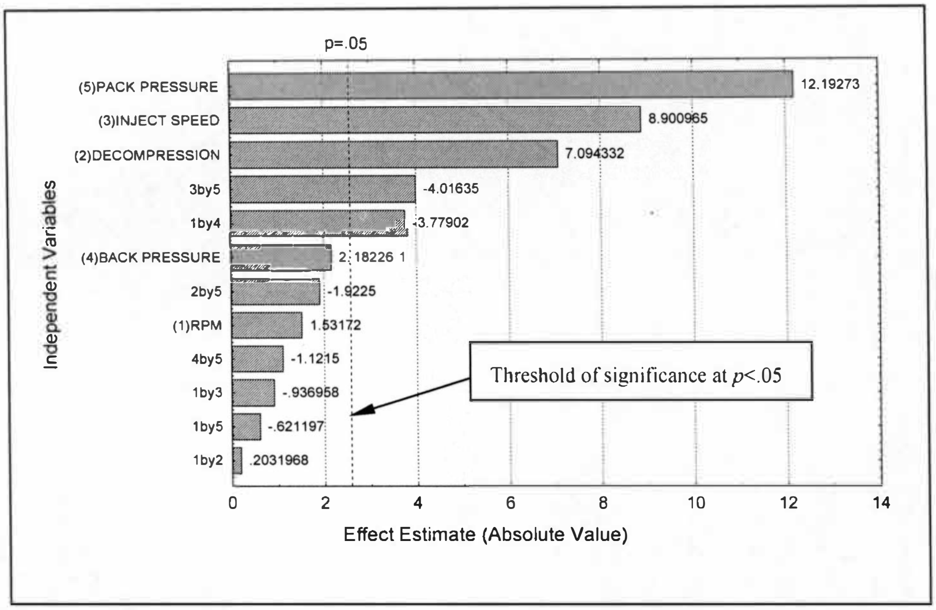


Figure 19. Pareto Chart of Standardized Effects - Weight Means for Polycarbonate and the OEM Valve.

A negative response from an interaction means that their effect is less that the main effects combined. Conversely, if the magnitude of the interaction was positive, then the effect was greater than the cumulative total of the individual effects. The effect of an interaction is explained as:

Response Value = Effect (Variable 1) + Effect (Variable 2) + Interaction (Variable 1 * Variable 2)

In this case, the main effects pack pressure and injection speed both have a positive impact on part weight mean. However, when increasing both variables at the same time, mean part weight increases, but the result is less than the sum of the two individual responses added together.

RPM and back pressure did not have a significant effect on mean part weight

(p>.05). The model used in this analysis of part weight means had a R^2 value of .98. This value means the independent variable effects of the model described 98% of the change in mean part weight.

Part Weight Variance. Each of the treatment runs produced an associated amount of variation in part weight. This response is known as part weight variance. Variance is a measure of the variation in the response (part weight) at a given treatment group. Variance is computed as the sum of squared deviations (from the mean) divided by n-1, where n is the number of observations. Weight variance is shown in Figure 20. The model for weight variance had a R^2 value of .88. This value means the independent variable effects of the model described 88% of part weight variance.

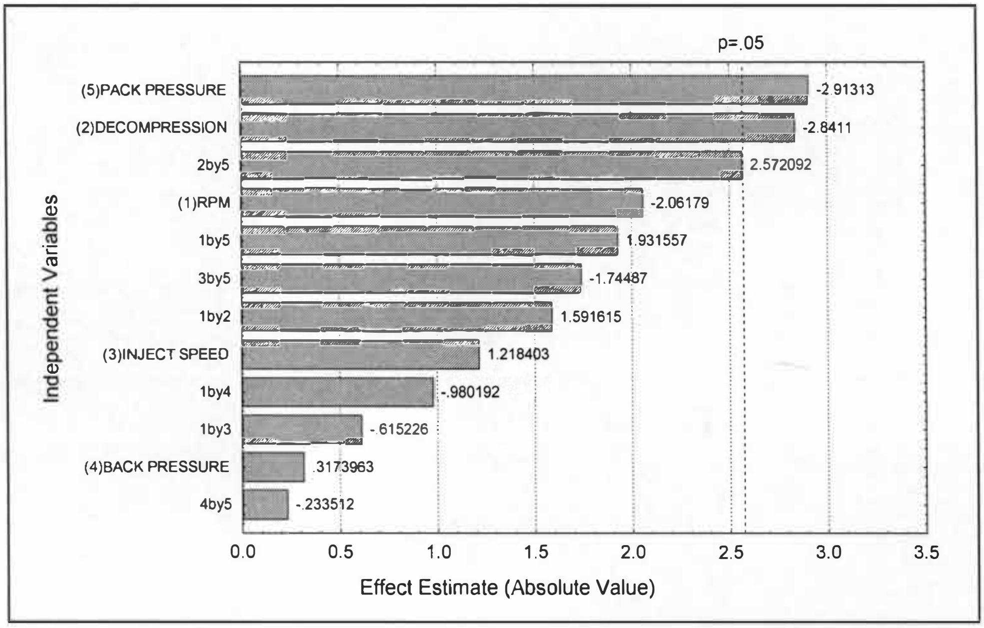


Figure 20. Pareto Chart of Standardized Effects - Weight Variance for Polycarbonate and the OEM Valve.

Pack pressure, decompression and their interaction were significant ($p<.05$). Pack pressure was shown to have the largest effect on shot weight variance. The effect for pack pressure was negative. This means that as pack pressure increased, part to part weight variation was reduced. The next largest effect was decompression. This effect was also negative. As decompression was added to the valve, the variation in part to part weight was reduced. This supported the theory that decompression was needed in order for the non-return valve to shut-off consistently. The interaction of pack pressure by decompression is positive. This means that increasing both pack pressure and decompression at the same time reduced variation more than the sum of the two individual responses if added together. RPM, injection speed and back pressure were not significant for part weight variance ($p>.05$).

EMI Three Piece Free-Flow Valve - ABS Resin

The next experiment discussed was the fifth of the six exploratory experiments conducted. The EMI free-flow valve was tested using an ABS resin. Weight variance had not been adequately explained from the previous four experiments. ANOVA results from the first test showed that there was a large amount of variance that remained unexplained for polycarbonate. Previous work had shown that melt temperature was a significant variable for amorphous resins (Engelmann, Dawkins, Monfore, & Vander Kooi, 1996). Therefore, barrel temperature was added as a variable to the experimental designs for tests three and four in order to try to resolve the unexplained variance. The variables RPM and Back Pressure were dropped from the design matrix since they were shown not to be significant ($p>.05$) in the previous experiments. The experimental plan developed was a three-variable, two-factor full resolution [2**(3-0)] design. This increase in design resolution also allowed three-way interactions to be estimated.

Part Weight Mean. A Pareto graph was used to summarize the results and is shown in Figure 21. Effect values are considered significant at a level of $p<.05$.

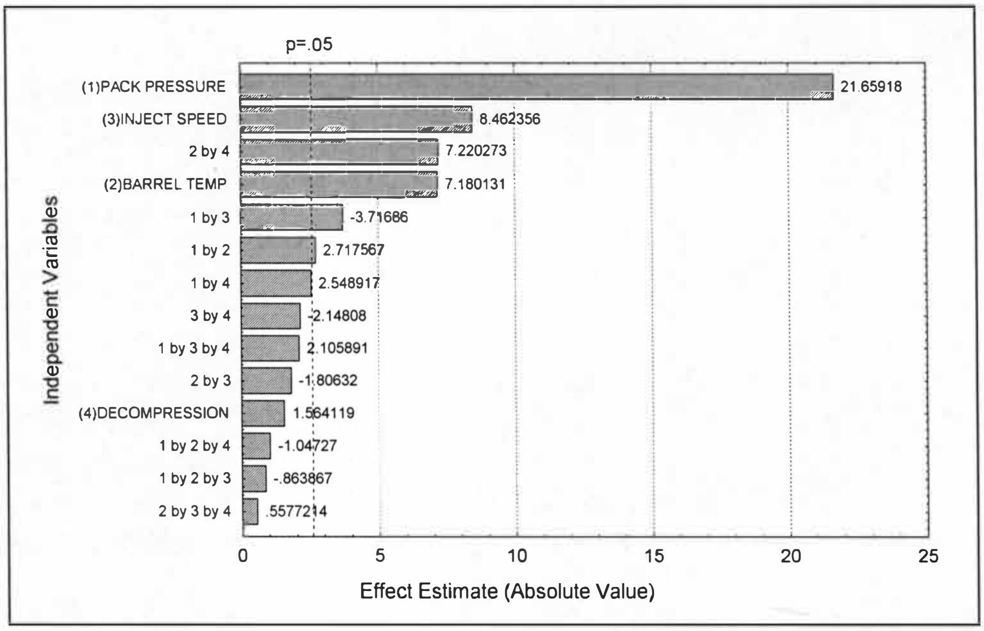


Figure 21. Pareto Chart of Standardized Effects - Weight Means for ABS With the EMI Free-Flow Valve.

The variables Pack pressure, injection speed and barrel temperature were shown to be significant, and the effects positive. Pack pressure had the largest effect followed by injection speed. The interaction of barrel temperature by decompression (2 by 4) was also shown to be significant, with the effect positive. The interaction of pack pressure by injection speed (1 by 3) was significant, with the cumulative effect being negative. The interactions of pack pressure by barrel temperature (1 by 2), and pack pressure by decompression (1 by 4) were also shown to be significant. The effects were positive.

Decompression was not significant. The remaining two and three-way interactions were also not shown to be significant. The R^2 value for the model was .99. This meant that 99% of the variation in the response data was explained by the model.

Part Weight Variance. Figure 22 shows a Pareto graph of the effects for part weight variance. Pack pressure was shown to have the largest significant effect. The effect was negative, meaning that as pack pressure was increased, the resulting variation in part weight was decreased. The second largest significant effect was the interaction of pack pressure by injection speed (1 by 3). The effect was negative. Injection speed was the third largest significant effect, with the effect being positive. This was followed by the interaction of pack pressure by decompression (1 by 4). The effect was positive. Decompression was significant, with the effect being negative. The three-way interaction of pack pressure by injection speed by decompression (1 by 3 by 4), was also shown to be significant, with the effect being positive.

Barrel temperature was not a significant effect ($p>.05$) for part weight variation. The remaining two and three-way interactions were not significant ($p>.05$).

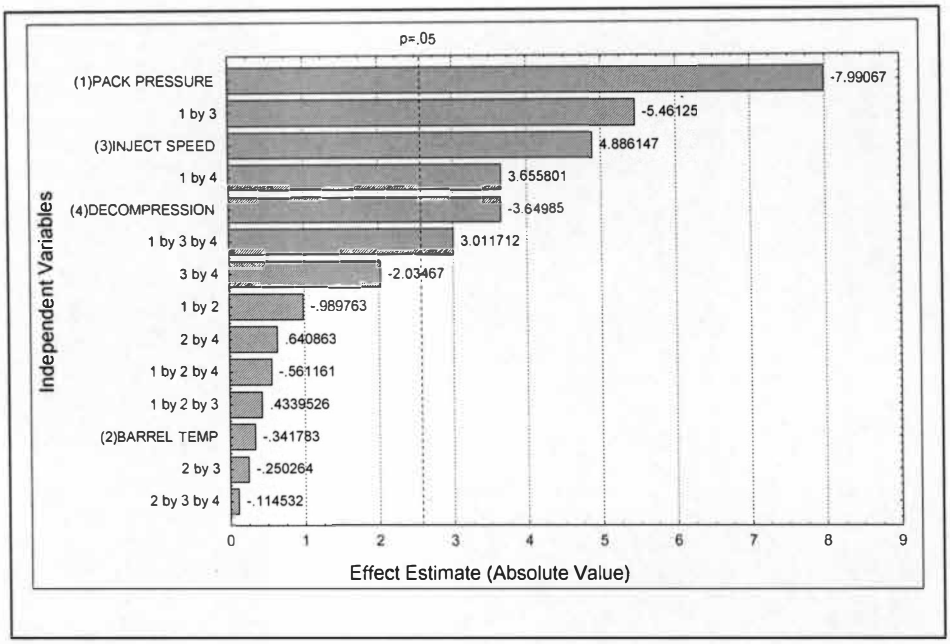


Figure 22. Pareto Chart of Standardized Effects - Weight Variance for ABS Resin and the EMI Free-Flow Valve.

Summary of Effects for all Exploratory DOEs

All experiments were conducted in similar fashion. Pareto charts were completed for all experiments. Significant effects for both weight means and weight variance were summarized in Tables 3 and 4, respectively.

Part Weight Means. Summarized effects for mean part weight are shown in table 3. Pack pressure and injection speed were highly significant ($p<.01$) for all experimental combinations except with the Dray valve. Pack pressure was the only variable significant (*p*<.05) for the Dray valve. Pack pressure and injection speed effects were positive. Barrel temperature was highly significant (*p*<.01) for the EMI valve with both ABS and polycarbonate and the effects were positive.

Table 3

Significance Levels for Independent Variables Affecting Weight Means

Variable / Valve type/Material	Pack Press	Barrel Temp	Inject Speed	Decompression	Back Press	RPM
ABS–EMI	*** (+)	*** (+)	*** (+)			
ABS–Dray	** (+)					
Polycarbonate–OEM	*** (+)		*** (+)	*** (+)	* (+)	
Polycarbonate–EMI	*** (+)	*** (+)	*** (+)	*** (+)		
Nylon–EMI	*** (+)		*** (+)	*** (+)		
Nylon-OEM	*** (+)		*** (+)	*** (+)		

Significance Levels for Weight Means

*** $p <= .01$
** $p <= .05$
* $p <= .10$

Decompression was shown to be highly significant (*p*<.01) with both the OEM and EMI valves using polycarbonate and nylon and the effects were positive. Back pressure was significant (*p*<.10) for polycarbonate with the OEM valve. Effects for both decompression and back pressure were also positive. RPM was non-significant (*p*>.10).

