This is to certify that the
thesis entitled

EFFECTS OF EXTRUSION BLOW MOLDING INTERNAL
COOLING TECHNOLOGY ON HDPE CONTAINER
PERFORMANCE

presented by

KIRK ALAN VALKO

has been accepted towards fulfillment
of the requirements for the

M.S. degree in PACKAGING

Harold Hughes
Major Professor's Signature

June 29, 2004
Date

EFFECTS OF EXTRUSION BLOW MOLDING INTERNAL COOLING TECHNOLOGY ON HDPE CONTAINER PERFORMANCE

By

Kirk Alan Valko

A THESIS

Submitted to
Michigan State University
In partial fulfillment of the requirements
For the degree of

MASTER OF SCIENCE

School of Packaging

2004

ABSTRACT

EFFECTS OF EXTRUSION BLOW MOLDING INTERNAL COOLING TECHNOLOGY ON HDPE CONTAINER PERFORMANCE

By

Kirk Alan Valko

The continuously growing demand for inexpensive, efficient manufacturing methods drives businesses to develop new technologies which can produce more products faster with equal or better quality. Companies take different approaches to increasing production by buying state-of-the-art machinery or retrofitting older machinery. FastiUSA engineers products for the blow-molding industry for the improvement of existing machinery through various technologies. One such product, the Blow Mold Booster, blows the product through the use of cold air which speeds cooling, therefore reducing cycle times. While some studies have been conducted to examine the effect that internal cooling has on the product, the goal of this thesis was to determine its effects on Extrusion Blow molded HDPE containers. The data shows that the addition of the Fasti internal cooling device significantly increases package production without significantly affecting container performance.

ACKNOWLEDGEMENTS

I would like to thank my professors Dr. Harold Hughes and Dr. Laura Bix of the School of Packaging, and Dr. Dennis Gilliland of the Department of Statistics and Probability for their support and contributions to this research.

I would like to thank all of my fellow grad students for their support and help in my studies, especially Napawan Kosituangchai and Krittika Tanprasert for their help training me on the testing equipment. Thank you, most of all, for your friendship.

Thank you to my family and friends outside for your support and patience; these things are often most valuable.

Thank you to the companies and individuals who contributed and donated supplies for my research:

Donation of Fasti Equipment: Barry Pucillo and Rainier Farrig, FastiUSA Elgin, IL

Donation of Blow Pin Machining: Jim Vassar, Fidelity Tool Addison, IL

Donation of Cutting Ring Machining: Don Maines, Triad Precision Products Thomasville, NC

Donation of Programming and Labor for Machine Programming: Everyone at Bekum America Williamston, MI

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

KEY TO SYMBOLS AND ABBREVIATIONS

B_V – Bottle Volume (mL)

B_e – Weight of Bottle Empty (grams)

B_f – Weight of bottle full of water (grams)

DSC – Differential Scanning Calorimeter

HDPE – High Density Polyethylene

ΔH_f – Heat of fusion of semi-crystalline polymer found using DSC in J/g

$\Delta H_f{}^*$ - Heat of fusion of 100% crystalline sample in J/g

J – Joules – Energy measurement

g – grams – Mass measurement

in – inches – Distance measurement

mL – Mililiters – Volume measurement

SCRU – A proprietary unit representing revolutions of the Extruder screw used by the motor drive on the Bekum Blow Molder

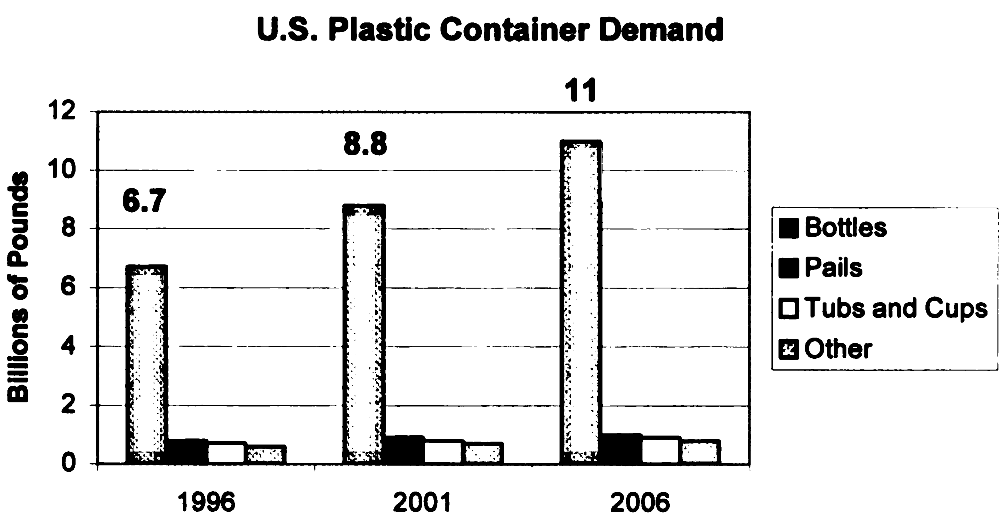
1 – INTRODUCTION AND LITERATURE REVIEW

1.1 Need for Development

Blow molding machines are used for the production of parts in many industries including packaging and automotive. Packaging, however, is the single largest user of blow molded thermoplastic containers in the US with approximately 70 percent of market (Rosato et. al., 2004).

The rigid and semi-rigid plastic packaging industry is an economic power that comprises 21 percent of the $115 billion packaging industry (Ernst and Young, 2002). Plastic containers alone totaled $11.4 billion dollars in 2001. Plastic bottle demand grows by more than four percent each year and is expected to reach 11 billion pounds by 2006 as shown in Figure 1.

Figure 1. Current and Projected US Plastic Container Demand (Freedonia Group, 2002)



The increasing demand for plastic bottles has forced bottle suppliers to gear up for the higher outputs required to meet customer demand. The steps taken to increase output include installing more equipment, retrofitting existing equipment, or replacing existing machinery with new state-of-the-art equipment. According to a survey by the Packaging Machinery Manufacturer's Institute (PMMI), 55.2 percent of respondents reported replacing existing machinery with new models rated for higher output, while 39 percent reported upgrading their existing equipment with state-of-the-art retrofit kits (PMMI, 2003). The first quarter of 2003 saw $21.8 million in blow molding machinery sales (SPI, 2003). Total sales for blow molding machinery in all industries in 2003 are estimated at $505 million compared to around $350 million for 1999 (Rosato et. al., 2004).

1.2 Extrusion Blow Molding

1.2.1 Process

The extrusion blow molding industry has been on the rise since its first successful commercially produced item, the "Stopette" deodorant squeeze bottle by Plax Corporation, in 1945. After this success, nearly every major company who made rubber machines and injection machines began to develop blow molders. Material limitations of the time made only small container blow molding possible (Belcher, 1999). High Density Polyethylene, made available in 1956, led to the success of low cost, reliable extrusion blow molded manufacturing in North America and allowed for the production of larger containers (Lee, 1990).

The process of extrusion blow molding was developed from modifications made to early injection molders as well as glass container machines.

Extrusion blow molding machines use the following process (Figure 2):

- Plastic pellets of a specific material are fed into the extruder to be melted
- Melted plastic is extruded into a tube called a parison and introduced into the mold chamber
- An aluminum mold with a cavity in the shape of the desired bottle is clamped around the parison clamping the bottom shut; the parison is then cut off at the top
- A blow pin drops into the neck opening of the bottle
- Plastic is mechanically forced into the "finish" of the bottle by the blow pin tip forming the threads and mouth of the container
- The blow pin (Figure 3) blows air into the tube, inflating the plastic tube like a balloon
- The tube is inflated into the walls of the mold cavity
- The mold cavity is water-cooled; when plastic comes in contact with the mold, the plastic cools and becomes hard
- The mold opens, the bottle flash is removed, and then the cooled and formed bottle is dropped onto a conveyor to proceed to a packing or filling operation

Figure 2. Conventional Extrusion Blow Mold Process

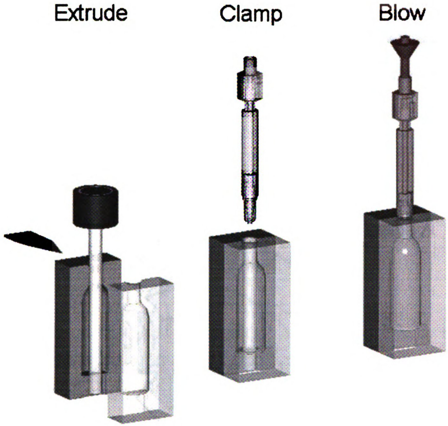
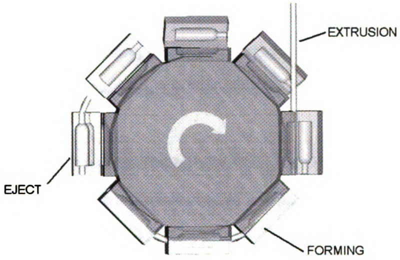


Figure 3. Conventional Blow Pin

Extrusion blow molding machines are capable of producing multiple containers simultaneously by using multiple-cavity molds. Many models, including the one owned by Michigan State University, operate on a continuous rather than stepwise operating process. During the steps when a bottle is being blown and cooled, the next parison is already being formed. As soon as one bottle is cooled and dropped onto the conveyor, the mold shuttles over and picks up the next parison for molding, greatly reducing cycle times. Other machines use rotary technology (Figure 4) where a continuously formed parison is wrapped around a wheel and several operations are performed on the parison as it advances around the wheel.

Figure 4. Rotary Extrusion Blow Molder



The wheel contains multiple molds and bottles are formed in each one. The wheel contains the air blowing mechanism, which punctures the parison to feed air inside. Rotary machinery is very expensive, due to the cost of the multiple molds and blow pins around the machine, but gives very high production rates. Rotary machines must produce millions of bottles to remain economical (Lee, 1990).

Manufacturers that do not produce extremely high volumes of bottles, but need to add capacity, are looking for new technologies that will improve the throughput of traditional blow molding equipment. One of the best areas to reduce cycle times is in the cooling and blowing stages. Total molding time for a single 22oz bottle on the current machine is 9.51 seconds; 6 seconds of this is the time required to inflate the parison into the mold and cool it, forming the bottle. In addition, 0.5 seconds is used to exhaust the air from the bottle before the cooled bottle is dropped out of the machine. These two processes make up more than two-thirds of the total cycle time. Reducing the time required for each of these stages would drastically lower cycle times and increase bottle output.

The blowing stage is required to inflate the bottle and to cool the plastic. The pressurized air is introduced to the inside of the container to hold the plastic against the mold cavity. The mold cavity is water-cooled and draws heat out of the plastic to bring it down to a temperature where it can maintain its shape and dimensions. The sooner the bottle is brought down to a stable temperature, the sooner it can be removed from the mold and another bottle can be formed. There are several ways of reducing bottle cooling time. Traditionally mold-makers have focused on the radiating effects of different cooling channels in the mold to reach all parts of the bottle, focusing on the thickest parts of the container, which require the most cooling. Some companies have taken cooling a step farther, opting for internal cooling to speed up cool-down times, thereby reducing blow and exhaust cycle times.

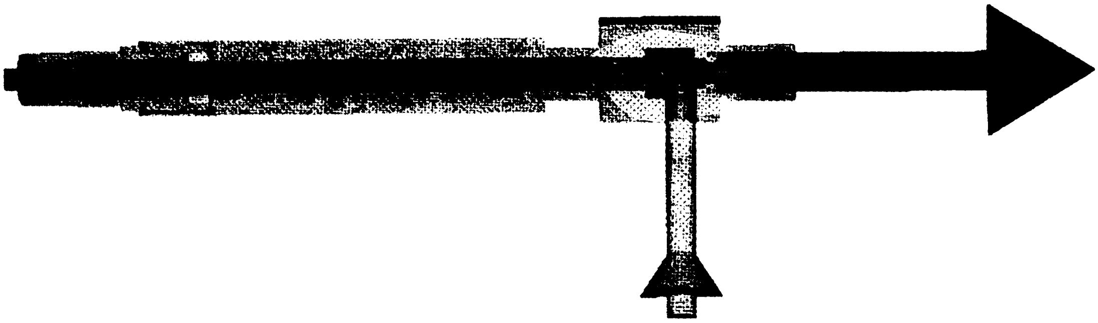
Internal cooling is the process of cooling the blow-molded part from the inside out. A standard blow pin inflates the container with room temperature, dry air. The air is forced into the container, where it remains during the entire blow-cycle and is allowed to escape during the exhaust cycle. While the air sits in the inflating container, it remains stagnant and does little to contribute to cooling since the hot plastic heats it. Water spray, liquid CO_2, nitrogen, circulated air, and supercooled air are all methods of internal cooling. Water spray methods work by spraying an air and water mix into the part. The water helps to cool the part and is then evaporated into steam. The continuous air stream cycles the steam out of the part through a pressure release valve. This method requires that the water mix be introduced after the inside walls of the container are solidified to prevent the water from affecting the internal surface finish. Finally, dry air must be blown in to remove any additional water left behind. Air/water sprays can reduce cycle times by as much as one-third but any residual water left behind can be undesirable in applications involving moisture sensitive product or where contamination is an issue (Lee, 1990). Liquid CO_2 and nitrogen systems work in similar ways. Internal cooling through cold circulated air is the basis of the Fasti Blow Mold Booster system.

1.3 Fasti System

1.3.1 Recirculating blow pin

The purpose of the Fasti system is to internally cool the container. The most important feature of this technique is the continuous removal of hot air while the system simultaneously introduces cold air into the part. This process of cycling the air is achieved by using a recirculating blow pin. The blow pin can be easily engineered for the specific machine and application. The pin consists of a central exhaust pipe, which pulls hot air out of the bottle and a fitting which sends cold air into the bottle around the outside of the exhaust pipe (See Figure 5). In addition, small channels send air around the circumference of the blow pin externally at the cooling sleeve to cool the moil or top flashing.