Pack pressure and injection speed had a positive affect on all combinations of materials and valves tested. This effect was logical and expected. The addition of valve decompression significantly increased mean part weight in all combinations except those tested with ABS resin. It is not understood why decompression affected one amorphous resin (PC) while not affecting another (ABS). Barrel temperature was significant for only one of the valves tested. Both materials in those cases were amorphous. Back pressure was significant in only a single case. Back pressure should be the last variable investigated pertaining to mean part weight.

Part Weight Variance. Summarized effects for part weight variance are shown in Table 4. Pack pressure was shown to be significant ($p<.01$) for the EMI valve with ABS, polycarbonate and nylon. Pack pressure was also shown to be significant for polycarbonate with the OEM valve ($p<.05$) and ABS with the Dray valve ($p<.10$). All pack pressure effects were negative.

Significant variables include pack pressure, injection speed, decompression, RPM, and barrel temperatures. Back pressure was not significant. Pack pressure was shown to have a negative effect on most combinations tested. This is intuitive since pack pressure is used to mask part weight variation. Decompression was shown to have a negative effect for polycarbonate with both the OEM and EMI valves. The EMI valve with ABS was also significantly affected by decompression.

Decompression did not have an effect on nylon. It appears that the low viscosity resin does not inhibit the ring from seating against the rear seat as a high viscosity resin may, and therefore, the ability to shut-off in not affected.

Table 4

Significance Levels for Independent Variables Affecting Weight Variance

Variable / Valve type/Material	Pack Press	Barrel Temp	Inject Speed	Decompression	Back Press	RPM
ABS–EMI	*** (-)		*** (+)	** (-)		
ABS–Dray	* (-)		* (+)			
Polycarbonate–OEM	** (-)			** (-)		** (-)
Polycarbonate–EMI	*** (-)	** (-)		* (-)		
Nylon–EMI	*** (-)		*** (-)			
Nylon-OEM						* (-)

Significance Levels for Weight Variance

*** $p <= .01$
** $p <= .05$
* $p <= .10$

Injection speed had a positive affect on ABS with both the EMI and Dray valve. However, it had a negative effect on nylon with the EMI valve. Polycarbonate was not affected. Screw RPM was shown to significantly affect the OEM valve when processing either nylon or polycarbonate. This was interesting since RPM was not significant with the same materials being processed with the EMI valve. This gives evidence that valve geometry and its contribution to the natural back pressure in the system are a phenomenon that may be difficult to anticipate. Barrel temperature was shown to be significant in one case with the combination of polycarbonate with the EMI valve, and should not be considered as a potential significant variable only after the previously discussed variables are explored.

Inject speed was significant ($p<.05$) for ABS resin and the EMI valve. The effect was positive. Inject speed was also significant ($p<.05$) for nylon resin and the EMI valve. However, the effect was negative. Inject Speed was significant ($p<.10$) for the Dray valve and ABS for part weight variance. The effect was positive.

Decompression was significant ($p<.05$) for the combinations of ABS and the EMI valve as well as polycarbonate and the OEM valve. Decompression was also significant ($p<.10$) for polycarbonate and the EMI valve. The effect for decompression was negative in all cases.

Barrel temperature was significant for polycarbonate and the EMI valve ($p<.10$). The effect was negative. RPM was significant ($p<.05$) for polycarbonate and the OEM valve. RPM was also significant for nylon resin and the OEM valve ($p<.10$). The effect for RPM was negative in both cases. Back pressure was not significant for any of the combinations ($p>.10$).

Test Development and In-Plant Experimentation

Pressure Test

85 Ton Van Dorn - OEM Valve

The first injection unit tested was the 35 mm Van Dorn at the WMU plastics processing laboratory. The material used was nylon 6/6 resin. A graph of hydraulic injection pressure vs. cushion position was shown in Figure 23.

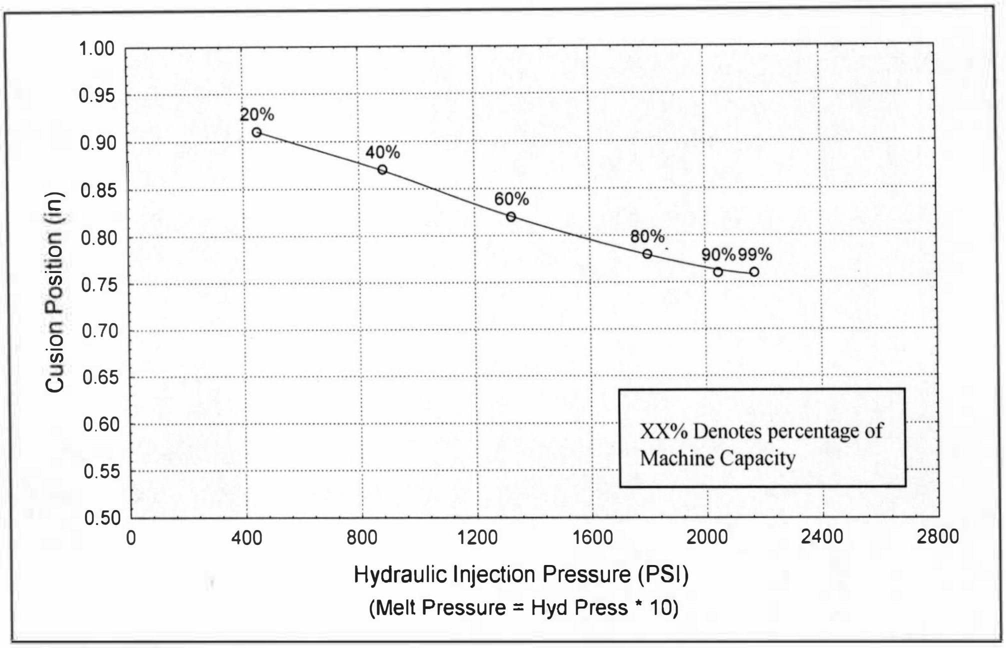


Figure 23. Injection Pressure Versus Cushion Position.

The first test condition was conducted using 20% of the available hydraulic injection pressure, or 450 PSI. The resulting cushion was 0.91 in. Further cushion readings were taken at 40%, 60%, 80%, 90% and 99% of available hydraulic pressure.

Cushion decreased in a linear fashion until a pressure set-point of 80%, or 0.76 in. There was less change in cushion from 80% to 90%. There was little change from 90% to 99%. The data show that, as pressure is increased, the cushion is reduced. The tests are set up so that there was sufficient time to observe screw movement. Forward screw movement stopped fairly abruptly at the lowest reading and held its position. The significance is that the decreasing cushion is a result of material compressibility, not due to leakage through or around the valve. Inspection of the screw, barrel and non-return valve showed all components were within wear specifications and did not have any visually notable wear.

Pressure Test: 250 Ton Toshiba – New Versus Old Valve

The next injection unit tested was a 60 mm 250 ton Toshiba with a four-piece valve. The test compared two valves, old and new, on the same machine. This was done to see if the performance of the machine changed when changing valves. The first valve tested was the valve that had been in production on the machine, which was considered the "old" valve. This valve had been on the machine for approximately two years according to maintenance records. The second valve was new, and of the same design. Inspection of both valves showed dimensional differences of no more than .001 in. This was determined to be acceptable. The old valve was removed after the first test and replaced with a new valve. The test was then repeated and the results produced with the two valves were compared. The material used was a 33% glass filled nylon resin.

The cushion position for all pressure settings was lower for the new valve as compared to the old valve (Figure 24). The cushion for the old valve increased at the high range of pressure. The change was not large, but was perceivable.

These results forced a re-evaluation of the original interpretation of the data. It appeared the new valve took longer to seat, or perhaps did not seat completely.

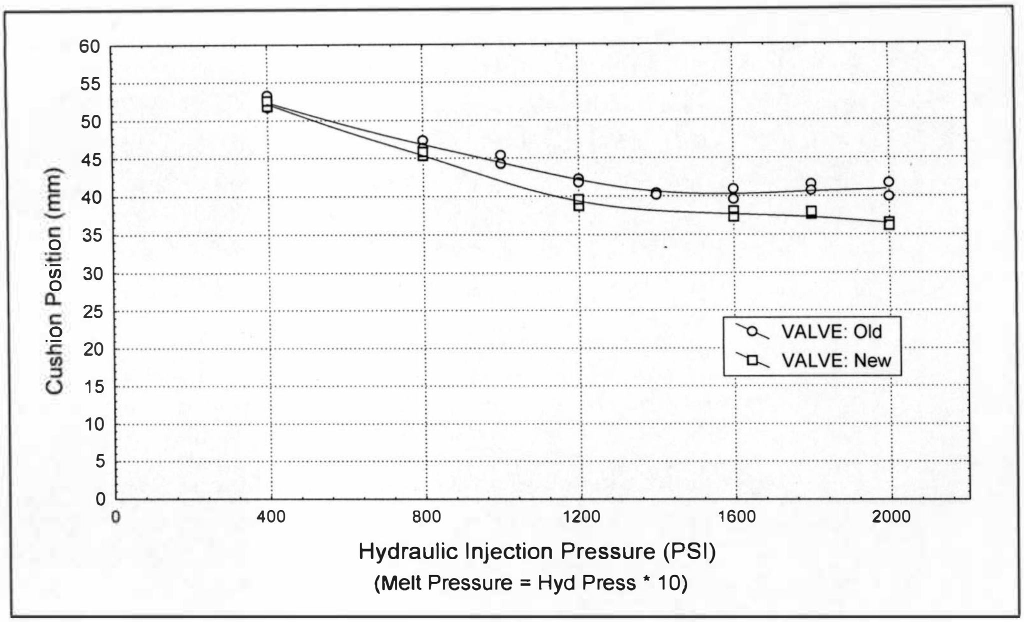


Figure 24. Injection Pressure Versus Cushion Position Between an Old Valve and a New Valve.

It was determined, from later experiments, that a new valve required a break-in period in order to seal completely. This was due to potential mismatch on the ground angles of the seating surface, which was usually very minor, but enough to prevent full seating. This was purposely done by valve manufacturers to provide a "pinch point" so that a new valve would be able to seal completely upon installation while allowing the seating surfaces to mate together as the valve wore. A valve that did not seat completely would leak during the hold phase, resulting in a gradually reduced cushion.

50 mm, 230 Ton Van Dorn

The next test was conducted on a 50 mm, 230 ton Van Dorn processing polypropylene. The pressure test was performed at three different inject forward time settings to see how the cushion changed over time. Figure 25 shows, that as injection forward time was increased from 2.5 to 4.0 and finally 5.5 seconds, the cushion position decreased at each injection pressure setting.

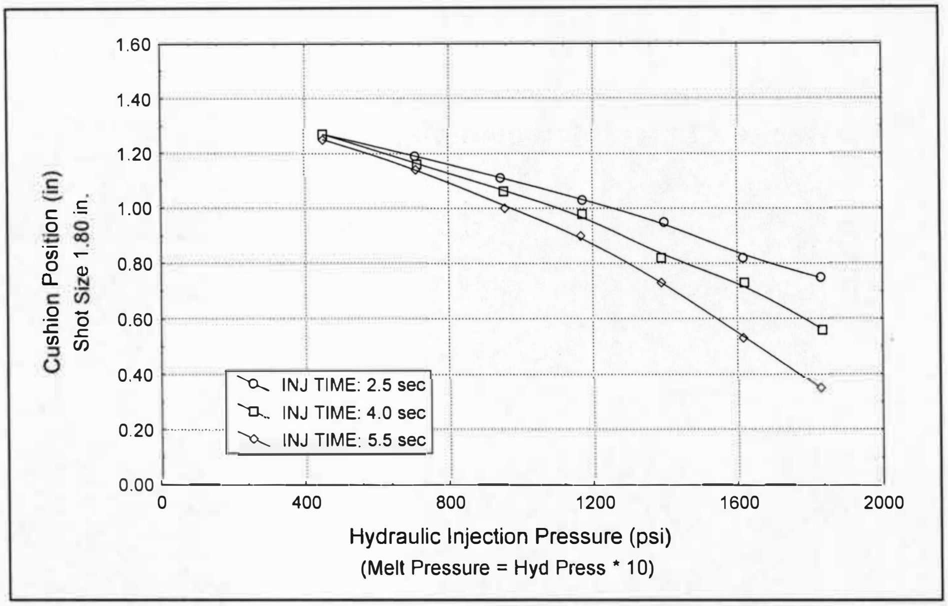


Figure 25. Injection Pressure Versus Cushion Position Using Multiple Inject Forward Times.

The cushion position appeared to drop at a greater rate as the pressure increased. This indicated that the material was leaking, not compressing. The process engineer suspected the press had a worn injection unit. It was determined the injection unit was leaking since cushion position would continue to reduce as long as pressure was applied. This test was designed to test the injection unit as a whole. Therefore, it is important to remember that the barrel, the non-return valve, or both may have been worn. In this case, the non-return valve was found to be worn during an inspection at a later date.

Decompression Test

65mm Toshiba

A decompression test was devised to learn how valve decompression affected part weight. The first in-plant tests were conducted on two similar 65mm Toshiba molding machines with similar 4-piece valves. The screw design and plastic resin used were the same in both cases. However, the valve in the second machine was relatively new as compared to the valve in the first machine, which had been in production for several years.

The molding machine was set up to mold short, or incomplete, shots. Pack and hold pressures were set to zero. Decompression was then set to 0.00 in. The resulting shot weights were recorded. The decompression value was then increased and the test repeated.

Decompression vs. part weight for the first machine was shown in Figure 26. The material used was a 33% glass-filled nylon. It was shown as decompression was decreased, part weight was stable until a decompression setting of approximately .15 in., at which point the mean part weight dropped. Variation in part weight also increased. These results suggest that a decompression value greater than .15 in. should be used on this machine to minimize part weight variation.

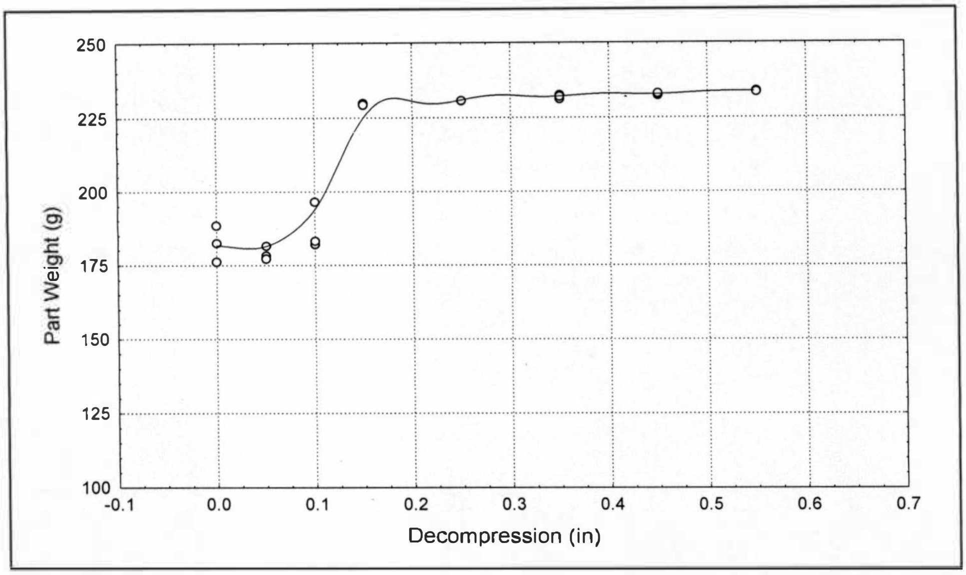


Figure 26. Decompression Versus Part Weight. Part Weight Drops Abruptly and Variation Increases Below .15 in. of Decompression.

Similar 65mm Toshiba Machines- Decompression Test

This test was also conducted on the second 65mm Toshiba using the similar 4-piece valve, which was relatively new, compared to the previous valve. The machine settings were the same between both machines. The results are shown in Figure 27. It can be seen that part weights for the new valve are higher than those for the old valve. The performance of the newer valve was more consistent than the old valve; there was not a drop off in part weight below 0.15 in. Part weight variation was also reduced, using the new valve, in decompression values below 0.15 in.

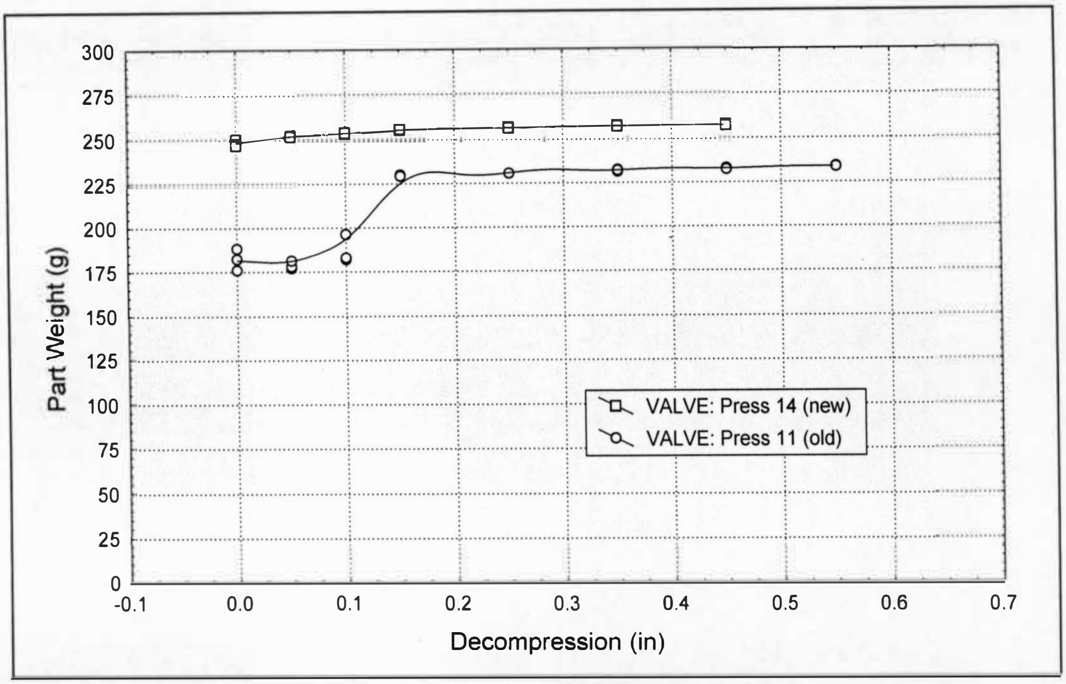


Figure 27. Decompression Versus Part Weight. The New Valve has a Stable Curve Compared to the Old Valve.

<u>Decompression Test: 250 Ton Toshiba – New Versus Old Valve</u>

Decompression tests were performed at ADAC Plastics at the same time the pressure tests were conducted in order to observe the differences between an old valve and a new valve in the same machine. The machine used was a 60 mm, 250 ton Toshiba with a four-piece valve. Material used was a 33% glass filled nylon resin. Inspection of both valves showed no visible or measurable dimensional differences of no more than .001 in. Performance of the old valve was considered good before pressure testing. The results are shown in Figure 28.

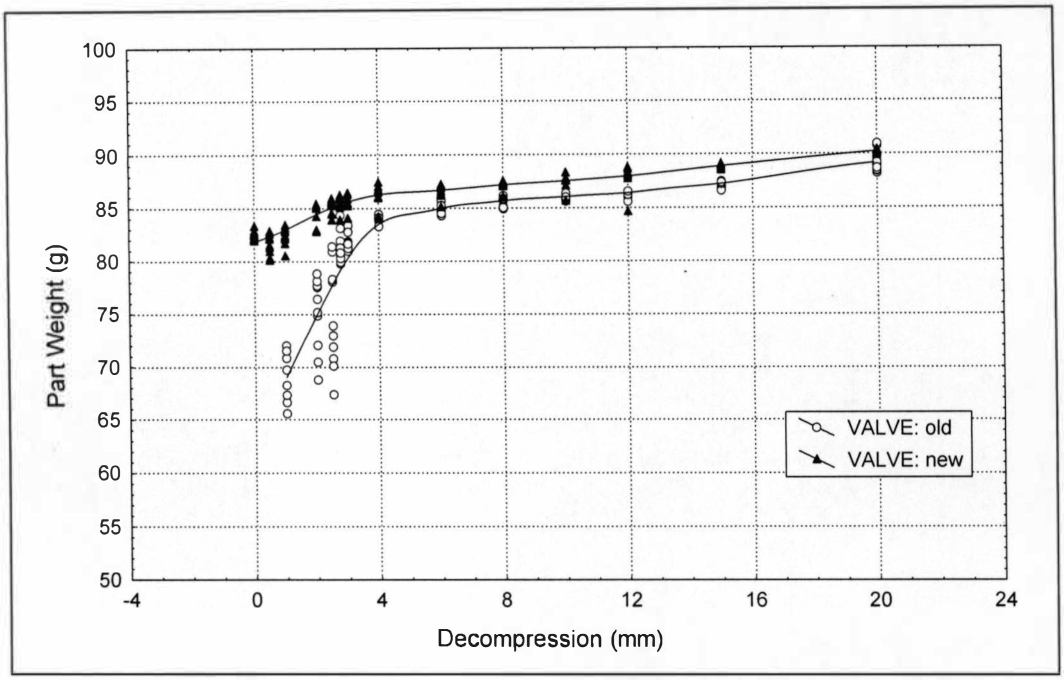


Figure 28. Decompression Versus Part Weight. Comparison Between an Old and New Valve.

It appeared that part weight for the old valve was stable until a decompression value of approximately 6.0 mm. Below 6.0 mm, part weight mean began to drop off while part weight variance increased. At a decompression setting of 2.5 mm, individual part weights varied from 67.4 grams to 81.4 grams. This was a difference of 14 grams, or approximately 18% of the total part weight. The least variation in part weight was observed at a decompression setting of 10 mm. The weight variation at this setting was only .7 grams, or .8% of the total part weight. Variation in part weight for the old valve was reduced by 95% by increasing the decompression setting from 2.5 mm to 10 mm.

In comparing performance of the new valve with that of the old valve, the overall part weight was shown to increase for all decompression settings with the new valve. It was also shown there was not as large of a weight drop-off at the lower decompression settings for the new valve. However, the relative variation of the new valve was more than the old valve at decompression settings between 4 mm and 12 mm. The variation at both 15 mm and 20 mm was less with the new valve.

From these data, it was shown the valves had an optimum setting or "sweet spot". The "sweet spot" was the set point or range of decompression where the valve yielded the least amount of variation in part weight. The "sweet spot" in this case was at a decompression setting of 10 mm for the old valve and at 8 mm for the new valve.

Back Pressure Effects on Decompression

There was some discussion among the research team members regarding the potential effect that increased back pressure might have on decompression and the resulting part weight variation. The theory was that since the resin was under pressure, the melt would have a tendency to decompress, or expand, more than if minimal back pressure was used. The increased pressure in the resin might then inhibit ring movement either when the screw was decompressed or when the valve closed on injection. This discussion took after the initial exploratory experiments were conducted at Western Michigan University. Laboratory results showed that back pressure was significant only for the combination of Polycarbonate and the OEM valve for part weight means. Back pressure was not shown to be significant ($p>.05$)

for part weight variance during any of the experiments.

To investigate this theory, an experiment was conducted using the same 500-ton Cincinnati machine used for the long-term wear study. The press had a 3.5 in. diameter screw. The results are shown in Figure 29. Increasing the back pressure from the low to high setting increased part weight at all decompression settings.

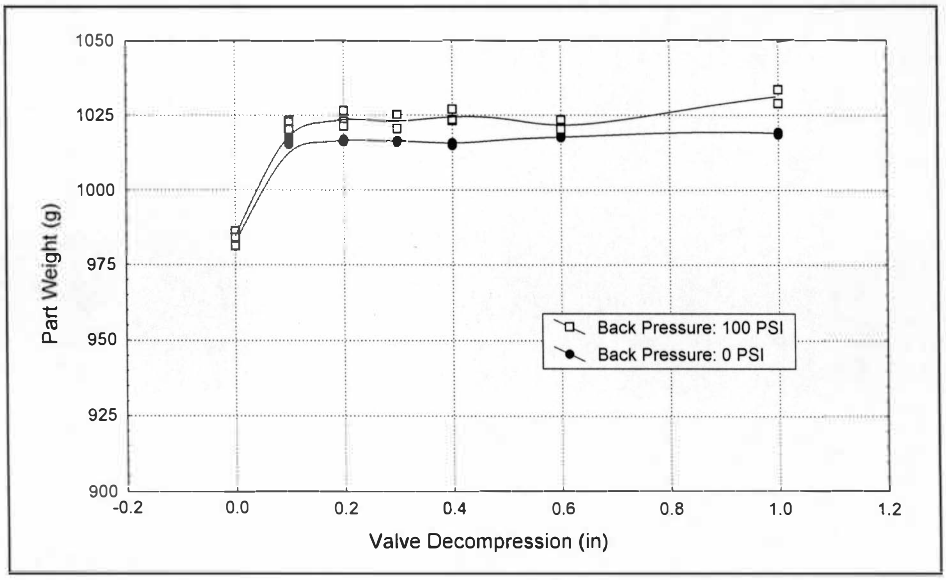


Figure 29. Decompression Test at Two Different Back Pressure Settings.

There was also an increase in part weight variation at all settings when the back pressure was raised.

Decompression Distance Versus Decompression Velocity

Decompression velocity was a controller set point that many new machines are equipped. Therefore, it was decided by the research team, to investigate the effect that decompression velocity had on part weight. Figure 30 shows the results of a decompression test using polystyrene and the OEM valve.

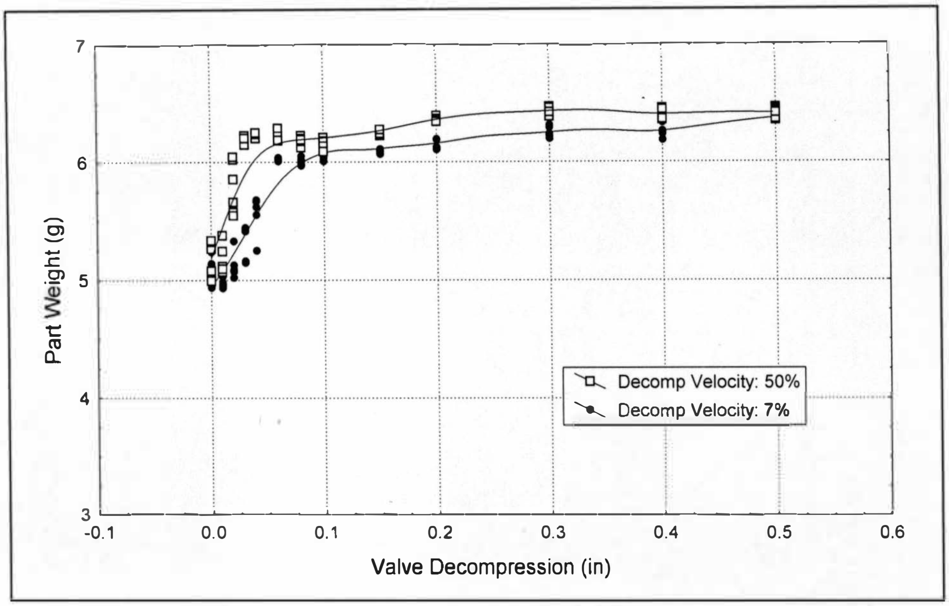


Figure 30. Decompression Test. Decompression Versus Part Weight Performed Using Fast and Slow Decompression Rates.

This test was conducted on Western Michigan University's molding machine. Decompression was set at both slow and fast velocities, 7% and 50% of machine ability, respectively. The profile of the curves was similar to that of curves generated from previous experiments. Part weight decreased and became erratic below decompression settings of approximately .050 in. The response curve for part weight was shifted higher by using a higher rate of decompression. There was, however, no perceptible difference between part weight variances.

In-Plant Wear Study

Processing conditions were monitored and wear of non-return valve components was measured during the nine month study. Results from the in-plant wear study came from two different methods of data collection. The first method consisted of performing a series of designed experiments to determine the effect certain process variables had on non-return valve performance. The second method involved tracking valve performance by observing and recording machine variables on a daily basis.