Figure 5. Recirculating Blow Pin



Blowing of the bottle becomes a three-stage process with the Fasti system described below and shown in Figure 6.

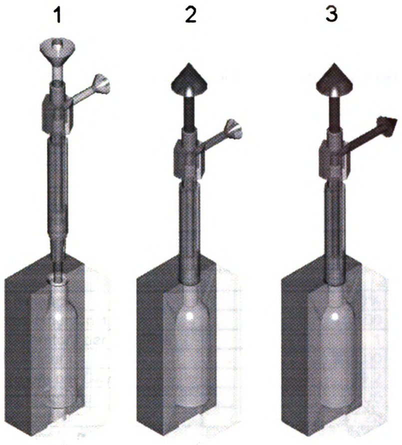
1. The pre-blow phase uses chilled air through both blow pin channels to inflate the parison inside the mold as quickly as possible, while the blow

pin is entering the bottle finish. The high-pressure pre-blow process forms the container, forcing out ambient air between the mold and parison through the mold vents. The bottle is inflated and comes in contact with the water-cooled cavity surfaces, which promotes the cooling of the bottle.

2. The blowing phase is used to do the actual cooling of the bottle with cold air. Upon inflation of the bottle in the pre-blow stage, only a small amount of back-pressure is required to maintain contact with the mold cavity walls. During this stage, air flow through the center channel of the blow pin is reversed, allowing hot air to escape while cold air is blown in through the outer channel. Cold air entering the container forces the cold air out the center channel. This allows the cold air to circulate instead of trapping the hot air inside the container as with a conventional process.

3. Finally, the venting stage where the air pressure is balanced between the container and the outside. At this stage, the container will have cooled sufficiently to maintain its dimensionality.

Figure 6. Fasti Blow Stages



The cost of a new recirculating blow pin averages from six hundred to seven hundred dollars, comparable to that of a traditional pin, but can vary due to size and complexity. Full Mechanical drawings of the blow pin used in this setup are available in Appendix B

1.3.2 Cooling system

The air cooling system itself is quite simple. Air is forced into the system and cooled by cold water. The refrigerated air is then directed into the blow pin for bottle blowing.

1.3.3 Costs

Total cost of the unit is listed in Table 1 along with an estimate of equipment payback time based on a three-shift production schedule at 80% efficiency.

Table 1. Fasti Cost Analysis and Payback Period Estimate (FastiUSA, 2004)

Costs		
Blow Mold Booster Unit Cost	$11,710.00	
Blow Valve Blocks	$1,490.00	
Blow Pin Design Cost	$1,100.00	
Blow Pin Machining Cost	$700.00	
Installed Investment	**$15,000.00**	
Values in US$		
	Conventional	**Fasti-BMB**
Operating Efficiency	80%	80%
Base Machine-Hour Cost	$80.00	$80.00
Number of Operators per Machine	1	1
Cost per Man-Hour	$20.00	$20.00
Productive Hours per Day	19.2	19.2
Product Weight, grams	25	25
Cost of Resin per Kilo	$1.25	$1.25
Cost of Resin per Part	$0.03	$0.03
Energy Consumption, KW/h	(Included in Base Cost)	7
Energy Cost per KW/h	$0.10	$0.10
Additional Energy Cost per Hour	$0.00	$0.70
Air Consumption, Nm3/h	(Included in Base Cost)	20
Cost of Compressed Air/Nm3/h	$0.02	$0.02
Additional Air Cost/h	$0.00	$0.39
Total Additional Costs	$0.00	$1.09
Manufacturing Cost per Hour	$100.00	$101.09
Increase in Production, %	0%	28%
Number of Parts Produced per Hour	379	485
Cost of Resin Consumed per Hour	$11.37	$14.55
Total Cost per Part	$0.29	$0.24
Savings per Part	N/A	$0.06
Savings per Day	N/A	$516.06
PAYBACK PERIOD, DAYS		**29.1**

1.3.5 Installation

Installation of the equipment required significant modifications to the machine including fabrication of mounting brackets for both the cooling unit and the valves. It was necessary to mount the cooling unit at a level higher than the blow pins and with as short a distance between the blow pin, cooling unit, and valves as possible. The size of the cooling unit required it to be mounted on top of the machine surround with a substantial bracket able to support its 90 pound weight. The final design for the mounting tray consisted of a three-point support with the main weight of the unit being carried by the machine surround and a third mount point inside the cabinet on a mounting plate. The mounting tray also needed a lip to contain the unit to prevent it from vibrating off. The valve units were mounted to the sheet metal sides of the machine surround using sandwich plates to stabilize them, this spread out the load further. Photos of the blow mold machine before and after modification are shown in Figures 7 and 8.

Figure 7. Machine Surround Before

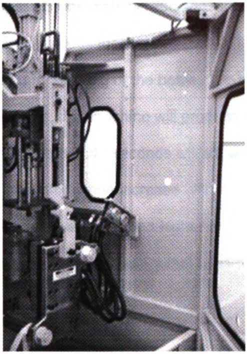
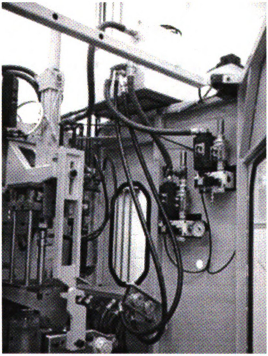


Figure 8. Machine Surround After



1.3.4 Efficiency

Fasti USA claims to increase production by reducing air blow cycles by as much as 35%. The entire forming process for one bottle is 9.51 seconds, with 6 seconds of that being used for blowing of the bottle. If a bottle machine produces one bottle every 9.51 seconds, that machine will produce 379 bottles in a 1-hour period. Reducing forming time to 7.42 seconds will allow the machine to produce 485 bottles in 1 hour, a 28% production increase. Production improvements like this will directly translate into lower costs and higher profits. Savings such as this could have significant impacts on any industry that uses blow-molding processes.

1.4 Objective

The question that remains is: what effect do the cooler temperatures and reduced cycle times have on the physical properties of the finished bottle?

1.4.1 Crystallinity

Forming temperatures have a direct relationship with the crystallinity and density of HDPE containers. Polymer crystallinity and density have a direct correlation with such properties as clarity, permeability, column crush strength, and impact strength (Hernandez, Selke, and Culter, 2000). The objective is to quantify what effect lower processing temperatures will have on bottle performance in these areas. Table 2 shows the effect of decreased crystallinity on various bottle properties

Table 2. Effect of Decreased Crystallinity in Polymers (Hernandez et al, 2000)

Crystallinity	decreases
Density	decreases
Permeability	increases
Opacity	decreases
Blocking	increases
Tensile Strength	decreases
Compression Strength	decreases
Clarity	increases
Tear Resistance	increases
Impact Strength	increases
Toughness	increases
Ductility	increases
Ultimate Elongation	increases
Heat Sealing Temperature	decreases
Heat Sealing Range	increases

As is evident in the table, reduction in crystallinity can have significant effects on bottle performance. Most notable for those involved in packaging are increased impact strength, reduced compression strength, and increased permeability.

"During processing, the major difference between amorphous and crystalline polymers is that amorphous polymers gradually lose their molecular mobility as the temperature cools, whereas crystallizing polymers (like HDPE) change suddenly from mobile liquids to crystalline solids at a sharply-defined melting/freezing point" (Rosato et. al., 2004). For this reason, crystallizing polymers are more difficult to blow mold because of their narrow workable temperature range. The rate of crystallization can be controlled by the cooling process and ultimate crystallinity may be reduced by quenching (Rosato et. al., 2004).

“Crystallization is useful in blow molding because (1) it freezes [the container] in the stretch orientation and thus gives the oriented structure permanence; and (2) it improves many end-use properties of particular importance in food packaging, including rigidity, dimensional stability on reheating, and impermeability. On the other hand, crystallinity tends to harm some useful properties such as ultimate elongation, impact strength, transparency, and environmental stress crack resistance” (Rosato et. al., 2004).

If we assume that ΔH_f is proportional to the % crystallinity of the test specimen and if we know the ΔH_f of the test specimen in pure crystalline form (100% crystallinity), we can compute the % crystallinity as follows:

$$\%Crystallinity = \frac{\Delta H_f}{\Delta H_f^*} x100\%$$

Where:

ΔH_f = heat of fusion of semi-crystalline polymer, J/g

ΔH_f^* = heat of fusion of 100% crystalline sample, J/g. For PE, this value is 286.2 J/g (Selke and Xiong, 2003).

The Fasti unit’s internal cooling technology is likely to affect crystallinity of the finished container due to the quicker cooling and therefore shorter period of time during which the bottle is at its crystallization temperature.

1.4.2 Wall thickness

In addition to impacting crystallinity, the Fasti system may also affect the wall thickness of the finished containers; reducing the amount of time that the plastic has to flow out into the mold may affect material distribution. Distribution changes may be solved using the parison programming to adjust the profile and maintain uniform wall thickness throughout the bottle and between forming methods.

1.4.3 Dimensionality

Bottle dimensions may be affected by cold air blowing. It is likely that dimensional stability will be affected by internal cooling. The quicker cooling and therefore "freezing" of the container shape will result in less warpage. Dimensional stability of the container is critical to maintain tolerances for the filling operations in terms of volume as well as dimensions in the finish area to allow the closure to work well with the container.

1.5 Hypothesis

An experiment was designed to test the hypothesis:

H_O: The use of internal cooling does not change the physical properties of extrusion blow molded HDPE bottles; specifically, mean compression strength, dimensions, and crystallinity do not change.

1.6 Statistical Methods

Means for variables measured on conventional and on Fasti bottles were compared with two sample t-tests. Analyses of residuals showed this to be reasonable for the comparisons.

Commonly, p-values of less than or equal to 0.05 are regarded as indicative of (statistical) significance. However, with large sets of multiple comparisons the level is made more stringent. For example, with the set of four or eight dimensional comparisons 0.01 is used and with a set of sixty-four thickness measurement points 0.001 is used.

2 – EXPERIMENTAL DESIGN AND TEST METHODS

2.1 Materials and Setup

2.1.1 Conventional Air Setup

Setup of the conventional blow settings was accomplished with the help of Bekum America. The settings are set so that the container is formed in the shortest amount of time possible that would still allow complete formation of the container. The cycle time of this setup as shown in Table 3 is 9.51 seconds. The parison program was designed to create approximately equal wall thickness throughout the wall and heel of the container. These set points are saved in the machine as "16OZ ROUND THESIS" along with the parison program.

Table 3. Bekum Blow Molder Conventional Blow Set Points

Action	Time (sec)
Extend Knife Delay	0.63
Retract Knife Cut Delay	0.63
Mold Close Delay Time	0.00
Carriage Down Delay	0.25
Blowing Delay	0.12
Blowing Time	6.00
Exhaust Time	0.50
Deflash Delay	0.00
Blow pin 1st Step Delay Time	0.14
Blow pin 2nd Step Delay Time	0.10
Container Blowoff Delay	0.00
Container Blowoff Time	0.00
Carriage Up Delay	0.30
Fasti Delay	~~~
Knife Pulse Cut	0.16
Carriage Up First Cycle Delay	2.00
Mold Crack Time	0.25
Mold Crack Hold	0.40
Controlled Support Air Delay	2.00
Controlled Support Air Time	2.00
Machine Cycle Timer	**9.51**
Extrusion Speed (SCRU)	~48.00
Blow Pressure (psi)	65.00
Back Pressure (psi)	~~~
Extruder Temperature Set points (deg F)	350.00

2.1.2 Fasti Cold Air Setup

Setup of the Fasti cold air blow settings was accomplished using trial and error. The settings are set so that the container is formed in the shortest amount of time possible that would still allow complete formation of the container. The cycle time of this setup as shown in Table 4 is 7.42 seconds. The parison program was designed to create approximately equal wall thickness throughout the wall and heel of the container. Another experiment, shown in Appendix E, attempted to determine the connection between various timer and pressure settings with container volume or shrinkage. The findings from this study were taken into consideration when setting up the machine. These set points are saved in the machine as "16OZ ROUND FASTI THESIS" along with the parison program.

Table 4. Bekum Blow Molder Cold Air Set Points

Action	Time (sec)
Extend Knife Delay	0.63
Retract Knife Cut Delay	0.63
Mold Close Delay Time	0.00
Carriage Down Delay	0.25
Blowing Delay	0.12
Blowing Time	4.50
Exhaust Time	0.35
Deflash Delay	0.00
Blow Pin 1st Step DelayTime	0.14
Blow Pin 2nd Step Delay Time	0.10
Container Blowoff Delay	0.00
Container Blowoff Time	0.00
Carriage Up Delay	0.30
Fasti Delay	0.85
Knife Pulse Cut	0.16
Carriage Up First Cycle Delay	2.00
Mold Crack Time	0.25
Mold Crack Hold	0.40
Controlled Support Air Delay	2.00
Controlled Support Air Time	2.00
Machine Cycle Timer	**7.40**
Extrusion Speed (SCRU)	~65.00
Blow Pressure (psi)	85.00
Back Pressure (psi)	18.00
Extruder Temperature Set Points (deg F)	350.00

2.1.3 Controls (Constants)

The following pieces of equipment were used in the experiments and setup of the machine. These items remained constant through all tests.

Plastic Type

- Union Carbide UNIPOL Polyolefins DMDA-6220 NT7 UNIVAL

Mold

- Manufactured by MC Molds, Williamston, MI

Blow Mold Machine

- Model H-111S Bekum America, Williamston, MI

Fasti Blow Mold Booster II (BMB II)

- FastiUSA, Elgin, IL

Closure

- Rexam Closures and Containers Evansville, IN
- Cap style: 28 DECO CC2 SPECIAL
- Color: Any
- Material: PLS 10
- Liner: 827
- Description: W01 base/GA4 lid crabsclaw o/s
- Orifice: 0.155

2.2 Experimental Methods

2.2.1 Sampling

Objective:

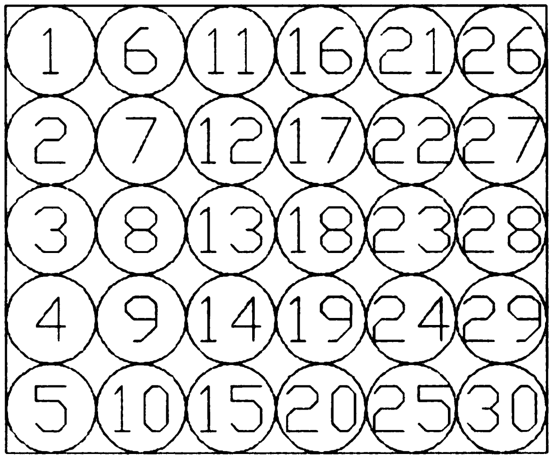
To obtain consistent samples in a regulated manner in order to facilitate labeling and tracking of containers.

Methods:

Containers were manufactured by the two different manufacturing methods: Fasti Cold Air blow and Conventional blow. Short run times were necessary due to machinery limitations, namely, air supply was inconsistent and only allowed production of 30 containers before pressures fell below the specified settings.

The manufacturing process was started up. The first five containers retrieved from the machine were discarded. From then on, each container made was removed in order and placed inverted (finish down) in a divided, numbered sample tray. The containers were inverted to give them time to cool and to prevent the bottom pinch-off from becoming fused to the container. 30 Samples were made per run. The bottles were laid out in the sample trays as shown in Figure 9.

Figure 9. Sample Tray Layout



Five minutes after the cycle was complete, the pinch-offs were removed by twisting them. The containers were then labeled by tray location and placed right-side-up in a new sample tray. The sample tray was labeled with the date, run number, and manufacturing method (Fasti or Conventional).

2.2.2 Conditioning

Objective:

To condition container samples after processing to maintain uniform testing results.

Methods:

Conditioning was performed in accordance with ASTM D-618-00 Standard Practice for Conditioning Plastics for Testing. The labeled sample trays were stored in the room where the bottles were formed and various tests were being performed and allowed to sit for a minimum of 40 hours before being tested.

Average temperature, checked by thermometer, of this room was 24.2 degrees Celsius.

2.2.3 Dimensional

Objective:

To determine the overall dimensions of a container and determine variance among samples.

Equipment:

Scherr-Tumico Industries Model 20-3500 Optical Comparator (0.0001")

Mitutoyo Model CD-6"BS Digital Caliper (0.0005")

Mettler PM2000 Scale (0.01g)

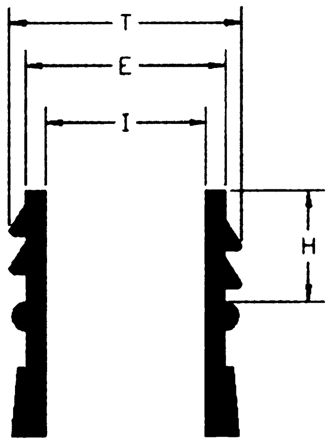
Magna-mike (0.0001")

Methods:

Container samples were measured according to ASTM D 2911-94 Standard Specification for Dimensions and Tolerances for Plastic Bottles.

Finish: Finish dimensions were measured using the optical comparator. Typical tolerances for a finish of this size have a range of around 0.020 inches. T indicates diameter of the finish at the tips of the threads. E indicates diameter of the finish at the base of the threads. H indicates the dimension from the top of the bottle to the transfer bead. I indicates the inside diameter of the finish area. A diagram of the different dimensions is shown in Figure 10.

Figure 10. Finish Dimensions



Volume: Containers were weighed empty, and then filled with water conditioned according to ASTM C2911-94 and weighed again. Container volume was calculated as follows:

$$B_V(\text{mL}) = (B_f - B_e) / 0.997$$

Bottle overflow Capacity Tolerance with a volume between 384 and 531mL is ±11mL.

Body Dimensions: Width is an average of the measurements at the parting line and then rotated 90 degrees. The width is measured using calipers 3" from the bottom of the container.

Table 5. Bottle Body Dimension Tolerances (ASTM D 2911-94)

Range of Dimensions inches			Width Tolerance inches
0	up to but not including	1	0.03
1	up to but not including	2	0.05
2	up to but not including	4	0.06
4	up to but not including	6	0.08
6	up to but not including	8	0.09
8	up to but not including	10	0.11

Body Wall thickness: Wall thickness was measured using the magna-mike with measurements taken at 0.25" increments up the container wall, as shown in Figure 11, as well as measurements in the heel. These measurements were taken at the parting line by the bottom detent at 12:00 as shown in Figure 12 and then repeated every 90 degrees around the container for a total of 64 measurements.

Figure 11. Magna-Mike Measurement Locations

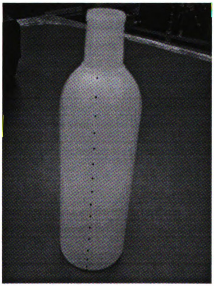
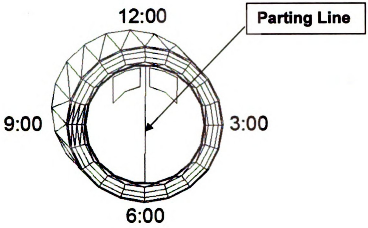


Figure 12. Container Rotation Callouts



2.2.4 Compression Testing

Objective:

Column crush tests provide information about the crushing properties of blown thermoplastic containers. Column crush properties include the crushing yield load, deflection at crushing yield load, crushing load at failure, and apparent crushing stiffness.

Equipment:

Lansmont Corporation Squeezer Compression Tester (0.1 lbs, 0.001 in)

Mettler AE 160 Scale (0.0001g)

Methods:

Crush testing was performed in accordance with ASTM D 2659-95 Standard Test Method for Column Crush Properties of Blown Thermoplastic Containers (ASTM

D 2659, 1995). Twenty samples from each manufacturing method were tested as shown in Figure 13 to determine crushing yield load, deflection at crushing yield load, crushing load at failure, and apparent crushing stiffness. A modified closure was applied to the container. The closure had a vent hole which allowed air to escape during testing as shown in Figure 14. The crown of the closure prevented the hole from sealing and causing pressure to build in the container which could affect compression strength.

Figure 13. Compression Testing Setup

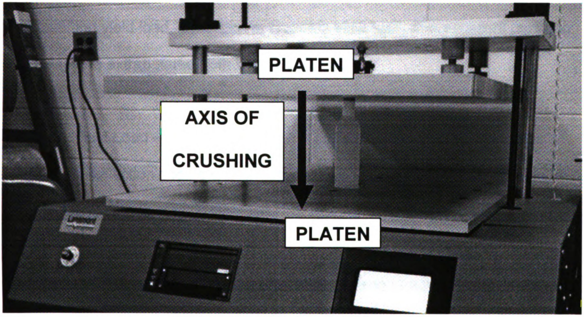


Figure 14. Compression Testing Vent Hole

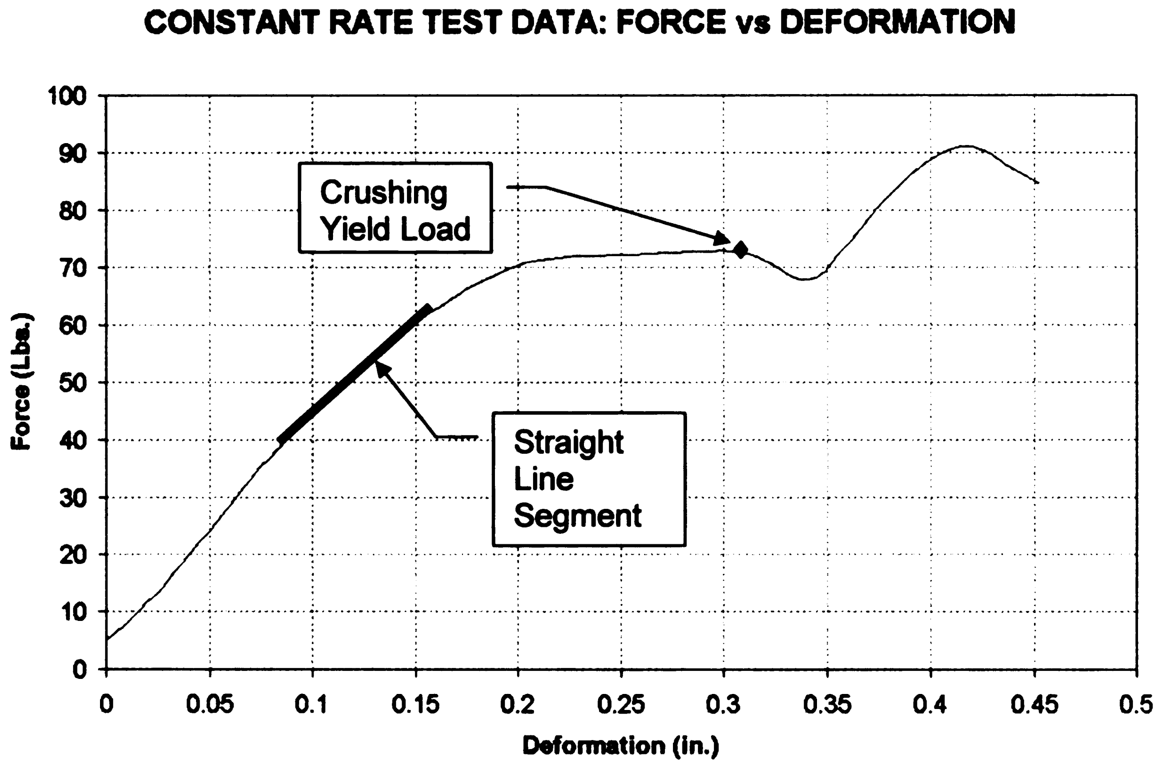
The data from the compression tester was exported to an Excel file for analysis. The crushing yield load, deflection at crushing yield load, and apparent crushing stiffness were extrapolated from the data as follows:

Crushing Yield Load – Point on the crush load/deflection curve at which an increase in deflection occurs without an increase in crush load expressed in lbs. to three significant figures (Figure 15).

Deflection at Crushing Yield Load – Reduction in height (x-axis of Figure 15) of the sample at the crushing yield load expressed in inches to three significant figures.

Apparent Crushing Stiffness – Calculated by selecting a point on the straight line segment of the crush load/deflection curve as shown in Figure 15 and dividing force at this point by the corresponding deflection expressed in pounds per inch to three significant figures.

Figure 15. Compression Data Example



2.2.5 Differential Scanning Calorimetry

Objective:

To determine the melting point and percent crystallinity of HDPE samples by differential scanning calorimetry.

Materials:

TA Instruments DSC Q 100 Differential Scanning Calorimeter

Mettler AE160 scale (0.0001g)

Methods:

Handle all samples with tweezers, cut a 9-10 milligram sample from the container, weighing sample in the bottom aluminum pan. Record sample weight then apply top pan and crimp sample closed as shown in Figure 16. Place sample in DSC centered on thermocouple. Using the settings shown in Table 6, run the experiment.

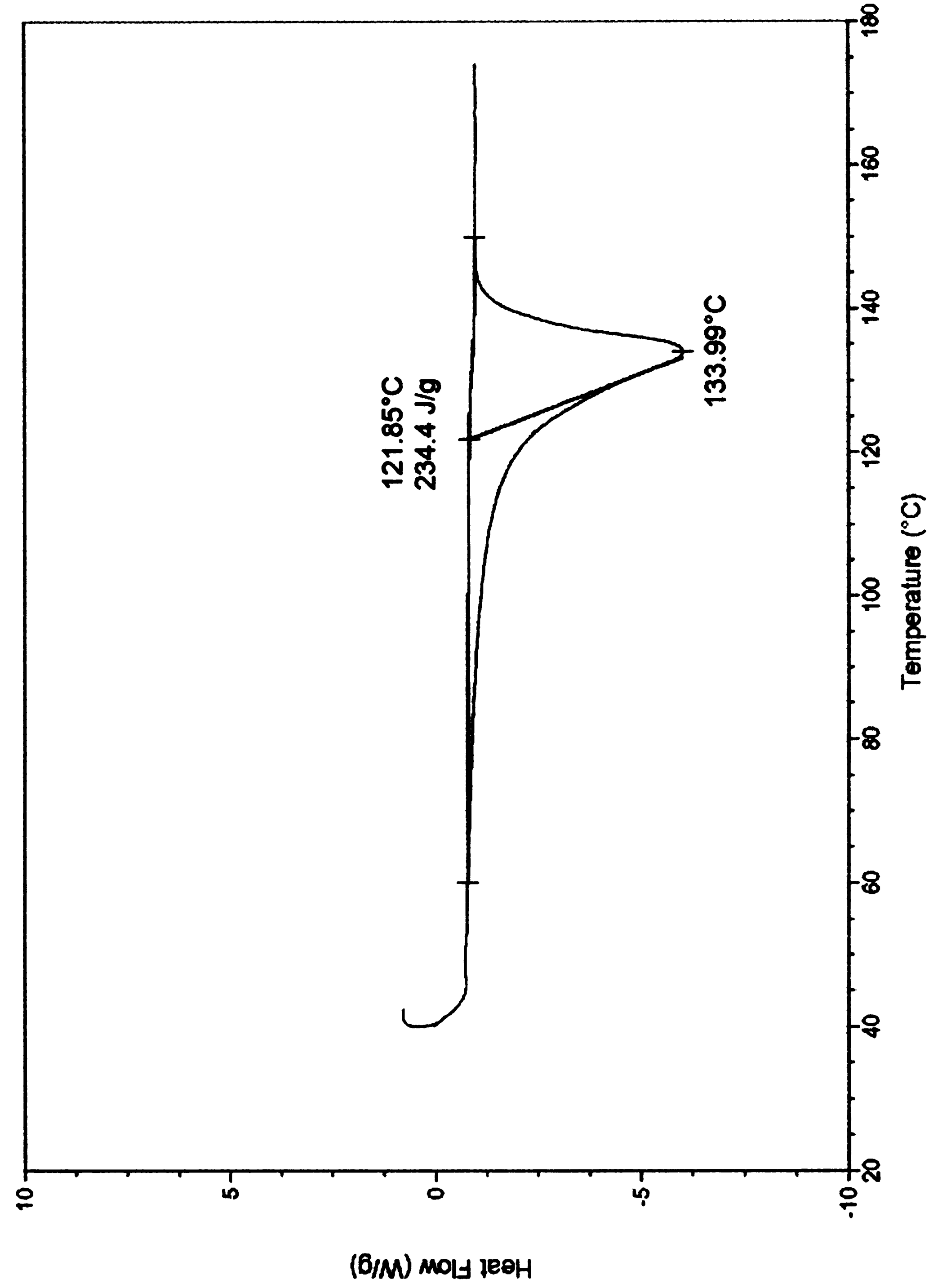
Figure 16. DSC Sample Pan Crimper

Table 6. DSC Heat/Cool/Heat Setup Method

1	Ramp 20.000°C/mi to 180.00°C
2	Mark end of Cycle 0
3	Isothermal for 2.00 min
4	Ramp 20.000°C/mi to 40.00°C
5	Mark end of Cycle 1
6	Isothermal for 2.00 min
7	Ramp 20.000°C/mi to 180.00°C
8	Mark end of Cycle 2

Integrate the curve shown by the analysis program shown in Figure 17 with the curve starting at 60°C and ending at 150°C. Calculate percent crystallinity from the result using 286.2 J/g as the baseline for 100% crystalline HDPE (Selke and Xiong, 2003).