The physical wear characteristics are discussed before the experimental results so that the reader has an understanding of the transformation that occurred through wear to the various valve components.

Physical Wear - Production Valve

It was previously mentioned that the material used to the wear study was a mineral filled (66%) thermoplastic elastomer considered highly abrasive. The effect of the abrasive material can most apparently be seen in the front seat and ring. Total wear for outer edge of the ring was approximately 3.0 mm (.12 in.) as shown in figure 31.

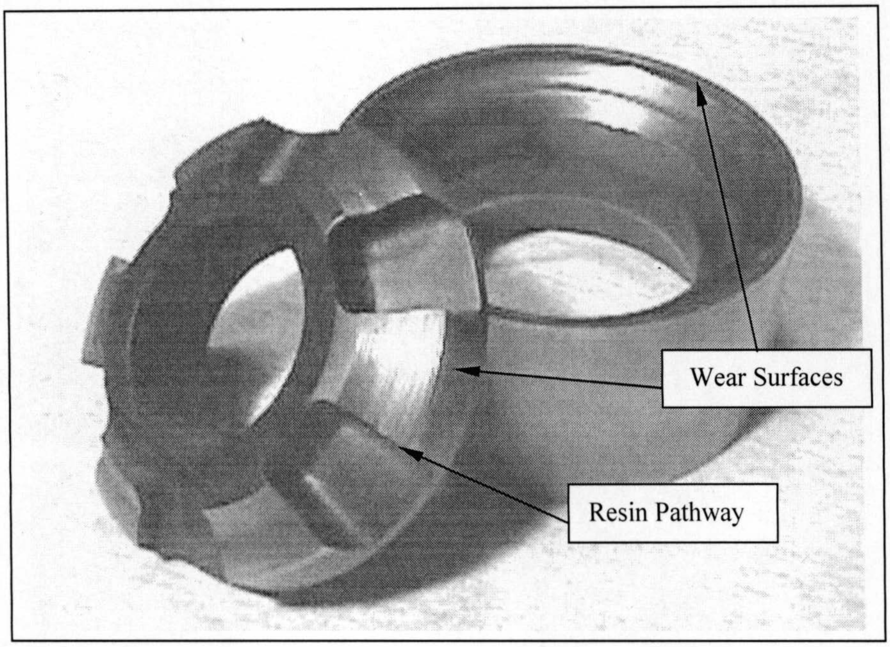


Figure 31. Wear on Mating Surfaces of Front Seat and Ring.

Figure 32 illustrates the wear region in a cross-section of the front seat. Total depth of wear at the outside edge of the front ring was 4.5 mm (.18 in). The profile of the wear surface was not the same as the original surface profile. However, the change in ring thickness did not affect the actual cross- sectional area for the resin to flow until the final month of wear. It should be noted that most ring-type designs allow for a certain amount of this type of wear without restricting resin flow.

As noted previously, there were three different depths of circles etched on the face of in the rear seat (see Figure 15). Periodic inspections revealed all three depths (the deepest depth was .0015 in.) of etched circles were worn away within two

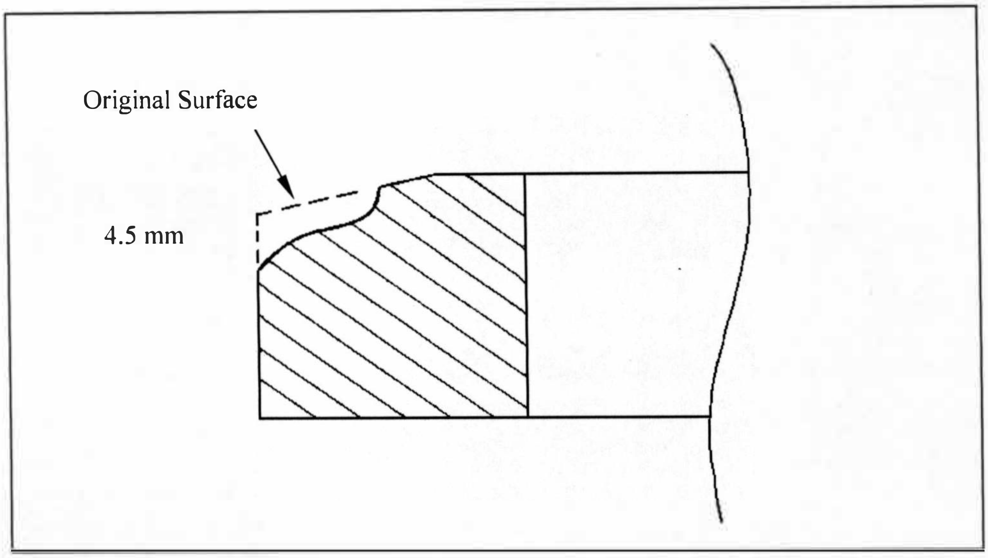


Figure 32. Cross Section of Front Seat Showing Abrasive Wear From the Resin and Ring.

months of processing. Final wear on the rear seat and ring was .38 mm (.015 in.) (Figure 33). The wear was abrasive and compressive in nature. The ring and front

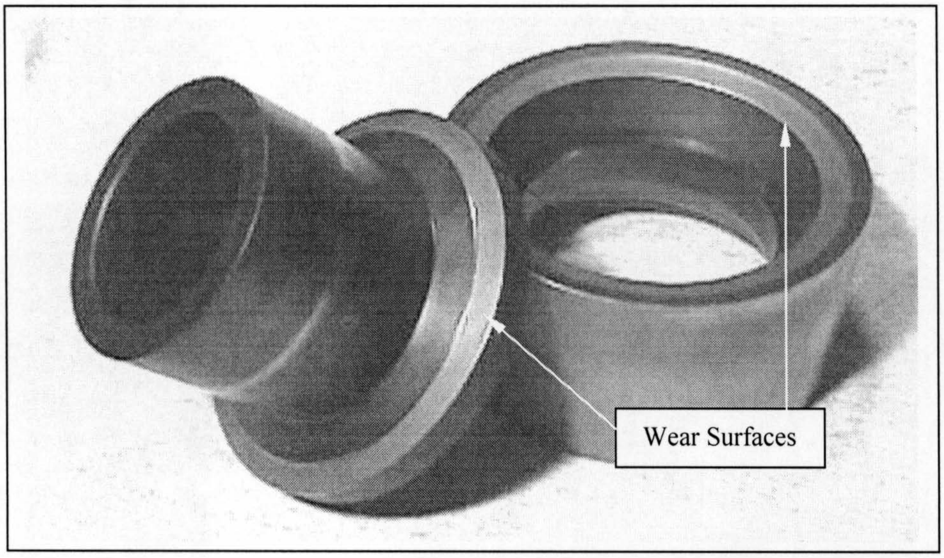


Figure 33. Wear Impression from Abrasion and Compression of Rear Seat and Ring Surfaces.

seat were lapped together producing smooth, matched surfaces between the two.

There were no reported production problems assigned to either the governing or shutoff function of the valve during this study even though the flow channel was beginning to be restricted. However, it was the practice at this plant to change the valve at less than half the amount of wear observed in this study, therefore, the valve was replaced during this inspection.

Wear Study Designed Experiments

The wear study began by testing the control valve to obtain a baseline, or control measurement, of the entire system. The control valve was then removed and the production valve installed. The production valve was run continuously over a nine-month period. The production valve was then removed, the control valve re-installed, and a second baseline measure of the system was conducted. The control valve measurements provide a measure of changes in the molding system not related to the non-return valve.

A series of designed experiments were performed on both the control and production valves. Independent variables selected for the wear study were: pack pressure, injection speed, decompression, back pressure, screw RPM and barrel temperature. Pack pressure was added as a blocking variable since its absence was thought to cause increased part weight variation. This means that high and low pack pressure settings were applied to each treatment group. The design used was a five-variable, two-factor, factional factorial, resolution III screening design consisting of eight unique treatments (Table 2). A center-point treatment was added to check for curvature and a replicate treatment was added to check for any drift during the experiment. This produced a total of ten runs. This basic design was used throughout the wear study. Part weight was selected as the dependent variable.

Control Valve

The first valve tested was the control valve. The baseline performance of the control valve was used to establish the amount of change in the system not attributable to the valve. The abbreviated treatments are shown in Table 5.

Table 5

Abbreviated Design: 2**(5-2) Fractional Factorial, Resolution III - Screening Type. Cascade Engineering Wear Study. Four-Piece Ring Valve.

Variable / Run	Treatment	BARREL TEMPERATURE (°F)	INJECT SPEED (inches/second)	BACK PRESSURE (PSI)	RPM	DECOMPRESSION (inches)
2	1 *	High (500)	High (4.0)	High (100)	High (80)	High (.30)
1	7 *	Low (420)	Low (1.0)	High (100)	High (80)	Low (.00)
3	4 *	High (500)	Low (1.0)	Low (0)	Low (35)	Low (.00)

* Treatments 1,4 and 7 were used for the periodic abbreviated testing.

Data were graphically analyzed using box-whisker plots as shown in Figure 34. The data was categorized into two groups, one group for each level of pack pressure used. Treatments were plotted against part weight. Mean part weight, part weight standard deviation and the minimum and maximum part weight values were calculated and graphed from the data for each treatment group.

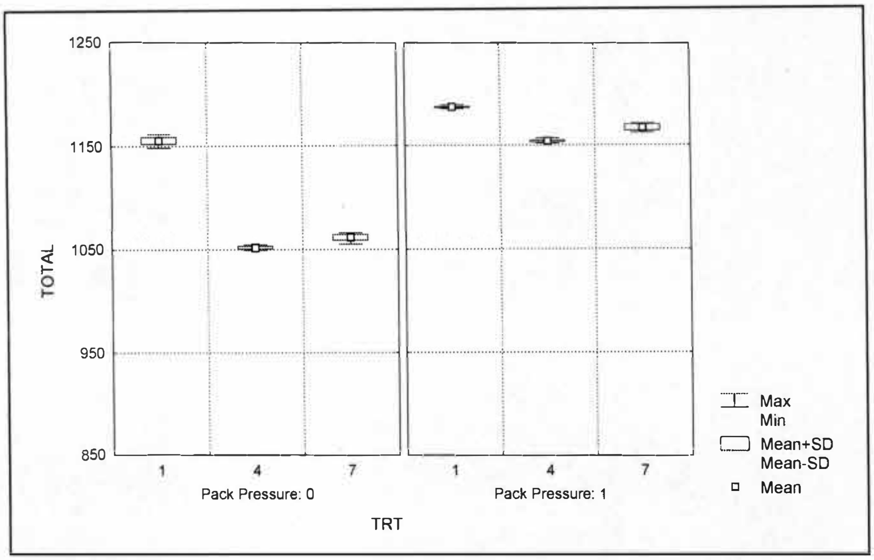


Figure 34. Part Weight Results for Initial Control Valve Testing.

It was shown that there is an interaction between pack pressure and treatments 1, 4 and 7. The interaction is positive, meaning that as pack pressure is increased, higher part weights are produced. Treatment 1 produced the highest part weight within each category followed by treatments 7 and 4.

Production Valve

The production valve was installed and the full 10 run experiment was performed. Data was analyzed using standard least squares analysis of variance methods.

Part Weight Mean. A Pareto graph was produced to summarize the effects of the independent variables on mean part weight (Figure 35). These results, for the order of magnitude, showed the data agree with mean part weight results found in the Discovery Phase.

Pack pressure, injection speed and decompression were shown to have a significant effect on mean part weight ($p<.05$). Pack pressure had the largest effect. The effect was positive. Injection speed had the next largest effect, followed by decompression. Both had a positive effect. Back pressure, RPM, and barrel temperature did not have a significant effect on mean part weight ($p>.05$).

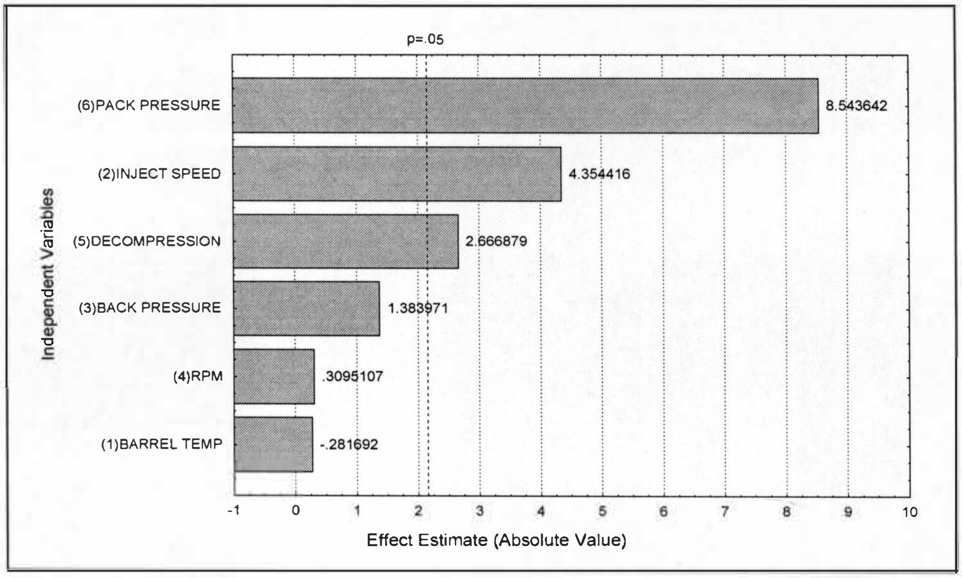


Figure 35. Pack Pressure, Injection Speed and Decompression Significantly Affected Mean Part Weight.

Part Weight Variance. Results were summarized in a Pareto graph for the effects of the independent variables on part weight variance (Figure 36).

Decompression was the only variable to have a significant effect on part weight variance ($p<.05$). The effect was negative, similar to the results in the discovery phase. Injection speed, back pressure, pack pressure, barrel temperature and RPM did not significant have a significant effect on part weight variance ($p>.05$).

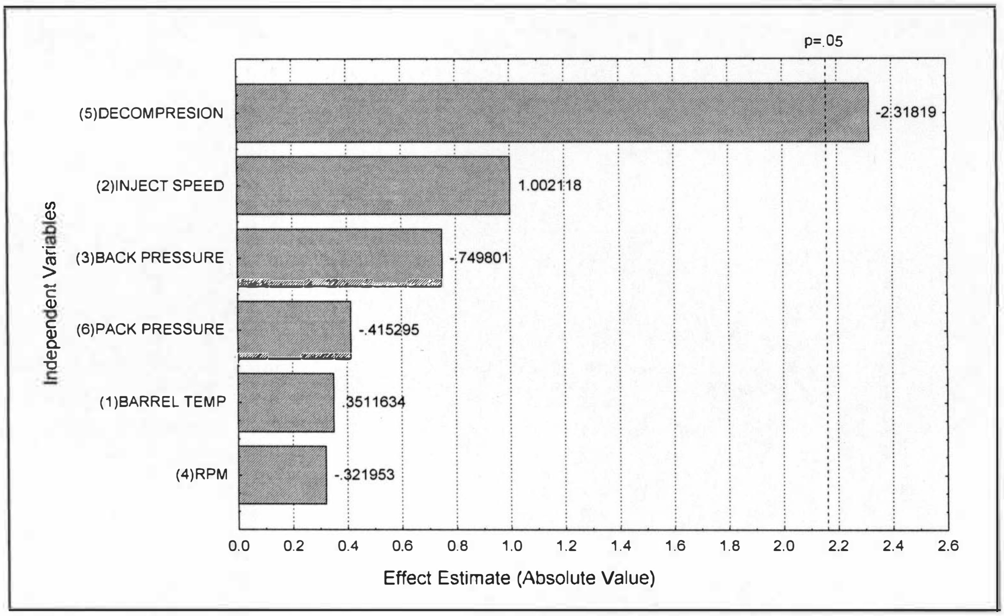


Figure 36. Decompression was the Only Variable to Significantly Affect Part Weight Variance.

Performance Tracking Over Time - Production Valve

Abbreviated experiments were conducted using treatments 1, 4 and 7 (Table 2) in order to track changes in the production valve performance over time. Part weight data were graphed and presented in Figure 37. The graph showed part weight in treatment 1 dropped over time for both high and low pack pressures. Treatment 1 included process settings at their high levels for all variables. Compared to the other treatment groups, the variability in treatment 1 was more consistent from the beginning to the end of the study. However, there was a notable shift in mean part weight from the beginning to the end of the experiment.

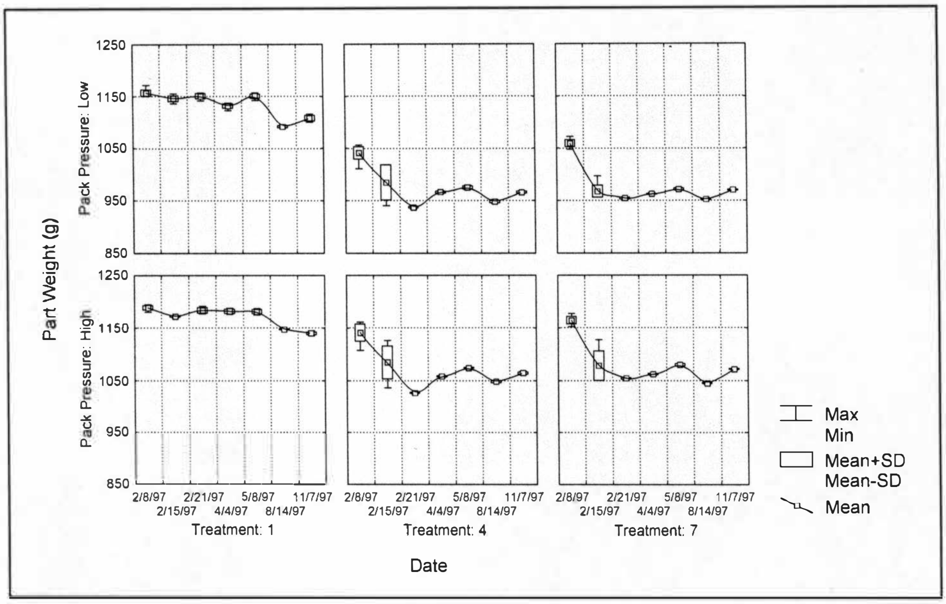


Figure 37. Box & Whisker Plot of Part Weight Versus Time. Valve Break-In Period Affected Trends in Part Weight.

Treatments 4 and 7 showed a relatively high amount of variation during the first two weeks the valve was in the press. Mean part weight also dropped rapidly during this time. This change may have been associated with the break-in of the valve. There was a slight upward trend in weight for the remainder of the study.

<u>Final Production Valve Experiment</u>

Results for the final full 10 run experiment were compared to the results for the initial experiment. There are nine months separating the two experiments. The graphs are similar to the Pareto graphs produced earlier except that there are two sets of data on a single chart shown in a 3-D view. This allowed a comparison of the independent variables from the beginning to the end of the experiment.

Mean Part Weight. Results for weight means are shown in Figure 38. The scale for the effect values was absolute. Negative effects are shown with a (-) sign on top of the corresponding bar. Pack pressure, injection speed and decompression were significant. They are ranked in the same order, from highest to lowest, as the results from the initial experiment. The effect for pack pressure does not change in magnitude. The effects for both injection speed and decompression increased in magnitude. RPM, barrel temperature and back pressure were not significant.

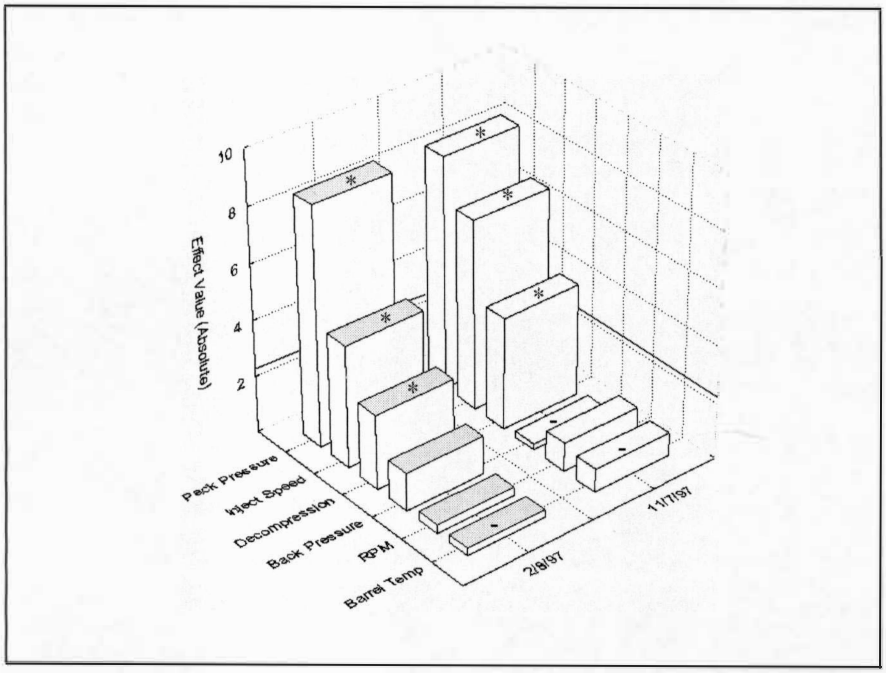


Figure 38. Change of Standardized Effects for Mean Part Weight Between Initial and Final Experiments.

Part Weight Variance. Results for weight variance were tabulated and combined with the results for the initial experiment and is shown in figure 39.

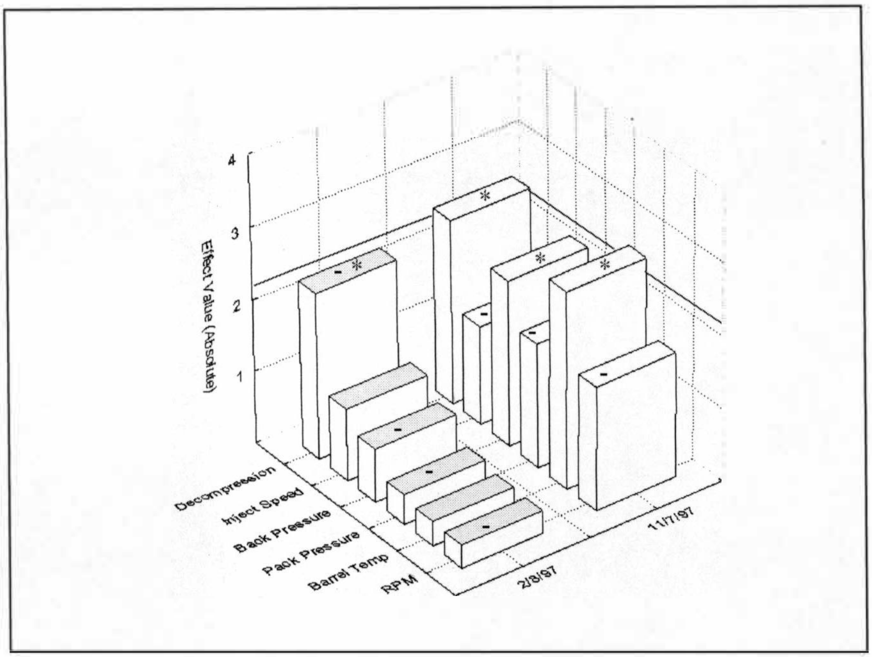


Figure 39. Change of Standardized Effects for Part Weight Variance Between Initial and Final Experiments.

The magnitude of the effects for weight variance increased for all variables. Barrel temperature, decompression and back pressure were shown to be significant. Barrel temperature was not significant during the initial test. However, it was shown to have the largest effect on part weight variance during the second test. The effect for decompression increased, but fell to second in ranking. The effect value for decompression changed from negative to positive. The magnitude of back pressure increased and the sign changed from negative to positive. RPM, pack pressure and injection speed were not significant.

Control Valve - Check for Experimental Drift

Treatments 1, 4 and 7 were performed on the control valve before the production valve was installed and after the production valve was removed. This comparison was necessary to establish the amount of change in the system not attributed towards the valve. The results are shown in Figure 40.

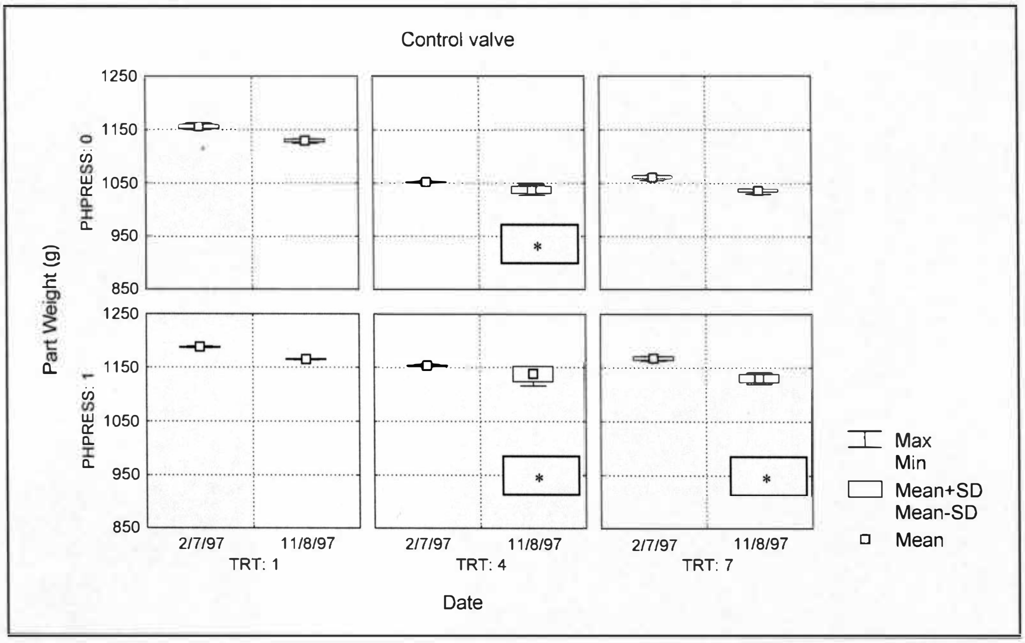


Figure 40. Box & Whisker Plot of Part Weight Versus Time. Change in Treatment Response of Control Valve Between Initial and Final Experiments.

There was a significant change, as denoted by the asterisks, in part weight for treatment 4 at both high and low pack pressure settings. There was also a significant change in part weight at the high pack pressure for treatment 7. In all three cases, the mean part weight dropped and the variation within the data set increased. These data indicate that there was a significant change ($p<.05$) in machine conditions during the course of the test.

Combined Control and Production Valve Data

Data from treatments 1, 4, and 7 from both the control and production valves were combined for analysis. The data is the same data shown previously in Figures 36 and 39. This was done in order to observe the effects over time compared to experimental drift experienced by the control valve. This is shown in Figure 41.

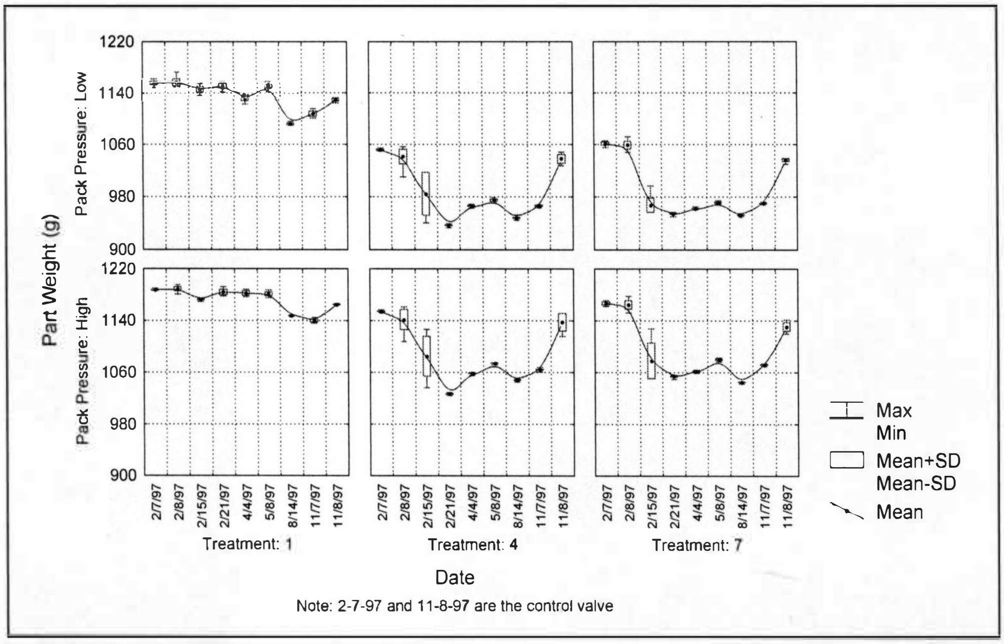


Figure 41. Box & Whisker Plot of Part Weight Versus Time. Production and Control Valve.