Figure 17. DSC Readout Example



3 – DATA AND RESULTS

3.1 Cycle time improvements

The improvement of cycle time was indeed significant, accomplishing a 22% decrease from 9.51 seconds per cycle to 7.42 seconds per cycle. Containers manufactured using the two methods were complete and correctly formed and similar in appearance.

3.2 Dimensionality

Comparison of container dimensions between Fasti and conventional manufacturing methods reveal several differences and are shown in Table 7. P-values shown in bold show statistical significance. The most striking difference between the containers is an overall shrinkage of the Fasti containers. While shrinkage after the forming process is common, this effect appeared to be magnified by the Fasti system. While the Fasti containers shrank more than the conventional bottles, the shrinkage was consistent across containers as displayed by the low standard deviation found among samples. Shrinkage does not entirely account for the reduced volume of the Fasti containers. This is explained by the increased part weight. More resin in the container walls makes the volume inside the container smaller.

Warpage after the forming process is also a common occurrence. Warpage of the body area of the Fasti containers was significantly lessened with the Fasti process as can seen in the "Body Diameter Difference" category of Table 7. This category is a calculation of the differences in diameter of the container across the parting line versus turned 90 degrees from the parting line. The decreased warpage is best attributed to the uniformity of the wall thickness at the measuring point. The container diameter was measured 3 inches from the bottom of the container at point 8 of the wall thickness measurements. Review of the wall thickness found in Appendix A proves that decrease of warpage is not related to varying wall thickness around the container. The likely reason for reduced warpage of the container is the internal cooling. Container thickness at the diameter measuring point is relatively thin and would receive the most cooling. This proves that the Fasti unit will actually "freeze" the container in place with more thorough cooling.

Table 7. Dimensional Test Result Comparison – Conventional vs. Fasti

	Conventional avg	Conventional std	Conventional max	Conventional min	Fasti avg	Fasti std	Fasti max	Fasti min	Statistics avgC-avgF	Statistics SE	Statistics t	Statistics P-value
B_E (g) Bottle Weight Empty	26.00	0.28	26.64	25.65	28.41	0.14	28.63	28.10	2.41	1.649	1.461	**0.000**
B_F (g) Bottle Weight Full	512.81	0.33	513.28	512.15	507.59	0.53	508.60	506.80				
B_V (mL) Bottle Volume	488.27	0.56	489.10	486.97	480.62	0.60	481.81	479.71	7.647	6.96	1.099	**0.000**
Body Diameter (at Parting Line)	2.3758	0.0043	2.3850	2.3705	2.3930	0.0068	2.4085	2.3795				
Body Diam. (90° from Parting Line)	2.4109	0.0035	2.4170	2.4035	2.3905	0.0059	2.4050	2.3820				
Diameter Difference	0.0351	0.0066	0.0455	0.0185	0.0067	0.0064	0.0215	0.0005	0.028	0.046	0.619	**0.000**
Body Diameter Average	2.3934	0.0022	2.3980	2.3903	2.3918	0.0045	2.3990	2.3825	0.002	0.001	1.439	0.161
T Major Diameter of Threads	1.0464	0.0022	1.0504	1.0432	1.0392	0.0039	1.0460	1.0319	0.007	0.001	7.149	**0.000**
E (90° from Parting Line)	0.9800	0.0030	0.9849	0.9741	0.9626	0.0060	0.9699	0.9487				
E (at Parting Line)	0.9681	0.0033	0.9750	0.9627	0.9692	0.0062	0.9789	0.9587				
E Difference	0.0119	0.0054	0.0208	0.0017	0.0104	0.0073	0.0260	0.0009	0.002	0.033	0.045	0.467
E Average	0.9741	0.0016	0.9778	0.9700	0.9659	0.0026	0.9743	0.9616	0.008	7E-04	11.94	**0.000**
H Top to Bead	0.3631	0.0031	0.3713	0.3591	0.3551	0.0040	0.3664	0.3511	0.008	0.001	7.114	**0.000**

The Fasti containers had a more consistent wall thickness throughout the container while conventional containers had thinner walls near the top as shown by the wall thickness data in Appendix A. The most statistically significant points (those with p-values less than 0.001) are shown in bold in Table 7. These values coincide with the thinnest spots on the conventional containers. This can be explained by the extrusion speed. The Fasti containers used a higher extrusion rate in order to prepare the parison faster. The slower extrusion rate of the conventional process allowed the parison to stretch under its own weight and therefore thin out near the top. This issue could be easily resolved by altering the parison profile or possibly by lowering the melt temperature in the conventional process.

Table 8. t-Score p-Values for Wall Thickness

	t-score p-values (3 df)			
Point	**12:00**	**3:00**	**6:00**	**9:00**
1	0.197	0.083	0.052	0.606
2	0.664	0.861	0.016	0.243
3	0.005	0.097	0.094	1.000
4	0.022	0.372	0.397	0.170
5	0.228	0.559	0.217	0.205
6	0.397	0.155	0.023	0.941
7	0.332	0.047	0.052	0.403
8	0.078	0.029	0.038	0.200
9	0.011	0.016	0.008	0.095
10	0.002	0.013	**0.001**	0.049
11	**0.000**	0.018	**0.000**	0.049
12	**0.001**	0.026	0.002	0.086
13	0.002	0.015	0.003	0.163
14	0.042	0.010	0.003	0.045
15	0.058	0.135	0.830	0.028
16	0.042	0.022	0.008	0.025

3.3 Compression Strength

Compression strength tests performed on the finished containers revealed very little difference between processes. In both cases, failure was seen in the heel area resulting in buckling of the bottle walls. Table 9 shows a comparison of the compression test results for conventional versus Fasti containers. The p-values in the table are less than 0.01 in each category showing that the data is statistically significant. The statistical significance however, does not speak of the practical significance of the effect the Fasti system has on the container. The higher crushing yield load of the Fasti container is likely attributed to the slightly higher average thickness of the container at the crush failure point displayed in the data in Appendix A.

Table 8 shows significant data difference in the apparent crushing stiffness of the containers to theorize that the Fasti containers may have a lower percent crystallinity and therefore lower stiffness as expressed in Table 9. This theory was tested in Section 3.4. All compression strength data is displayed in Appendix B.

Table 9. Compression Test Results – Conventional vs. Fasti

	Specimen Weight (g)	Crushing Yield Load (lb.)	Deflection at Crushing Yield Load(in.)	Apparent crushing stiffness (lb./in.)
Conventional				
Xbar	25.8795	72.225	0.29855	409.124
s	0.26863	3.20836	0.00635	14.9418
Fasti				
Xbar	28.2515	76.115	0.27105	371.583
s	0.0981	1.60173	0.00876	15.0963
Statistics				
avgC-avgF	-2.372	-3.89	0.0275	37.5409
SE	0.06395	0.80184	0.00242	4.74952
t	37.0927	4.85131	11.3675	7.90416
p-value	1E-22	4.2E-05	2.7E-13	1.5E-09

3.4 Crystallinity

Crystallinity of the container is determined by processing conditions. The average crystallinity of the virgin HDPE resin pellets, as displayed in Table 10, is 76.32%.

Table 10. Percent Crystallinity of Virgin HDPE Resin

	J/g	%Cry
Pellet 1	220.8	77.15%
Pellet 2	213.8	74.70%
Pellet 3	220.7	77.11%
Avg	218.4	76.32%

Initial crystallinity tests involved removing a sample from three points on the bottle: in the heel, in the body 3 inches above the bottom, and in the shoulder. These samples were taken without regard to their orientation on the container as far as container rotation. This may explain the large variance percent crystallinity between container samples shown in Table 11. For example, the shoulder sample from conventional bottle 28 from sample tray as shown in Figure 9 was taken at the 12:00 position while conventional bottle 29 was taken from 5:00. Wall thickness data in Figures 18, 19, and 20 in Appendix A show significant wall thickness differences from point to point around the container at the shoulder (thickness measurement 16).

Table 11. Percent Crystallinity of Conventional vs. Fasti Containers

	Body	Shoulder	Heel
Conventional			
Bottle 28	218.7	219.1	231.6
Bottle 29	219.2	234.4	226.5
Bottle 30	220	228.8	223.5
Avg	219.3	227.4333	227.2
%-Crystallinity	76.62%	79.47%	79.39%
Fasti			
Bottle 28	230.8	233.2	220.3
Bottle 29	234.8	227.9	209.8
Bottle 30	230.9	228.9	215.5
Avg	232.1667	230	215.2
%-Crystallinity	81.12%	80.36%	75.19%

More thorough and controlled testing was done on a single sample container for each conventional and Fasti container at the heel. A sample was taken at each of the four points of rotation as shown in Figure 12 after the container was measured for thickness. The thickness measurement at the sample area corresponds to measurement point 2 of the data shown in Figure 20 and Figure 23 in Appendix A. Table 12 shows the thickness at each measuring point and its corresponding percent crystallinity. This data shows that there is no significant correlation between wall thickness and percent crystallinity in the heel area.

Table 12. Percent Crystallinity at Points in Heel

	12:00	3:00	6:00	9:00
Conventional				
Thickness (in.)	0.0261	0.0175	0.0256	0.0192
J/g	220.5	222.8	226.8	234.5
%-Crystallinity	77.04%	77.85%	79.25%	81.94%
Fasti				
Thickness (in.)	0.0223	0.0180	0.0289	0.0177
J/g	225.8	225.7	231	236.7
%-Crystallinity	78.90%	78.86%	80.71%	82.70%

Of further interest is the difference in crystallinity between conventional and Fasti containers. The data in Table 12 shows no significant difference in percent crystallinity between manufacturing methods.

4 – CONCLUSIONS AND RECOMMENDATIONS

The addition of Fasti internal cooling technology to the Bekum blow molder significantly increased production rates of the machine. Production increases as high as 22% were seen between conventional and Fasti molding methods despite limitations with our equipment including insufficient air-supply. An increased air supply would likely drastically lower the blow air temperature released from the Fasti unit. Decreased blow temperatures would result in more thorough cooling and more stable container properties.

Dimensional analysis of containers proves that reduced warpage is a positive effect of internal cooling. The proof is found in the more consistent container diameter of Fasti containers, which is not associated with wall thickness. The thorough cooling and therefore setting of the body walls with low blow air temperatures reduced warpage after being released from the mold. Further proof of this could come from continued research upon implementation of a more reliable air supply. Fasti container formation resulted in a higher overall container weight which caused a reduction in volume. Without container and closure drawings it is difficult to determine if the container finish dimensions fell within desired tolerances but a low standard deviation among samples of the same manufacturing method displayed consistency and low standard deviation.

Compression tested containers showed very little difference in performance that could be directly attributed to changes in crystallinity, container dimensions, or wall thickness. Compression strength could be improved for certain applications by increasing wall thickness in the heel area.

Study of the containers by Differential Scanning Calorimetry at various container locations reveals that the percent crystallinity of the container is independent of container wall thickness. Furthermore, the percent crystallinity did not appear to be dramatically affected by blow temperature.

It should be noted that the tests were run on containers produced through short run times. Increasing the reliability of the air supply and therefore lengthening run cycles would produce greater sample sizes and allow more thorough testing.

In summary, the Fasti internal cooling technology greatly increased output without making considerable changes to container performance. Any shortcoming found with the system can easily be programmed out with a combination of changes in processing temperatures, air flow, and parison programming. The positive effects of the Fasti system including reduced cycle times and reduced warpage would likely be magnified with the use of more air volume resulting in lower temperatures.

5 – RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Utility Needs

In order to properly use the Fasti internal cooling equipment, it is necessary to have a more reliable air supply. The current setup allows only around 5 minutes of continuous operation of the machine with sustained air pressure. Air pressure was monitored throughout the forming process with the use of an added-on gauge at the wall. If pressures dropped below what was required for the machine, forming was stopped. It is likely that the longer the machine is left to run, the process will become more stable. Higher air volumes used for producing the containers will also allow faster and more complete cooling.

Many solutions are feasible for this problem, the most reliable being an upgrade for the air compressor unit to one capable of a higher volume output (cubic feet per minute). Another possibility would be the addition of a large surge tank near the machine itself. This would allow longer runs, though not necessarily more volume.