Mean Part Weight. The initial data, at the beginning of the study (2-7-97 and 2-8-97), for both valves was examined to determine the differences between the valves and any machine conditions. Tukey honest significant difference (HSD) tests were conducted to determine if there was a significant difference ($p<.05$) in part weight means between the production and control valve results.

Part weight means for treatment 4 were significantly different ($p<.05$) between the production and control valves. The difference in part weight means occurred at both the low and high pack pressure settings. There was no significant difference ($p>.05$) between the production and control valves, at low or high pack pressure settings, for treatments 1 or 7.

Mean part weight for treatment 1 gradually falls over time from the beginning of the study to the end of the study. However, treatments 4 and 7 show a large drop in part weight mean, at both low and high pack pressure settings, during the first two weeks of the test and then hold relatively steady to the end of the test.

At the end of the study (11-7-97 and 11-8-97) there was a significant difference ($p<.05$) in mean part weight between the production valve and the control valve for all three treatment groups by the end of the study. The differences occurred at both low and high pack pressure settings. The difference was most pronounced for treatments 4 and 7. This was attributed to wear of the production valve.

Part Weight Variance. Leven tests of homogeneity were conducted to test for significant differences in variances between the production and control valves at the beginning and end of the test. At the beginning of testing there were significant differences ($p<.05$) between the control and production valves for treatment 4 at both low and high pack pressure settings. Treatments 1 and 7 showed no significant difference ($p>.05$) between the two valves at the beginning of the experiment at either low or high pack pressure settings. Testing at the end of the experiment showed that there was a significant difference ($p<.05$) in variances, between the control and production valves, at all three treatment conditions at low and high pack pressures.

<u>Machine Variation.</u> During the first two experiments (2-8-97 and 2-15-97) for the production valve there was a large amount of variation that took place during each experiment, with the largest amount of variation occurring on 2-15-97. The data for the three experiments were shown in Figure 42. Line plots for experiment dates 2/8/97, 2/15/97 and 2/21/97 are plotted showing treatments 1, 4 and 7 for each date.

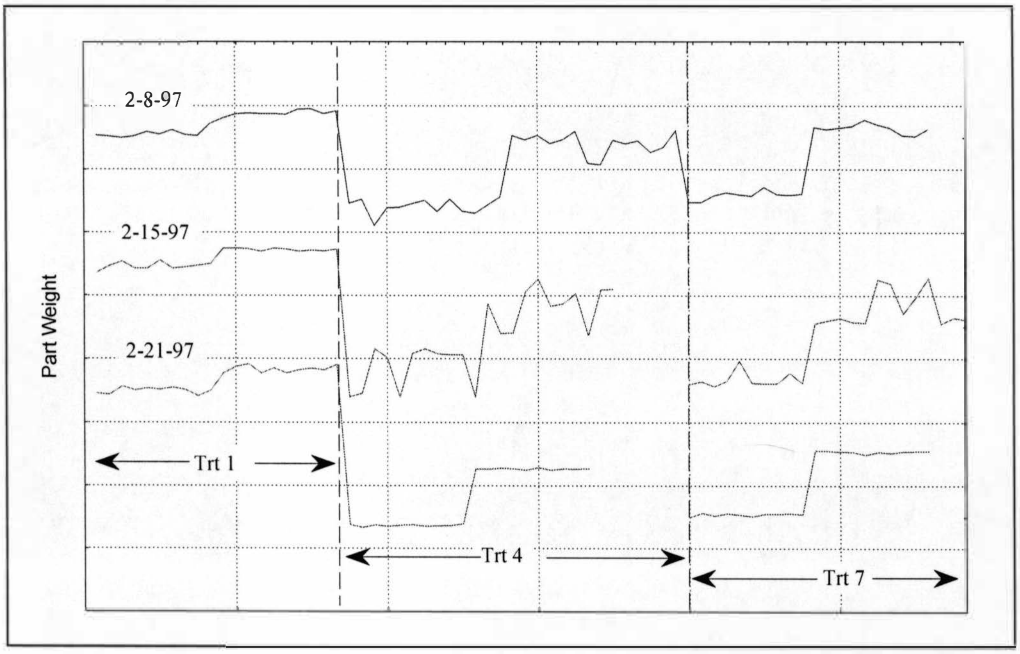


Figure 42. Line Plot of Raw Data Showing Part Weight Versus Treatment Group on Three Different Dates.

The data values for 2-15-97 and 2-21-97 have been offset so that the three line plots may be distinguished from each other.

Data from the week of 2/21/97 showed relatively minimal variation for each of the three treatment groups. The variation was increased for treatments 4 and 7 during week of 2/15/97. These conditions had low injection speed and decompression in common. The magnitude of variation observed on 2/15/97 was not observed during the remainder of the testing.

The variation was determined to be attributed to a defective machine controller card. The problem was intermittent and affected the injection pressure and pack pressure of the machine. The effect could be observed by monitoring the injection hydraulic pressure real-time. There was an oscillation in the pressure during the pack phase. The hydraulic pressure would intermittently vary between the correct pressure set-point and an offset value that was approximately 200 psi below the actual set-point. This oscillation in hydraulic pressure was translated into the variation in part weight observed in the data.

Machine Monitoring

Recovery time, fill time, cushion, cycle time and cavity pressure at transfer were recorded. The data from the study were then entered into a spreadsheet for analysis. Scatter-plots were then produced to show the change in the mean and variation of the response variables.

It should be noted that it was difficult to conduct a long term experiment in a production environment. The fact the site was not located within close distance to the research team compounded the difficulty of managing such a project.

The process was adjusted for various reasons, by the process technicians, throughout the duration of the test. These changes affected machine response and the data that were taken. The documented reasons for each change did not include enough information to aid in resolving the data. It was quite common that, on a given day, only one shift would enter data. Data was also taken intermittently. The supply of forms ran out several times, not being replenished until a member of the research team discovered the problem. At one point during the test, a replacement form was made by Cascade personnel. However, the form prompted only for the shift average. This made the two sets of data incompatible.

Recovery Time

A scatter-plot was constructed to show the change in recovery time over the nine month period. As shown, in Figure 43, there was a large drop in the mean recovery time between the weeks of 2/19/97 and 4/18/97.

The change in mean recovery time was most likely due to a change in the set point for the screw rotate speed. This change was documented several times on dates that did not match the logged data. Initial wear on the valve would not have affected recovery time. The wear in the front seat was not enough to create a restriction in the flow path, thereby influencing recovery time. It did appear, after 4-18-97, there was a general trend for mean recovery time to increase throughout the experiment.

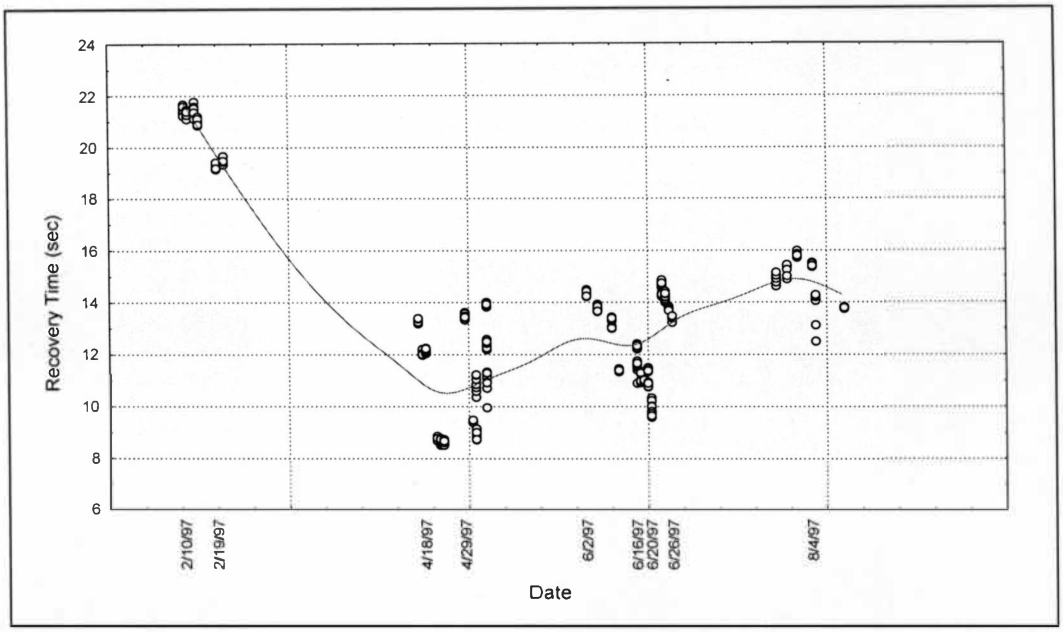


Figure 43. Long Term Wear Study. Recovery Time Versus Date.

Variation of recovery time shown in the graph, from 4-18-97 and after, were actually changes to machine set-points between different dates. The amount of variation recorded on a single day was small as shown by the overlaying dots. A log sheet was used to record process changes that were made, but the entries did not sufficiently explain the variation among days.

Fill Time

A plot of fill time was shown in Figure 44. There did not appear to be a correlation between fill time and the progressive wear of the valve. Variation observed in the beginning of the study was similar to the variation observed at the end of the study.

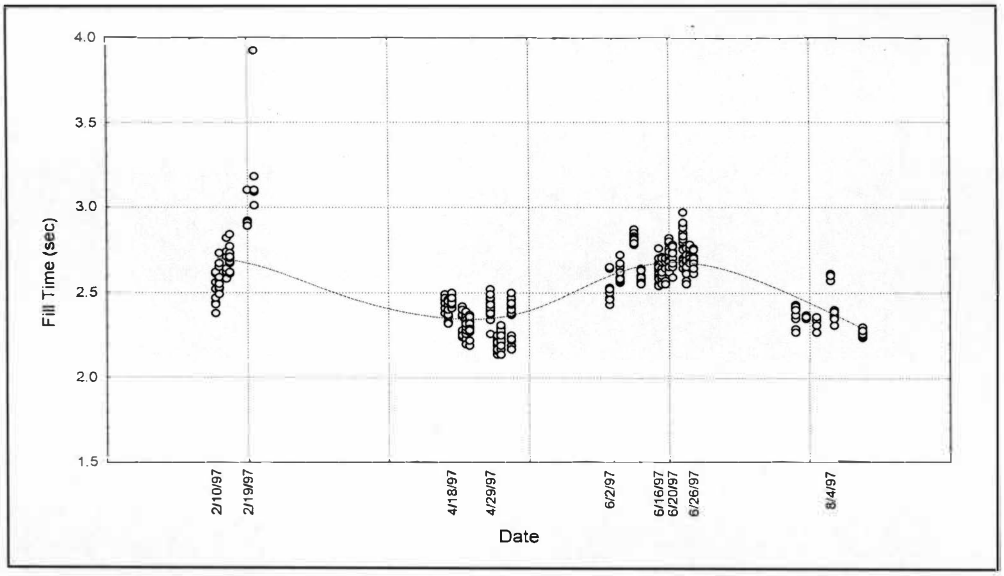


Figure 44. Long Term Wear Study. Fill Time Versus Date.

Cushion Position

A plot of cushion position is shown in Figure 45. There was similarity between the trends for both fill time and cushion position.

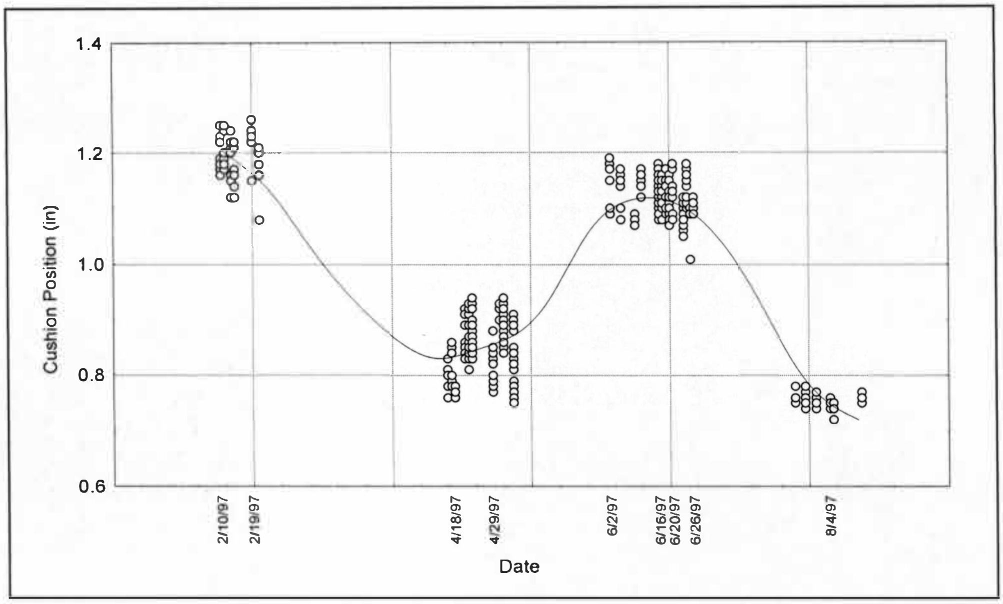


Figure 45. Long Term Wear Study. Cushion Position Versus Date.