5.2 Redesign of Mold

The mold that was supplied with the machine uses a finish which is very outdated. The threads used are a custom thread design available only from Rexam Closures. Various attempts to acquire sample caps, finish drawings, production tolerances, turned up little information. A very small number of caps were acquired for studies but the hinged lid is not acceptable for many performance tests. It would be desirable to redesign the finish area of the mold. This section is removable and could be replaced with a more standard thread for which closures are more readily available.

In addition, the use of the Fasti system would produce better quality bottles with less shrinkage in the finish area if the water channels allowed better cooling. Redesigning the mold for the new finish would allow the opportunity to redesign these cooling channels.

5.3 Regrind

The School of Packaging has a granulator which could be used for regrinding containers. Studies could then be conducted regarding the changes in processing temperatures and conditions with the use of the regrind material. Furthermore, studies could be done using various mixes of regrind and virgin material and their effects on container performance.

5.4 Different Containers

The use of the Fasti machine on a 16 fluid ounce container from this mold does not compare to the benefits realized from a larger container with thicker walls. According to Fasti, a common application for the Fasti unit is for the production of blow molded gas tanks. These containers have very thick coextruded walls requiring long blow times to cool the tank and set the plastic. Factors like shrinkage may be magnified in the larger part. Investigating the effect of container size and volume on cooling time and container shrinkage is recommended.

5.5 Environmental Stress Cracking

Another important test which could be run on these containers is an environmental stress cracking test. Comparisons could be made between the two manufacturing methods following the test procedures outlined in ASTM D2561-95, Environmental Stress-Crack Resistance of Blow-Molded Polyethylene Containers.

5.6 Impact Testing

Impact testing of HDPE containers is difficult through standard testing methods including ASTM D 2463-95 Drop Impact Resistance of Blow-Molded Thermoplastic Containers. The problem lies in the incredibly high inherent strength of the materials. Preliminary testing failed to produce any impact failure at all. Possible solutions to this problem could include freezing of the containers before testing to increase brittleness.

5.7 Torque Testing

The different manufacturing methods could potentially produce different results in closure torque testing. Application and removal torque could be tested for each of the containers.

5.8 Optical Microscopy

Optical microscopy is another method for analyzing the physical composition of a container including crystallinity by observing crystalline regions.

5.9 Permeability Testing

Permeability could be conducted on different containers produced by the machine.

5.10 Resin

Various resins could be tested in this machine with the current setup. The current extruder screw is capable of running polyethylene including HDPE and LDPE as well as polyethylene blends. Further information could be obtained from Bekum America regarding the compatibility of this screw for other materials as well as possibly acquiring a new screw capable of a wider array of material compatibility.

APPENDICES

APPENDIX A

Dimensional Results

Table 13. Wall Thickness Results – Conventional

	Conv DSC 1				Conv Bottle 2				Conv Bottle 1			
	9:00	6:00	3:00	12:00	9:00	6:00	3:00	12:00	9:00	6:00	3:00	12:00
1	0.0170	0.0309	0.0167	0.0317	0.0170	0.0294	0.0165	0.0321	0.0173	0.0332	0.0170	0.0295
2	0.0192	0.0256	0.0175	0.0261	0.0191	0.0231	0.0191	0.0254	0.0183	0.0253	0.0178	0.0257
3	0.0298	0.0298	0.0271	0.0325	0.0285	0.0278	0.0263	0.0314	0.0290	0.0294	0.0275	0.0317
4	0.0353	0.0318	0.0317	0.0340	0.0331	0.0298	0.0299	0.0326	0.0341	0.0309	0.0316	0.0334
5	0.0356	0.0317	0.0321	0.0336	0.0341	0.0297	0.0307	0.0317	0.0344	0.0303	0.0318	0.0329
6	0.0337	0.0293	0.0307	0.0310	0.0318	0.0280	0.0289	0.0298	0.0329	0.0284	0.0288	0.0310
7	0.0315	0.0285	0.0284	0.0301	0.0296	0.0270	0.0269	0.0295	0.0305	0.0280	0.0268	0.0304
8	0.0295	0.0271	0.0267	0.0287	0.0278	0.0254	0.0252	0.0282	0.0284	0.0264	0.0247	0.0274
9	0.0275	0.0259	0.0251	0.0272	0.0265	0.0248	0.0238	0.0266	0.0268	0.0248	0.0233	0.0262
10	0.0266	0.0245	0.0242	0.0253	0.0257	0.0245	0.0235	0.0252	0.0256	0.0241	0.0222	0.0254
11	0.0265	0.0229	0.0238	0.0241	0.0251	0.0229	0.0225	0.0233	0.0252	0.0226	0.0218	0.0241
12	0.0268	0.0232	0.0238	0.0239	0.0248	0.0222	0.0228	0.0241	0.0249	0.0223	0.0219	0.0241
13	0.0267	0.0226	0.0239	0.0235	0.0254	0.0227	0.0229	0.0232	0.0250	0.0220	0.0221	0.0233
14	0.0267	0.0250	0.0236	0.0255	0.0245	0.0251	0.0226	0.0267	0.0251	0.0246	0.0225	0.0258
15	0.0357	0.0327	0.0318	0.0329	0.0338	0.0339	0.0294	0.0352	0.0341	0.0231	0.0309	0.0349
16	0.0515	0.0460	0.0460	0.0475	0.0471	0.0436	0.0432	0.0457	0.0485	0.0460	0.0447	0.0490

Table 14. Wall Thickness Results – Fasti

Point	Fasti DSC 1				Fasti Bottle 2				Fasti Bottle 1			
	9:00	6:00	3:00	12:00	9:00	6:00	3:00	12:00	9:00	6:00	3:00	12:00
1	0.0164	0.0355	0.0163	0.0309	0.0171	0.0358	0.0163	0.0269	0.0173	0.0404	0.0157	0.0217
2	0.0177	0.0289	0.0180	0.0223	0.0180	0.0283	0.0181	0.0218	0.0189	0.0295	0.0186	0.0295
3	0.0284	0.0318	0.0265	0.0280	0.0273	0.0299	0.0244	0.0285	0.0316	0.0314	0.0244	0.0270
4	0.0333	0.0322	0.0317	0.0310	0.0331	0.0311	0.0289	0.0311	0.0315	0.0312	0.0293	0.0296
5	0.0344	0.0319	0.0336	0.0320	0.0335	0.0314	0.0320	0.0322	0.0315	0.0313	0.0308	0.0307
6	0.0344	0.0309	0.0334	0.0318	0.0331	0.0305	0.0312	0.0315	0.0306	0.0301	0.0302	0.0303
7	0.0338	0.0299	0.0325	0.0315	0.0321	0.0298	0.0307	0.0311	0.0296	0.0289	0.0293	0.0296
8	0.0333	0.0291	0.0308	0.0313	0.0309	0.0286	0.0298	0.0304	0.0286	0.0278	0.0280	0.0289
9	0.0335	0.0284	0.0301	0.0311	0.0304	0.0284	0.0293	0.0303	0.0282	0.0275	0.0273	0.0292
10	0.0315	0.0275	0.0291	0.0306	0.0297	0.0278	0.0288	0.0298	0.0277	0.0272	0.0268	0.0291
11	0.0301	0.0270	0.0273	0.0296	0.0293	0.0275	0.0283	0.0300	0.0271	0.0269	0.0258	0.0296
12	0.0291	0.0266	0.0271	0.0288	0.0292	0.0274	0.0280	0.0298	0.0265	0.0265	0.0253	0.0289
13	0.0285	0.0256	0.0275	0.0276	0.0294	0.0267	0.0272	0.0282	0.0258	0.0258	0.0257	0.0269
14	0.0295	0.0271	0.0270	0.0281	0.0281	0.0270	0.0264	0.0293	0.0275	0.0266	0.0254	0.0274
15	0.0317	0.0294	0.0296	0.0316	0.0306	0.0286	0.0284	0.0322	0.0287	0.0293	0.0293	0.0296
16	0.0441	0.0403	0.0407	0.0433	0.0420	0.0398	0.0401	0.0442	0.0409	0.0397	0.0380	0.0411

Table 15. Dimensional Test Results – Conventional

	H	E Avg.	E Diff.	E (P/L)	E (90° from P/L)	T	Diam Avg.	Diam Diff.	Diam (90° from P/L)	Diam (P/L)	B_V (mL)	B_F (g)	B_E (g)
	Conventional												
1	0.3670	0.9778	0.0056	0.9750	0.9806	1.0439	2.3918	0.0355	2.4095	2.3740	486.97	512.15	26.64
2	0.3713	0.9738	0.0120	0.9678	0.9798	1.0453	2.3903	0.0345	2.4075	2.3730	487.08	512.24	26.62
3	0.3660	0.9744	0.0084	0.9702	0.9786	1.0452	2.3908	0.0335	2.4075	2.3740	487.74	512.49	26.21
4	0.3670	0.9743	0.0148	0.9669	0.9817	1.0458	2.3904	0.0318	2.4063	2.3745	487.54	512.40	26.32
5	0.3614	0.9753	0.0086	0.9710	0.9796	1.0439	2.3935	0.0280	2.4075	2.3795	488.36	512.75	25.86
6	0.3630	0.9740	0.0184	0.9648	0.9832	1.0480	2.3923	0.0385	2.4115	2.3730	488.22	512.79	26.03
7	0.3601	0.9761	0.0133	0.9694	0.9827	1.0450	2.3943	0.0455	2.4170	2.3715	488.29	512.77	25.94
8	0.3633	0.9728	0.0156	0.9650	0.9806	1.0488	2.3978	0.0305	2.4130	2.3825	488.25	512.94	26.15
9	0.3591	0.9761	0.0118	0.9702	0.9820	1.0445	2.3940	0.0440	2.4160	2.3720	488.66	513.01	25.82
10	0.3640	0.9731	0.0208	0.9627	0.9835	1.0504	2.3920	0.0400	2.4120	2.3720	488.59	513.10	25.98
11	0.3622	0.9753	0.0089	0.9708	0.9797	1.0473	2.3933	0.0425	2.4145	2.3720	488.53	512.89	25.83
12	0.3594	0.9745	0.0208	0.9641	0.9849	1.0492	2.3928	0.0445	2.4150	2.3705	488.50	513.10	26.07
13	0.3611	0.9733	0.0017	0.9724	0.9741	1.0442	2.3933	0.0385	2.4125	2.3740	488.73	513.08	25.82
14	0.3645	0.9735	0.0162	0.9654	0.9816	1.0498	2.3923	0.0365	2.4105	2.3740	488.59	513.20	26.08
15	0.3609	0.9723	0.0061	0.9692	0.9753	1.0450	2.3953	0.0335	2.4120	2.3785	488.63	512.97	25.81
16	0.3603	0.9700	0.0100	0.9650	0.9750	1.0488	2.3963	0.0335	2.4130	2.3795	488.50	512.88	25.85
17	0.3639	0.9744	0.0110	0.9689	0.9799	1.0451	2.3915	0.0340	2.4085	2.3745	489.10	513.28	25.65
18	0.3643	0.9732	0.0183	0.9640	0.9823	1.0467	2.3980	0.0290	2.4125	2.3835	488.48	512.79	25.78
19	0.3637	0.9731	0.0045	0.9708	0.9753	1.0432	2.3935	0.0290	2.4080	2.3790	488.82	513.00	25.65
20	0.3591	0.9741	0.0116	0.9683	0.9799	1.0477	2.3943	0.0185	2.4035	2.3850	487.83	512.29	25.92

Table 16. Dimensional Test Results – Fasti

	Fasti	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
B_E (g)		28.10	28.44	28.52	28.51	28.24	28.57	28.31	28.55	28.29	28.63	28.27	28.55	28.28	28.50	28.38	28.53	28.34	28.54	28.32	28.36
B_F (g)		508.13	508.05	508.54	507.71	508.60	507.49	507.48	507.94	507.49	507.17	508.15	507.25	507.10	506.82	507.19	506.80	507.38	507.01	507.65	507.88
B_V (mL)		481.47	481.05	481.46	480.64	481.81	480.36	480.61	480.83	480.64	479.98	481.32	480.14	480.26	479.76	480.25	479.71	480.48	479.91	480.77	480.96
Diam (P/L)		2.3855	2.3795	2.3875	2.3830	2.3945	2.3885	2.4085	2.3900	2.3930	2.3955	2.3995	2.3880	2.3925	2.3965	2.3950	2.3930	2.4045	2.3935	2.3940	2.3975
Diam (90° from P/L)		2.3865	2.3855	2.3860	2.3870	2.3935	2.3930	2.3870	2.3990	2.3975	2.3915	2.3860	2.3870	2.3865	2.3960	2.3820	2.4050	2.3850	2.3945	2.3950	2.3870
Diam Diff.		0.0010	0.0060	0.0015	0.0040	0.0010	0.0045	0.0215	0.0090	0.0045	0.0040	0.0135	0.0010	0.0060	0.0005	0.0130	0.0120	0.0195	0.0010	0.0010	0.0105
Diam Avg.		2.3860	2.3825	2.3868	2.3850	2.3940	2.3908	2.3978	2.3945	2.3953	2.3935	2.3928	2.3875	2.3895	2.3963	2.3885	2.3990	2.3948	2.3940	2.3945	2.3923
T		1.0460	1.0352	1.0428	1.0412	1.0396	1.0371	1.0362	1.0423	1.0446	1.0354	1.0438	1.0406	1.0394	1.0400	1.0382	1.0440	1.0356	1.0319	1.0356	1.0353
E (90° from P/L)		0.9602	0.9662	0.9696	0.9619	0.9624	0.9538	0.9626	0.9573	0.9520	0.9658	0.9665	0.9687	0.9617	0.9583	0.9630	0.9487	0.9665	0.9699	0.9666	0.9693
E (P/L)		0.9782	0.9640	0.9789	0.9717	0.9719	0.9719	0.9674	0.9733	0.9780	0.9643	0.9611	0.9605	0.9717	0.9720	0.9717	0.9744	0.9649	0.9587	0.9675	0.9615
E Diff.		0.0180	0.0022	0.0093	0.0098	0.0095	0.0181	0.0048	0.0160	0.0260	0.0015	0.0054	0.0082	0.0100	0.0137	0.0087	0.0257	0.0016	0.0112	0.0009	0.0078
E Avg.		0.9692	0.9651	0.9743	0.9668	0.9672	0.9629	0.9650	0.9653	0.9650	0.9651	0.9638	0.9646	0.9667	0.9652	0.9674	0.9616	0.9657	0.9643	0.9671	0.9654
H		0.3529	0.3519	0.3664	0.3576	0.3583	0.3550	0.3524	0.3511	0.3538	0.3568	0.3590	0.3584	0.3528	0.3511	0.3513	0.3605	0.3527	0.3526	0.3534	0.3532