Cavity Pressure

Figure 46 shows the change in cavity pressure (end of fill) at the transfer position over time. There was an upward trend in cavity pressure throughout the experiment. Cavity pressure was directly related to the set-point for cavity pressure cutoff, as discussed previously. Therefore, the changes in the cavity pressure shown were directly related to the process being adjusted over time.

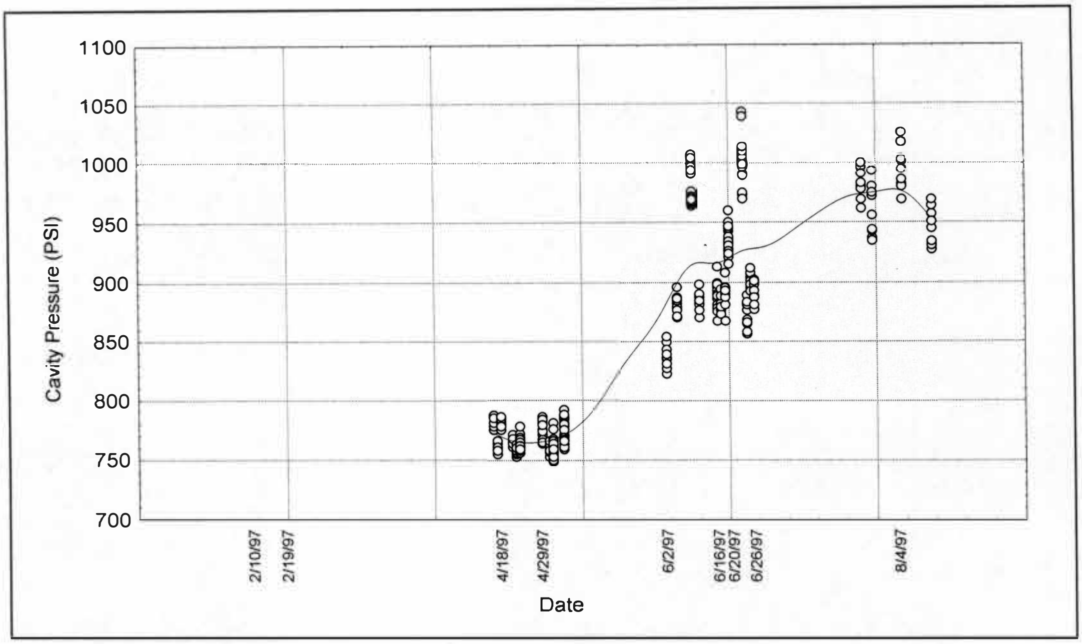


Figure 46. Long Term Wear Study. Cavity Pressure Versus Date.

Economic Justification of Non-Return Valve Replacement

One of the original directives of this study was to develop an economic guideline to justify the replacement of the non-return valve as performance deteriorates. The intent was to be able to assign a cost to product variation, or scrap, in order to justify replacement costs. However, the research conducted leading up to this point has reinforced the idea that the non-return valve functions as part of the injection unit as a whole. In addition, the variables that effect part weight variance could not be sufficiently resolved to adequately isolate the effects of the non-return valve.

It was also determined, through informal discussions, that molders have accepted the cost of replacing the non-return valve as a part of the cost of maintenance. Through discussions with PCIM member facilities, it was revealed that all four of the practices mentioned earlier were in effect regarding determining valve replacement: reacting to process problems, evaluation during periodic inspection, fixed replacement schedule, and predictive maintenance. It was also determined that cost (valve cost and labor to install) was not a factor in determining valve replacement. The larger issue was due to either scheduling, or uncertainty of the problem and how wear affects the molding process.

In fact, in discussions with various management personnel, it appeared to be a non-issue as to whether or not a valve would be replaced if it was known to be worn. It was as simple as the ability to make parts - Shut the machine down, find out what the problem is, and correct it. Discussions with the technical people on the plant floor, on the other hand, revealed that there was pressure to find a way to "process around" the problem in order to finish the production run. It is unclear whether this pressure was real or perceived. However, it was clear that there was a desire by personnel on the plant floor to either determine the root cause of the problem, or process around the problem. Discussions with all the molders also revealed that there was a desire to develop methodology that could be incorporated into a preventative or predictive maintenance program. Both of these items coincide with the research conducted to this point.

The research work to identify which variables affect the performance of the non-return valve, or injection unit, will help processors to better understand how to optimize non-return valve performance. In addition, the development of the injection unit pressure test and the decompression test will help the molder to determine and, more importantly, monitor performance of the injection unit. These procedures will compliment a preventative maintenance plan, and provide a foundations for a beginning a predictive maintenance program.

As previously mentioned, replacing a typical non-return valve can take anywhere from a couple of hours to an entire shift depending on the size and design of the press. Proper inspection and measurement of all relevant components in the injection unit can often take multiple shifts, as the components need to cool to room temperature for measurement. The lean environment that plants are operating in forces many molders to shortcut preventative maintenance procedures when, in fact, that is precisely what is needed most to keep equipment operating at their optimum performance. Therefore, tools that can readily be used on the production floor to quantify machine performance are desired.

A simple scenario has been developed to illustrate the point of delaying inspection of the injection unit. If either productivity (cycle time) or quality (scrap) is compromised, the cost of running production increases the longer valve replacement is delayed.

Increased Scrap

A change in scrap rate is directly proportional to the cost to produce the product. If the production rate is 100 pieces per hour (36 second cycle) with a standard 0% scrap rate, then the time to produce 100 pieces is 1 hour. If the scrap rate increases 2%, then in order to produce 100 pieces, the machine needs to run 100 cycles + 2%, or 102 cycles. This translates into a 2% increase in production costs. Although a 2% increase does not sound bad, the impact to profit can be significant. For example, if the typical molder is making 8% profit on a part that costs $1 to produce, then this translates to a selling price of $1.0870 (8% profit = $.0870). The selling price remains the same, but now the cost to produce has increased to $1.02, leaving $.0670 profit – a reduction of approximately 23%.

Admittedly, this is a simple overview of a complicated cost structure. An argument could be made that true costs, such as lost production, or overtime, were not captured. This added detail would only serve to bolster the argument for a robust preventative maintenance program.

CHAPTER V

RECOMMENDATIONS AND CONCLUSIONS

This research produced information and methods for specifying, evaluating, and maintaining non-return valves which best meet the molders needs. At the beginning of the project it was decided that determining the best valve on the market is was not appropriate due to previous research indicating that other factors, such as resin type, were involved in part weight variance. Even establishing guidelines for specifying a non-return valve was a difficult task because of all the factors involved. Instead, a list of design considerations has been compiled and is shown below. In addition, significant variables were identified for both part weight mean and variance. Finally, the injection unit pressure test and the decompression test will help to provide molders the tools to quantify and optimize the performance of the injection unit.

Non-Return Valve Guidelines

Design Criteria to Consider When Specifying a Valve

- Free-Flow Index - Use the free-flow index to compare the cross-sectional areas of both the valve and the metering section of the screw to make sure the valve will be compatible with the design of the screw for the desired materials to be processed.
- Pre-determined flange diameter - This exists either at the end of the

metering section of the screw, or in the rear seat of the non-return valve. This may adversely effect processing of shear sensitive materials.

- Limit press RPM to that recommended by the screw and valve manufacturers. See appendix A.
- Corrosion and Wear Resistance - Consult valve suppliers when selecting valve materials for proper corrosion and wear resistance.
- Physical valve inspection - Inspect the valve before purchase to assure dead spots, sharp corners and restrictive flow paths are minimized. Often, a particular valve design will vary greatly between machine make and size and may not look like the one pictured in the brochure.

Significant Process Variables

Statistically designed experiments conducted in Western Michigan University's laboratory revealed how process variable affect performance of the non-return valve. Three valve types were evaluated using three different resins. Valves used included a standard OEM style three-piece, three-piece EMI free-flow, and a Repeater® valve. Materials tested included two amorphous resins, ABS and Polycarbonate, and one crystalline resin, Nylon. Valve performance was measured using mean part weight and part weight variance.

Part Weight Mean

A summary of the independent variables, and their response effect to mean part weight, are shown in table 3. Variables that were significant include: pack pressure, injection speed, decompression, barrel temperature, and back pressure.

RPM was not significant.

Pack pressure and injection speed had a positive affect on all combinations of materials and valves tested. This effect was logical and expected. The addition of valve decompression significantly increased mean part weight in all combinations except those tested with ABS resin. It was not understood why decompression affected one amorphous resin (PC) while not affecting another (ABS). Barrel temperature was significant for only one of the valves tested. Both materials in those cases were amorphous. Back pressure was significant in only a single case. Back pressure should be the last variable investigated pertaining to mean part weight.

Part Weight Variance

It was expected that this research would reveal the variables that significantly affect part weight variance due to the non-return valve. While significant responses were observed, there does not appear to be a clear pattern to the variables and their affect on part weight variance. A summary of the independent variables, and their response effect to part weight variance, are shown in table 4.

Although the combination of valves and materials is relatively small, they represent a common cross-section of the components and resins in use at the PCIM facilities. These effects should prove a valuable starting point for optimizing the function of the non-return valve.

Test Procedures

Throughput Test

The results of the throughput test showed that the non-return valve had a significant role in the ability of the screw to adequately melt resin. While no fast rule came from this testing, the knowledge that the non-return valve plays such a large role should be considered when looking at valve geometry, including the free-flow index, when specifying a non-return valve for a particular application. Additionally, while the throughput test yielded useful data, this procedure was best used in a laboratory setting due to the difficulty of setting up the experiment.

Decompression Test

Results from the decompression test showed that variation produced by the valve depends greatly on the amount of decompression used (see Appendix F). There was not a clear relationship between decompression and part weight variance in the designed experiments. However, performing the decompression test revealed that, in most cases, there was a minimum threshold value that decompression must be set in order to assure a stable processing window for both part weight and variation. In fact, there was a "sweet spot" regarding the amount of decompression used. The sweet spot was the range of decompression settings that yield the least amount of variation in part weight.

It was also shown that there is a significant difference in valve performance between new and old valves. This evidence showed that new valves require a break-in period. In fact, there was an observed increase in variation for several cases where a new valve had been installed. This could have a large impact on products that have critical dimensional tolerances. This exhibited itself either through increased variation at all decompression settings or by a shift in the location of the sweet spot. Therefore, new valves should be evaluated periodically after installation to track any changes, in magnitude or position, of the sweet spot. In most cases observed, the amount of variation reduced as the valve wore during break-in.

Injection Unit Wear

Pressure Test

The pressure test was developed to help determine the injection unit's ability to maintain plastic pressure while in a production environment (see Appendix E). The pressure test was shown to be an effective tool for quantifying an injection unit's ability to maintain plastic pressure by plotting hydraulic pressure against the resulting cushion.

This test is an ideal candidate for integration into a preventative maintenance plan. Machines benchmarked with resins that are common to that press will provide historical data that could be used to track injection unit performance graphically over time. These data could be correlated with physical inspection to determine when an injection unit's performance is beginning to compromise processing conditions before failure. The need for costly machine time requirements during inspection is reduced. This data collected over time will provide the foundation for a predictive maintenance plan.

Machine Monitoring

Monitoring recovery time and cushion was the easiest method of obtaining useful information regarding valve wear from the machine assuming that machine operation remains consistent. Although the data collection process conducted during the wear study had many shortcomings, it is still believed that monitoring recovery time and cushion will provide correlation of wear between the front seat and the ring of the valve. Monitoring the time to build peak cavity pressure will give an indication of the consistency of the non-return valve closing.

Economic Justification

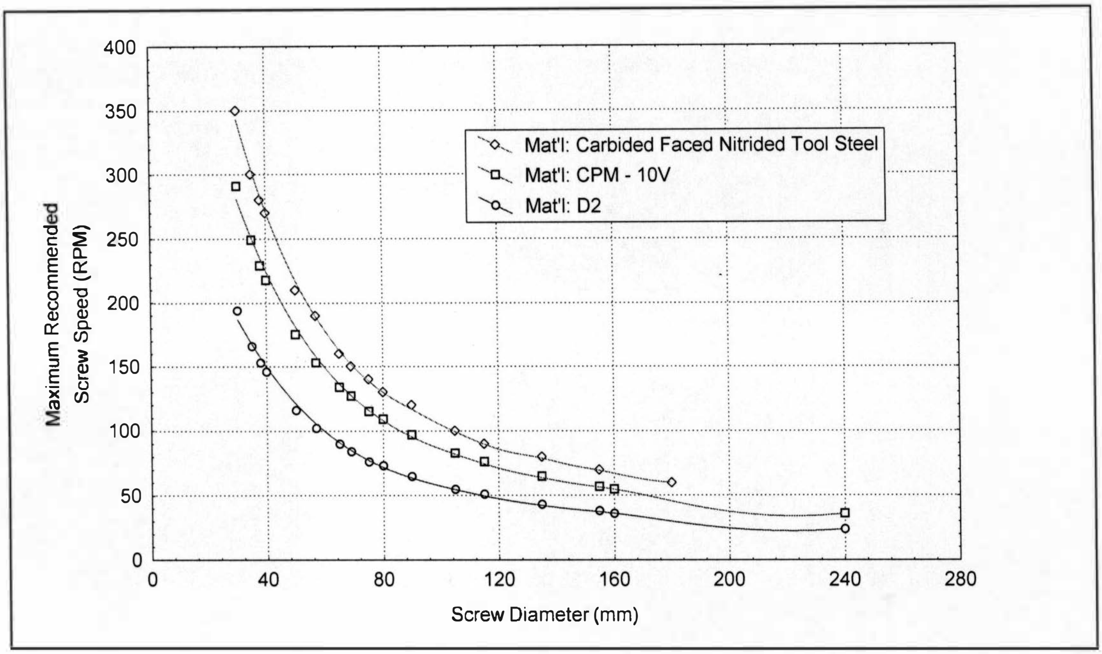
It was shown that the cost of production increases, and profits drop, the longer replacement is delayed if cycle time is increased, or especially if product quality is sacrificed. Therefore, it is imperative that preventative maintenance procedures, such as the injection unit pressure test and decompression test, are in place to allow for planned injection unit evaluation.

Summary

Two procedures, the injection unit pressure and decompression tests, were developed to provide molders the tools to evaluate the valves in use at their facilities. The decompression test, used in conjunction with rigorous mold tryout procedures, will help establish and maintain robust processes. Both the decompression and pressure tests will provide quantitative data as to the performance of the injection unit. By incorporating these procedures into a maintenance program, that includes periodic physical inspection, the data can be correlated to the wear of the machine's injection unit, providing a foundation for a predictive maintenance program.

Appendix A

Recommended Maximum Screw RPM Versus Screw Diameter



Recommended Maximum Screw Speed. Valve Material Versus Screw Diameter.

Source: Compiled from multiple sources including Brownlee, 1996 and Zeiger Industries, 1996.

Appendix B

Questionnaire to Determine Types of Non-Return Valves in Use at PCIM Member Plants

PCIM Non-Return Valve Questionnaire

To: PCIM Committee Members

Don Bittner	ADAC Plastics Inc.
Mike Quador	ADAC Plastics Inc.
Marc VanderKooi	ADAC Plastics Inc.
Jim Ponchaud	Cascade Engineering
Dave Schneider	Cascade Engineering
Russ Malek	Prince Corporation
Paul VanderLaan	Prince Corporation
Richard Johns	Wright Plastic Products
Jim LaCroix	Wright Plastic Products

Enclosed is the survey that will be used to identify the various valves in use by each of the plants. This initial survey will allow us to use the same types of valves in our research that are in use at the plants.

This form is being sent to the people (listed below) that were designated as the person responsible at each plant for specifying non-return valves. If this person is no longer applicable, please forward to the appropriate person.

Please take a moment to fill out the survey and fax it back to the heading on the next page by 10-23-96. This information will be presented and discussed at the next PCIM Technical Committee meeting on 10-25-96.

Company / Plant	Contact
Cascade Engineering	Bernie Hallock Brendon Fitzgerald Chuck Buursma
Prince Corporation	John Gick Dean VanLier Tim Brunen John Nelson
Wright Plastic Products	Jim LaCroix Art Kestner
ADAC Plastics Inc.	Mike Quador

PCIM Non-Return Valve Questionnaire

Please complete and return by 10-23-96

Return to: Eric Dawkins - Western Michigan University
Fax #: (616) 387-4075

Survey completed by: ______________________________ Date: ____________

1. Please fill out the requested information below as best as possible.

Press Size (US Tons)	Valve Type(s)	Valve Manufacturer(s)
50-250 Tons	3-piece ring 4-piece ring Poppet Ball Other (Specify)	
250-750 Tons	3-piece ring 4-piece ring Poppet Ball Other (Specify)	
750 + Tons	3-piece ring 4-piece ring Poppet Ball Other (Specify)	

2. What was the worst non-return valve (type and manufacturer) that you have used that gave you the poorest performance and/or shortest life? What material(s) were you running and what was the problem with the valve?

Valve Type	Valve Manufacturer	Problem Description
3-piece ring 4-piece ring Poppet Ball Other (Specify)		

Appendix C

PCIM Non-Return Valve Questionnaire

PCIM Non-Return Valve Questionnaire

To: PCIM Committee Members and Plant Representatives

Company	**Committee Members**	**Plant Representative**
ADAC Plastics Inc.	Don Bittner Mike Quador Marc VanderKooi	Mike Quador
Cascade Engineering	Jim Ponchaud Dave Schneider	Bernie Hallock Brendon Fitzgerald Chuck Buursma
Prince Corporation	Russ Malek Paul VanderLaan	John Gick Dean VanLier Tim Brunen John Nelson
Wright Plastic Products	Richard Johns Jim LaCroix	Art Kestner Jim LaCroix

Old non-return valves are needed from each of the plants to be studied for wear. As these valves are taken from the presses in production, please save and send them WMU at the address below for evaluation. Fill out and attach the included labels with each valve.

Approx. # of hours in use________ Type of resins run through valve. Resin Fillers? PP /PE ____________ PA ____________ PBT ____________ PC ____________ PC/ABS ____________ ABS ____________ Other______________	Reason why valve was pulled

Return to: Eric Dawkins
Western Michigan University
Dept. of Industrial and Manufacturing Engineering
College of Engineering and Applied Sciences
Kalamazoo, MI 49008-5061

Appendix D

Matrix of Experiments Performed During Non-Return Valve Study

Experimental History

Type	Location	Date	Material	Valve Type	Design	Type
Exploratory Experiments	WMU	11-23-96	PC – GE Lexan EM 3110	OEM 3 pc ring	9 runs (1 rep)	2(4-1), res IV
	WMU	12-4-96	Nylon – Zytel 101	OEM 3 pc ring	10 runs (1 rep, 1 ctr)	2(4-1), res IV
	WMU	2-11-97	Nylon – Zytel 101	EMI Free-flow	18 runs (1 rep, 1 ctr)	2(5-1), res V
	WMU	2-25,28-97	PC – GE Lexan 121-112	EMI Free-flow	20 runs (3 rep, 1 ctr)	2(5-1), res V
	WMU	3-20-97	ABS - Dow 344	EMI Free-flow	10 runs (1 rep, 1 ctr)	2(3-1), full
	WMU	3-22-97	ABS - Dow 344	Dray	10 runs (1 rep, 1 ctr)	2(3-1), full
Wear Study	Cascade	1-31-97	Multibase PP	4 pc ring	3 run partial	
	Cascade	2-7-97	"	"	3 run partial	
	Cascade	2-8-97	"	"	10 run full	2(5-2), res III
	Cascade	2-15-97	"	"	3 run partial	
	Cascade	2-22-97	"	"	3 run partial	
	Cascade	4-4-97	"	"	3 run partial	
	Cascade	5-8-97	"	"	3 run partial	
	Cascade	8-14-97	"	"	3 run partial	
	Cascade	11-7-97	"	"	10 run full	2(5-2), res III
	Cascade	11-8-97	"	"	3 run partial	

Experimental History (continued)

Type	Location	Date	Material	Valve Type	Design	Type
Procedural	WMU	12-4-96	Nylon 33%	OEM 3 pc Ring		Decompression test
	Wright	6-27-97	Nylon 33% G.F.	4 pc ring		Pressure & Decompression test
	WMU	9-23-97	Nylon 33% G.F.	OEM 3 pc Ring		Decompression test
	Wright	10-9-97	Nylon	4 pc ring		Decompression test
	Wright	10-9-97	Nylon	4 pc ring		Pressure & Decompression test
	WMU	11-6-97	Nylon 33% G.F. & Polystyrene	OEM 3 pc Ring		Decompression test
	Cascsde	11-8-97	Multibase	4 pc ring		Decompression test
	ADAC	3-26-98	Nylon 33% G.F.	4 pc ring		Pressure & Decompression test
	Prince	3-19-98	Polycarbonate & Polypropylene	4 pc ring		Pressure & Decompression test

Appendix E

Pressure Test Procedure and Nozzle Cap Diagram

Injection Unit Pressure Test

A practical test has been developed to test for combined wear in the injection unit as it is treated as a whole. The test accounts for wear in both the shutoff functions of the valve as well as the barrel. This test will indicate if the system is capable of delivering the melt at a determined pressure.

This test is designed to be used while the press is using the material in question. If the mold uses a cold runner configuration or a simple hot sprue, the runner will be used to block material flow into the mold. If the mold uses a hot-runner manifold, a nozzle cap needs to be constructed for the nozzle of the machine since there is not an easy method to shut off flow of material through the manifold. Presses equipped with a shut-off type nozzle are ideally suited to this test.

The press should set up to run the material in question. The press should be cycling so that the material sees the normal residence time in the barrel.

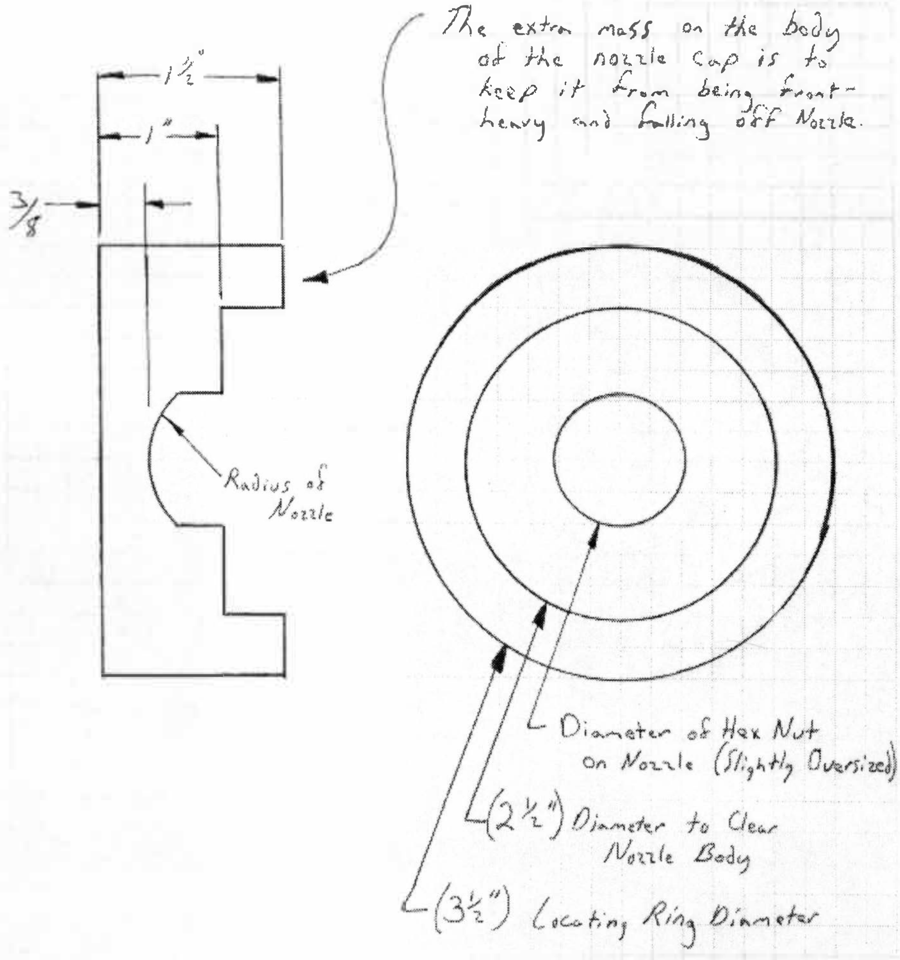
1. Set the "maximum injection pressure" set point to 20% of the maximum.
2. Make sure that the "maximum injection time" set point is set to a reasonable time. If the injection time is very short, less than 1 second, set the time-out between 2 or 3 seconds so that the valve will experience pressure longer than the requirement for the fill time. This will allow an chance to observe the cushion.
3. Trim the runner so that only the sprue and a minimum amount of runner remain for orientation in the mold. Any vestige from the sprue inlet should be trimmed as well.
4. Spray the sprue with mold release so that material will not stick to the sprue. It is important that the same sprue be used for consistency.
5. Insert the sprue into the mold and cycle the machine. The screw will try to reach the transfer position but will be unable to.
6. Record the hydraulic injection pressure observed as well as the cushion position.
7. Allow the press to complete a normal cycle so that material does not sit too long in the barrel.
8. Raise the "maximum injection pressure" set point in increments of 10% and repeat the test.
9. As the hydraulic pressure is increased, the resulting cushion will be reduced due to the compressibility of the resin.
10. The test is complete when either the maximum injection pressure has been reached or a rapid decrease in cushion has been observed.
11. Graph cushion by hydraulic pressure for interpretation of the data.

The test can be performed at different locations in the barrel by varying the shot size. This gives the molder the ability to test the pressure capability at the position where the cushion typically occurs.

Nozzle Pressure Cap

The Nozzle pressure cap is designed to be placed temporarily over the nozzle tip while injecting on-cycle. This allows the molder identify the capability of the injection unit while limiting the injection pressure. This prevents damaging the tool by over-packing or parts sticking due to short shots.

The dimensions on the cap are general and meant as a guideline. It is important to make sure that the necessary dimensions are verified for use on your particular machine.



Appendix F

Decompression Test Procedure

Decompression Test

This test is designed to show the relationship between decompression and part weight. In order to effectively perform this test, the tool must be capable of running short shots (without pack/hold pressure) and a scale should be used at the press to log part weight. Part weight should be measured to a resolution of .1%.

Non-return valve performance is most vulnerable in the absence of pack/hold pressure. Therefore, the machine is to be set up to run without pack/hold pressure. The resulting parts will show the most variation when run in this mode. This test should be performed carefully when using with a valve that depends upon melt pressure to force the valve closed, such as a Dray™ type valve.

1. Begin by processing the tool to the normal setup.
2. Set decompression to zero.
3. Wait 2 shots.
4. Weigh the next 3 shots and record:

   Part Weight
   Decompression Value

5. Increase the value for decompression by a practical amount.*
6. Repeat steps 3 - 5 until a practical decompression level has been reached.*
7. Graph Decompression vs. Part Weight and interpret results.

A practical amount of decompression is dependent on the screw diameter and the valve being used. For small screw diameters, decompression should be increased in small increments. Larger increments should be used for larger screw diameters. For example: A 65mm screw would typically have decompression set at 1 to 2 mm. Therefore the initial test would be performed by increasing decompression in increments of .02 - .03 mm.

For example: A 65mm screw would typically have decompression set between 3 and 10 mm. Therefore the initial test would be performed by increasing decompression in increments of .05 - 1.0 mm.

Appendix G

In-Plant Wear Study: Machine Data Logging Form

PCIM Non-Return Valve
Process Parameter Tracking Sheet

Date:

Shift: 1 Time: Initials:

Shot #	Fill Time	Recovery Time	Cushion	Cycle Time	X-fer PSI
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					

Shift: 2 Time: Initials:

Shot #	Fill Time	Recovery Time	Cushion	Cycle Time	
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					

Shift: 3 Time: Initials:

Shot #	Fill Time	Recovery Time	Cushion	Cycle Time	
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					

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