Figure 18. Conventional Wall Thickness 1

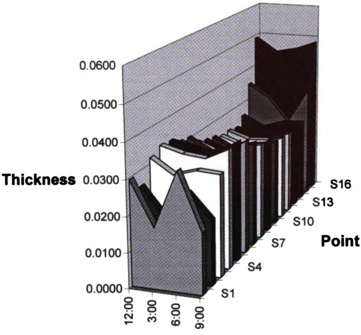


Figure 19. Conventional Wall Thickness 2

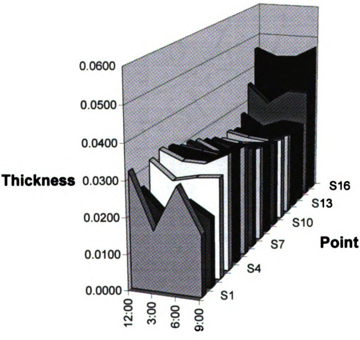


Figure 20. Conventional Wall Thickness 3

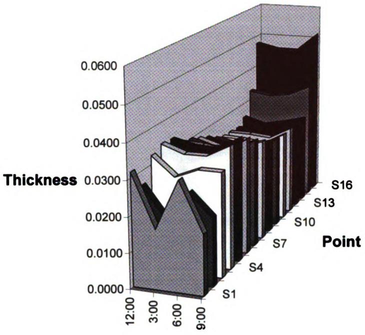


Figure 21. Fasti Wall Thickness 1

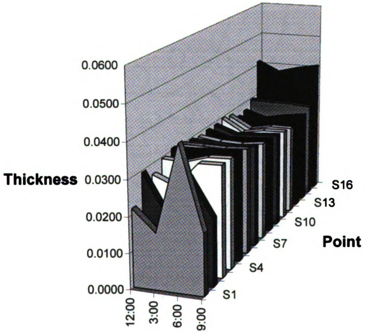


Figure 22. Fasti Wall Thickness 2

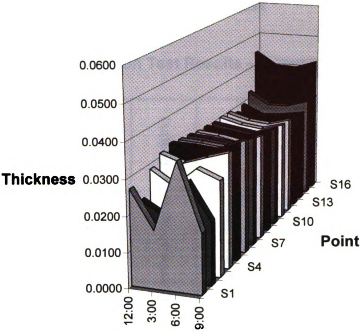
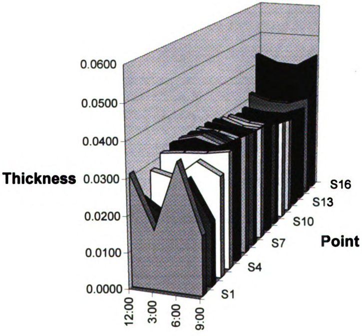


Figure 23. Fasti Wall Thickness 3



APPENDIX B

Compression Test Results

Table 17. Compression Test Results – Conventional

	Specimen Weight (g)	Crushing Yield Load (lb.)	Deflection at Crushing Yield Load(in.)	Load on Straight Line	Deflection on Straight Line	Apparent Crushing Stiffness (lb./in.)
Conventional						
1	26.50	77.5	0.299	50.1	0.116	431.90
2	26.56	76.9	0.299	50.5	0.120	420.83
3	25.93	70.4	0.304	50.7	0.129	393.02
4	26.09	71.6	0.295	50.1	0.120	417.50
5	25.81	67.9	0.295	50.1	0.129	388.37
6	25.89	68.1	0.295	50.9	0.129	394.57
7	25.72	68.3	0.304	49.8	0.129	386.05
8	25.85	71.0	0.303	50.4	0.129	390.70
9	25.80	69.6	0.291	50.5	0.124	407.26
10	25.88	72.7	0.316	50.9	0.129	394.57
11	25.39	70.3	0.295	50.8	0.129	393.80
12	25.96	69.6	0.291	51.1	0.124	412.10
13	25.64	68.0	0.291	49.9	0.124	402.42
14	26.03	75.4	0.303	50.5	0.120	420.83
15	25.76	73.8	0.295	50.3	0.120	419.17
16	25.75	74.3	0.291	50.3	0.120	419.17
17	25.73	74.1	0.299	50.0	0.120	416.67
18	25.84	77.5	0.307	51.1	0.120	425.83
19	25.65	74.5	0.299	49.9	0.120	415.83
20	25.81	73.0	0.299	50.1	0.116	431.90
Xbar	25.8795	72.2	0.2986	50.4	0.123	409.1243
s	0.2686	3.2	0.0064	0.4	0.005	14.9418

Table 18. Compression Test Results – Fasti

	Specimen Weight (g)	Crushing Yield Load (lb.)	Deflection at Crushing Yield Load(in.)	Load on Straight Line	Deflection on Straight Line	Apparent Crushing Stiffness (lb./in.)
Fasti						
1	28.41	74.7	0.274	60.6	0.170	356.4706
2	28.15	74.2	0.265	59.6	0.166	359.0361
3	28.3	76.7	0.253	60.1	0.149	403.3557
4	28.21	76.6	0.278	61.0	0.166	367.4699
5	28.37	77.9	0.286	60.4	0.162	372.8395
6	28.19	76.5	0.270	60.2	0.149	404.0268
7	28.36	77.1	0.278	59.7	0.157	380.2548
8	28.16	76.5	0.278	60.0	0.157	382.1656
9	28.32	76.3	0.274	60.4	0.161	375.1553
10	28.14	76.0	0.265	60.3	0.162	372.2222
11	28.32	76.3	0.274	60.2	0.157	383.4395
12	28.18	74.6	0.261	62.6	0.178	351.6854
13	28.33	75.6	0.261	60.5	0.166	364.4578
14	28.19	74.9	0.282	59.9	0.166	360.8434
15	28.33	79.6	0.257	62.9	0.178	353.3708
16	28.14	73.8	0.270	60.9	0.174	350
17	28.23	74.8	0.278	60.8	0.161	377.6398
18	28.38	79.4	0.278	61.3	0.161	380.7453
19	28.25	76.6	0.265	60.6	0.166	365.0602
20	28.07	74.2	0.274	59.8	0.161	371.4286
Xbar	28.2515	76.1	0.271	60.590	0.163	371.5834
s	0.098102	1.6	0.009	0.862	0.008	15.09633

APPENDIX C

BEKUM

H-111S

Extrusion Blow Molding Machine

Operations Manual

Contact Dr. Harold Hughes for assistance

This Machine Was Supplied By:

Bekum America

1140 W. Grand River

Williamston, Michigan 48895

(517) 655-4331

Bekum Blow Molder Operating Instructions

Service Personnel: John, Lee, Jose (517) 655-4331

<u>These instructions were developed by School pf Packaging personnel, not taken from the Bekum Manual</u>

<u>Safety</u>

This machine operates with components in excess of ***350 degrees Fahrenheit*** and can cause severe burns. While advanced safety mechanisms prevent pinching accidents, they *do not protect you from hot surfaces, hot plastic, and the sharp cutting knife*. Please be careful and stay out of the Yellow cabinet while the machine is on or still hot. Plastic parts remain hot even after coming out of the mold.

If extra extrusion or bottles become wrapped around machine components please do your best to carefully remove them before they set to prevent malfunctions and messes.

<u>Startup</u>

1) Retrieve key from electrical cabinet (Large Tan Doors)
   a) Unlock Padlock
   b) Use Screwdriver to turn catch above door handle
   c) Retrieve Key and place in lock on front panel
   d) Close doors and replace lock

i) Note: Electrical power handles must be aligned to "OFF" position to close doors

2) Turn on Both Power Handles marked "230V" and "460V"
   a) Controller Display will activate and display
      i) Model Number
      ii) Serial Number
      iii) Controller Number
3) Turn on Water Supply on wall marked "Bekum Water"
   a) Turn knob Counter-Clockwise to turn on
   b) Turn on both yellow water valves inside yellow cabinet to the right of blow pin
      i) Yellow levers will be parallel to pipes when on
   c) You will see and hear water running through the system and into the drain near the wall
4) Use Yellow arrows to move cursor to security code (green box will flash)
   a) Type in security code
      i) Level 1 – Default: code 1, press [Enter](yellow button)
      ii) Level 2 – code 5566, press [Enter]
      iii) Level 3 – code 5455, press [Enter]
5) Press button under Blue box Labeled [Main Menu]
   a) Displays general information about machine status
6) Press [Temp 1-11 Monitor]

a) "SP1"(set point one) temperatures are the required operating temperatures

7) Pull Red "Emergency Stop" knob out to "On" position

8) Press "Control Power" White button (will light up)

9) Start Hydraulics

   a) Red Handle on reservoir (near rear of machine on wall-side) must be horizontal to start pump.

   b) Press Black [HYDR MOTOR ON] Button on control panel

   c) You will hear hydraulic pump start up

***CRITICAL: It takes at least 1.5 hours to heat up the machine regardless of temperature readings. This time is required for heat to soak through plastic in extruder, which will have solidified in the barrel.

<u>If you attempt to operate the machine before this soak-down time you **WILL** break the extruder screw causing a lot of damage! PLEASE be patient.</u>***

10) Watch Temperature monitors to see that all temperatures are up to their setpoints

   a) It takes 1.5 hours for plastic and machine components to heat up

   b) It takes around 45 minutes (With the Hydraulic motor running!) to heat up the hydraulic oil

   c) The Flashing Strobe light on top of the machine will stop flashing once the machine is up to temperature

i) The strobe will not indicate if the plastic in the screw is melted

11) Keep resin hopper full to avoid running out of resin. The hopper must be manually filled. Do not allow debris to enter the hopper, metal shavings will be sorted out but paper and other items will go through extruder and either burn or end up in a bottle.

Operation

1) Manual Operation
   a) Note: Security code must be set above 1
   b) Turn Key Switch to "MAN" (Manual)
   c) Remove the leather cover from the cut knife
   d) Turn on Hydraulic Pump
      i) Set Red Lever near rear of machine to vertical
   e) Press Black [Manual Mode] Key
   f) Press key for the function you want to control ([Knife], [Blow Pin], [Carriage], or [Mold])
      i) Key will light green
   g) Control the function with the yellow Pendant
   h) To change functions
      i) Press the key for the function you want to control
         (1) Key will light green
      ii) Press the key for the function you were previously using
         (1) Green light on key will turn off

i) Only one function may be used at a time

2) Automatic Operation (Bottle Making)

   a) Turn Key Switch to "MAN"

   b) Remove the leather cover from the cut knife

   c) Press Black [Manual Mode] Key

   d) Turn on Hydraulic Pump

      i) Set Red Lever near rear of machine to vertical

   e) Press [Extruder Start] Key

   f) Press [FWD] on Baldor Motor drive

      i) This will start the extruder turning

      ii) You will hear some popping or cracking as air escapes, this is ok

   g) Press Yellow key with Up arrow [▲] to increase extruder speed to about "48.00 SCRU"

   h) Trim off extrusion with manual mode knife (cut from right to left) as extruder comes up to speed

   i) Turn Key Switch to "Auto"

   j) Press Black [Auto Mode] Key

   k) Yellow [Move To Basic] Key will flash, press it

   l) Black [Cycle Start] Key will flash, Press it

   m) Bottles will be made

   n) Press red [Cycle Stop] key to stop system

   o) Press Red [STOP] key on Baldor drive to stop extruder

   p) Trim excess extrusion with manual mode knife (cut from right to left)

Operating Notes

1) If you must enter the yellow cabinet, pull the door firmly and quickly to avoid shutting off the hydraulic pump and having to reset Red handle to horizontal, etc.
2) Opening any doors during operation will initiate safety shut-downs. I.E. Pulling open the yellow cabinet doors during operation will stop all motion in cabinet and leave you with a mess of melted plastic
3) Formed bottles are HOT and should not be handled immediately after forming, especially the top and bottom flashing.

Shut Down

1) Turn off both Water Supply valves inside yellow cabinet (levers perpendicular to feed lines
2) Return leather cover to cut knife
3) Turn off water supply knob on wall behind machine
4) Turn off hydraulic motor [HYDR. MOTOR OFF]
5) Return Red Hydraulic Pump lever to Horizontal
6) Press Red "Emergency Stop" Button
7) Turn Key to "OFF"
8) Turn off both Power Handles marked "230V" and "460V"
9) Return key to electrical cabinet (Large Tan Doors)
   a) Unlock Padlock

b) Use Screwdriver to turn catch above door handle

c) Return Key

d) Close doors and replace lock

    i) Note: Electrical power handles must be aligned to “OFF” position to close doors

APPENDIX D

Blow Pin Drawings

Figure 24. Assembly Drawing

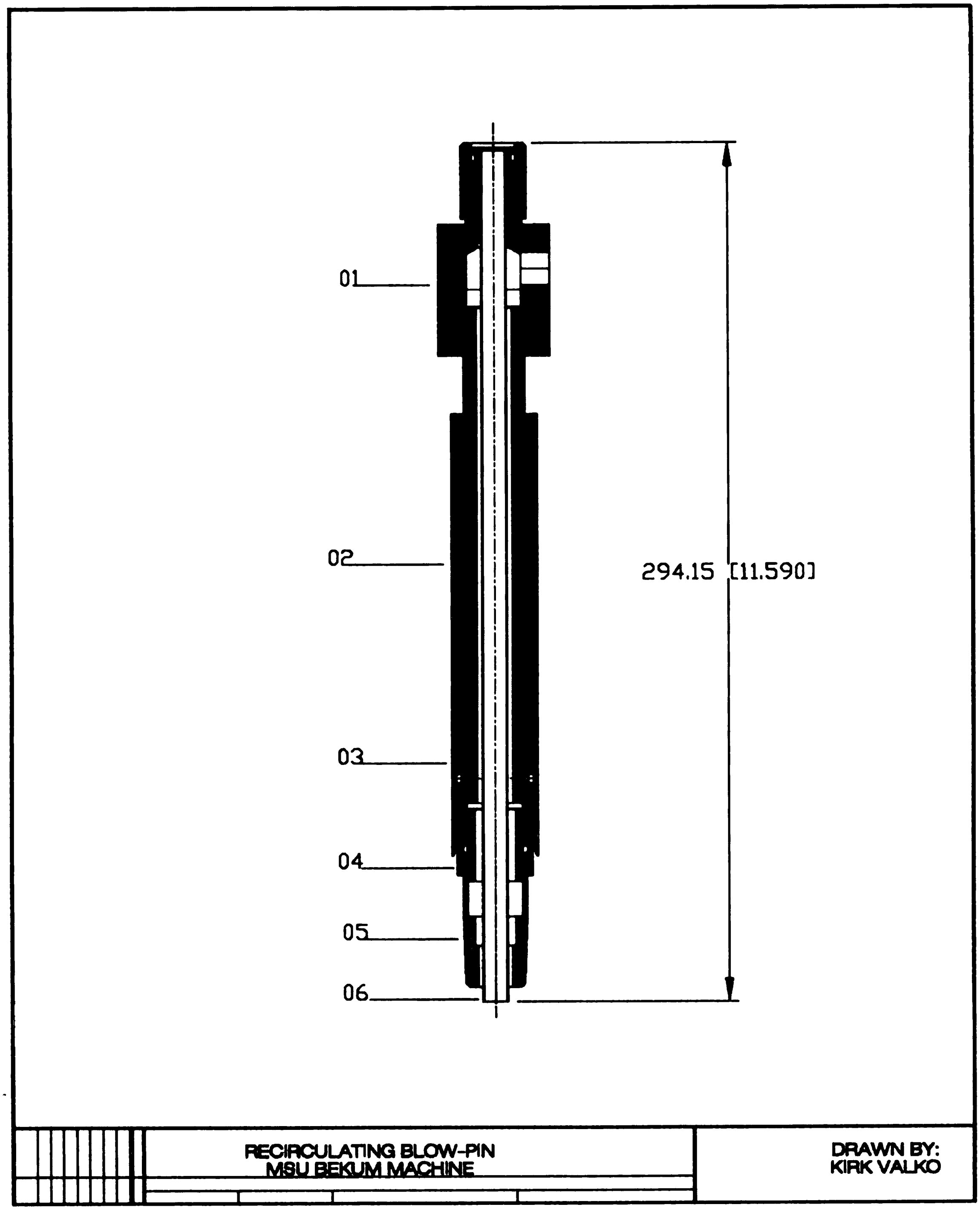


Figure 25. Detail 01 – Adaptor

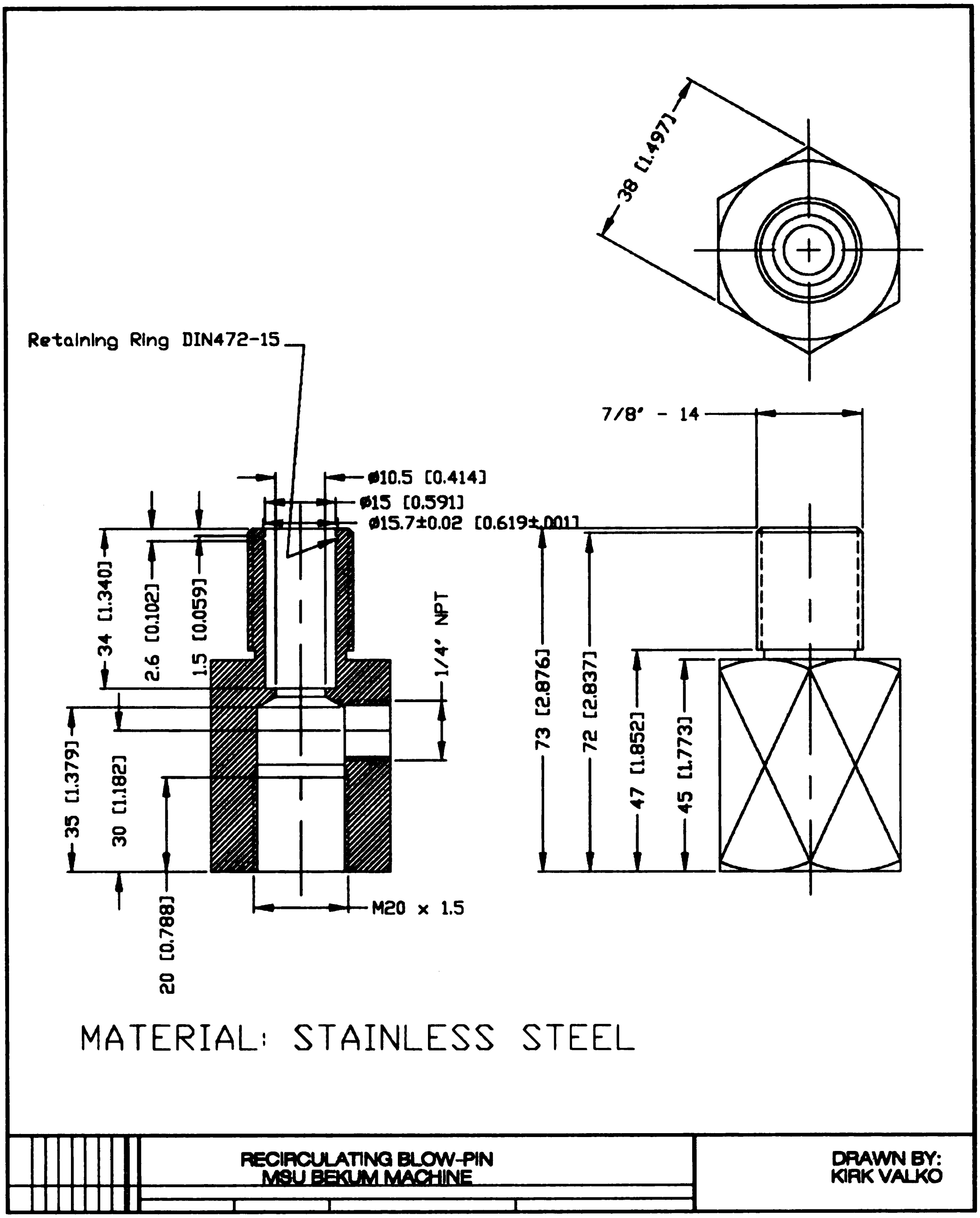


Figure 26. Detail 02 - Stem

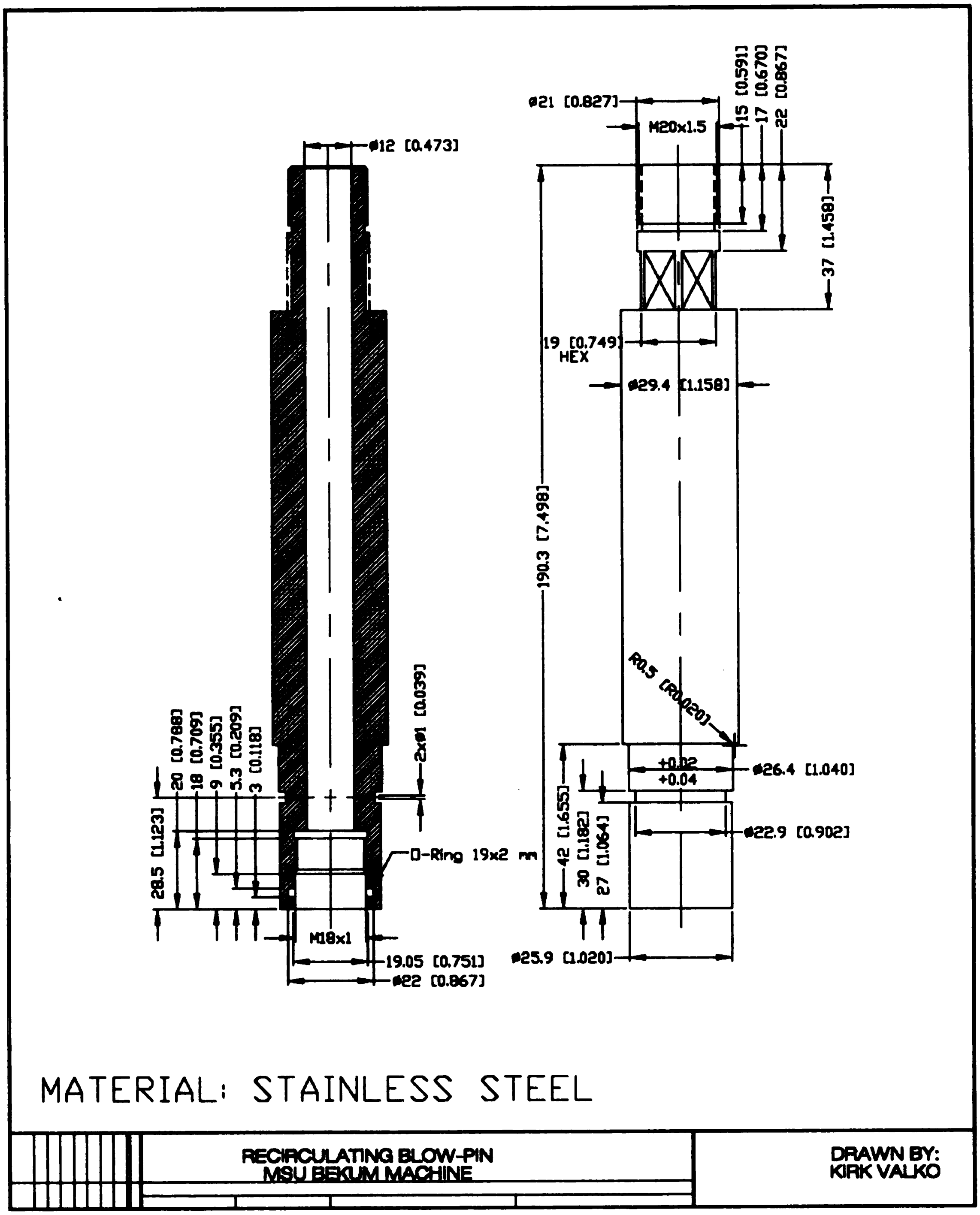


Figure 27. Detail 03 - Cooling Sleeve

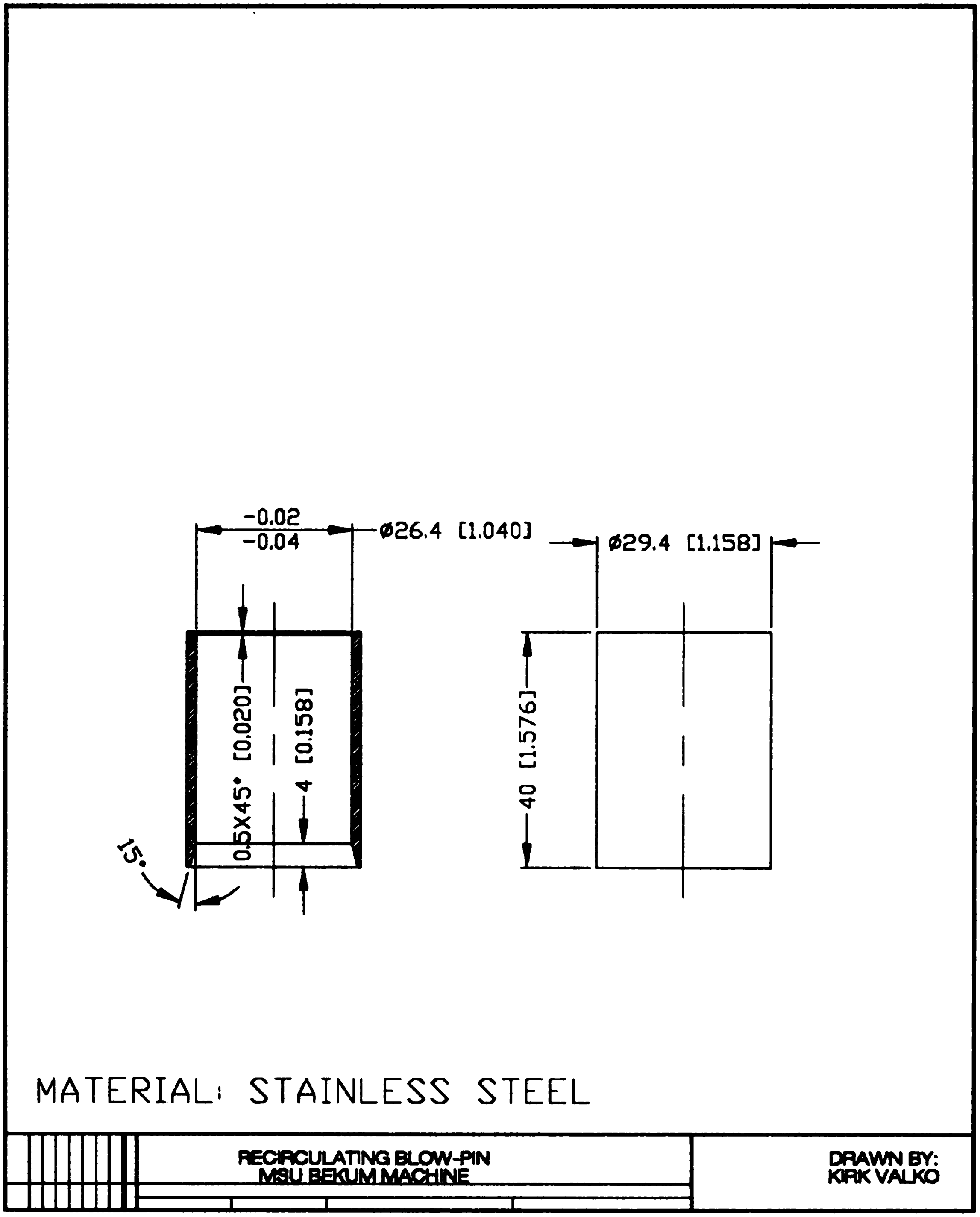


Figure 28. Detail 04 - Cutting Ring

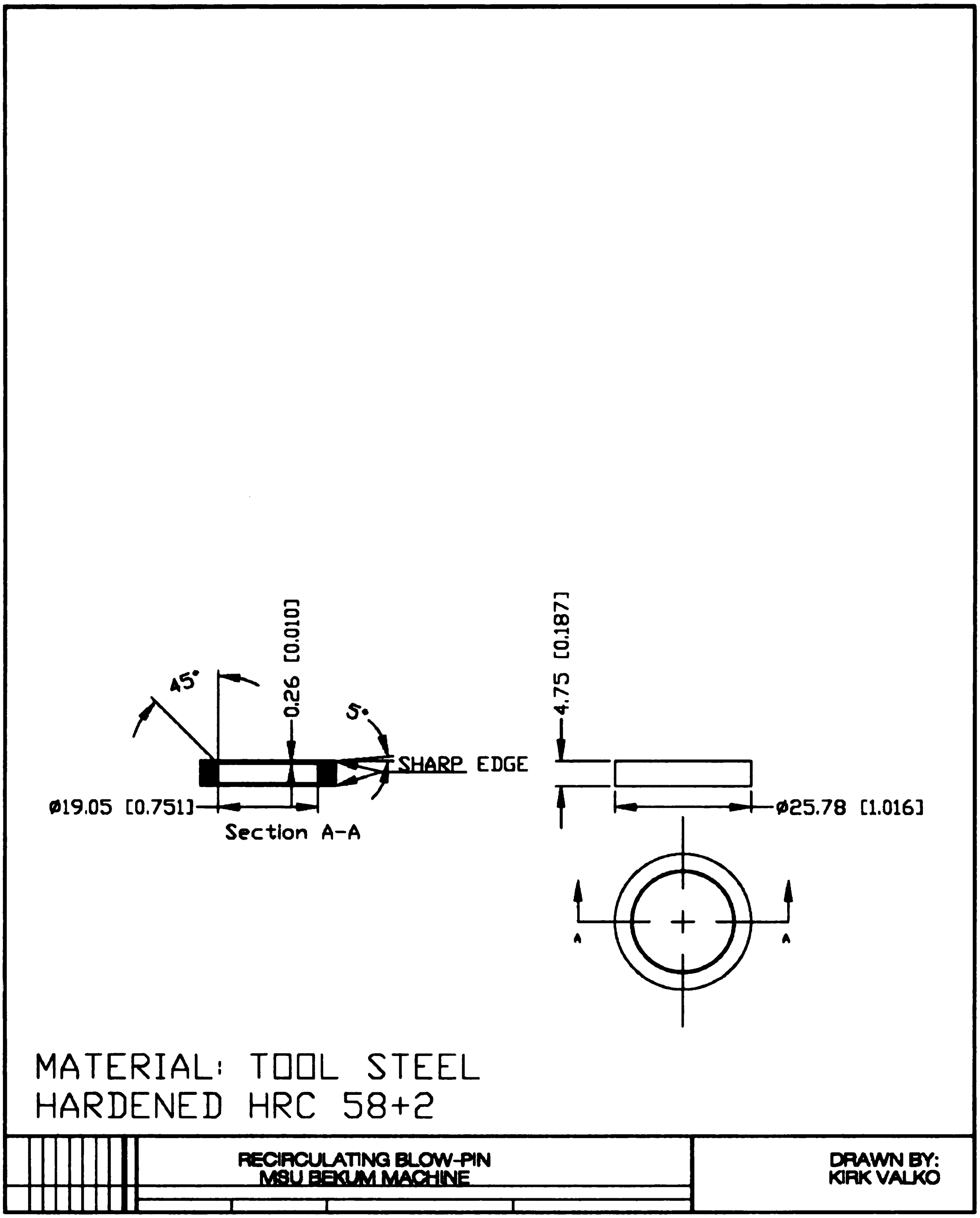


Figure 29. Detail 05 - Tip

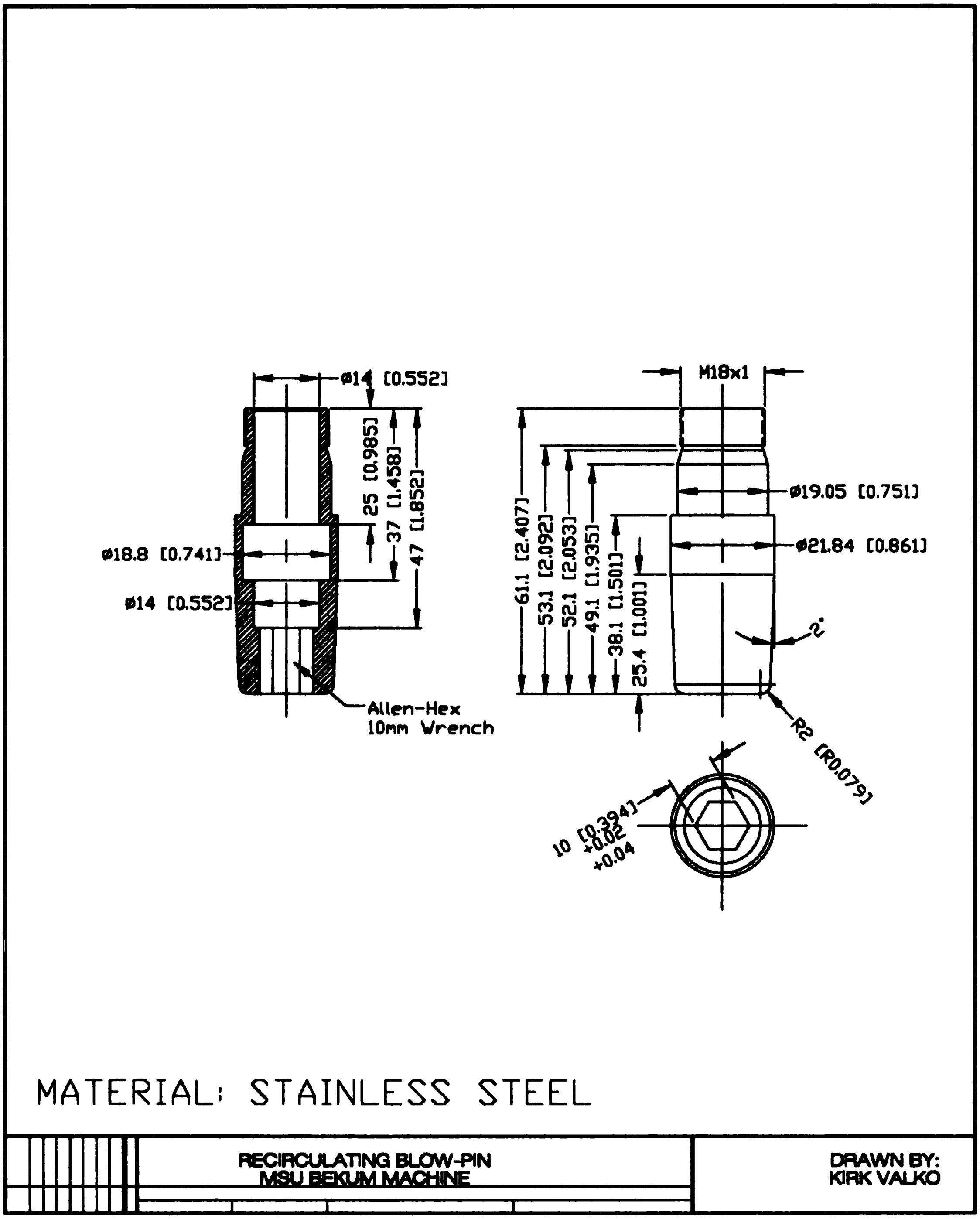
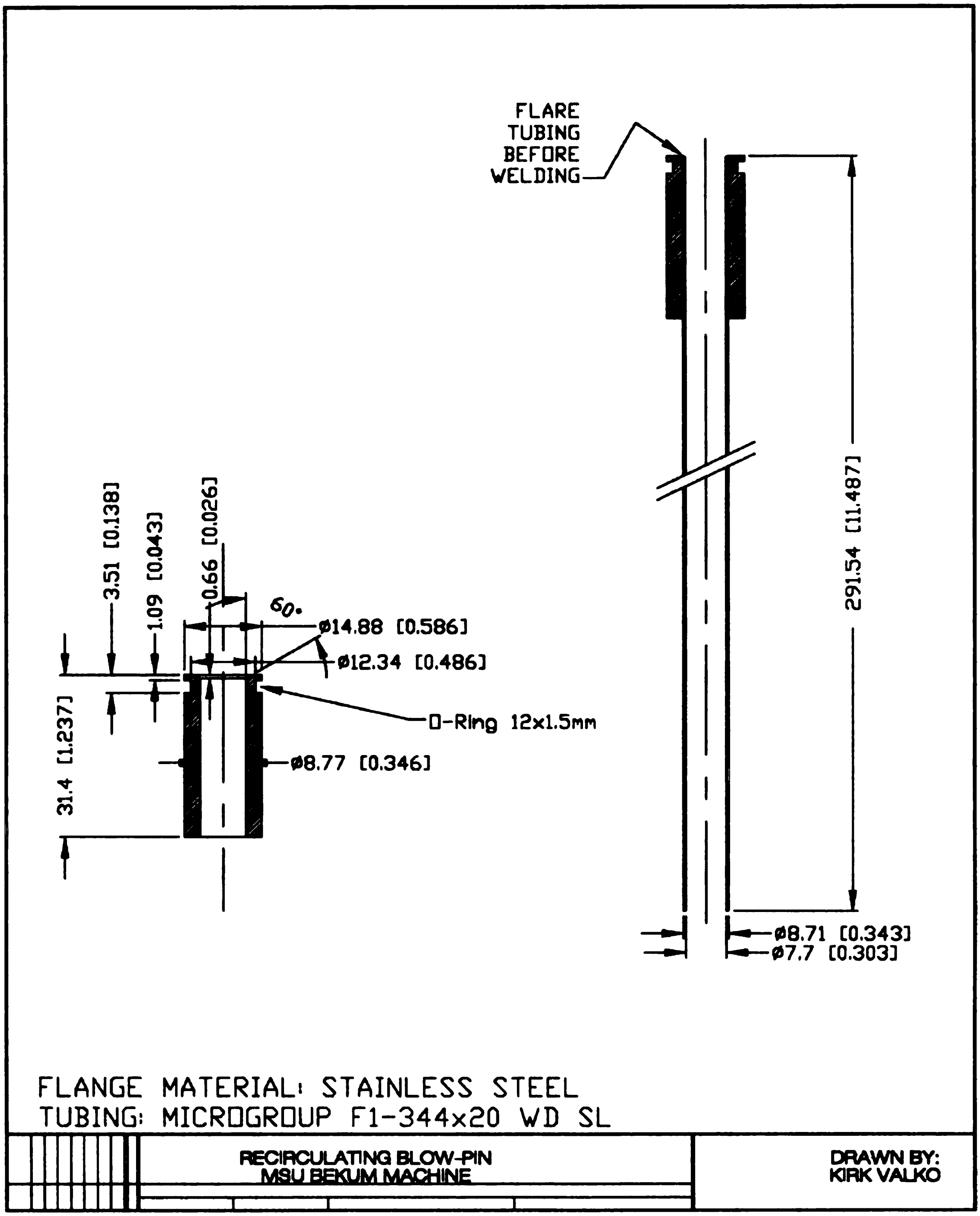


Figure 30. Detail 06 - Pipe



APPENDIX E

Fasti Setup Experiment

Effect of Timings and Air Pressure on an Extrusion Blow Molding Process

A 2_V^{5-1} Factorial Experiment

Introduction

Optimizing an extrusion blow molding machine is a complicated and in depth process which involves many variables, all of which contribute to the final quality of the produced part. In packaging it is important to take into consideration the size of the produced part as it directly affects the capacity of the containers. Containers are often filled with product using level filling, where a machine detects the depth of the product in the container. This is the quickest method for filling and gives the customer the most satisfaction seeing that each container is filled to the same amount. However, a more accurate approach is to fill a container by volume, making it much easier for the producer to meet legislation requiring a product be filled within certain tolerances of the stated capacity. In order to maintain container volume and account for shrinkage of the container after leaving the mold, we must develop a machine setup which minimizes shrinkage and maintains consistency between containers.

Experimentation

The experiment involves 5 two-level factors in a 2_V^{5-1} factorial design.

The Factors are as follows:

A: Fasti Delay – The amount of time the bottle is given to inflate in the mold before cooling operation starts.

B: Back Pressure – The amount of internal pressure maintained in the bottle during the cooling process

C: Blow Time – The amount of time the air is blow into the bottle to maintain contact with the mold and cool from the air

D: Exhaust Time – The amount of time that the bottle is given to sit in the mold to finish setting without pressurization

E: Air Pressure – The amount of air pressure being blown into the container for cooling

Response Variable: Container volume measured by weighing the empty bottle, filling the bottle with water, weighing it full and then calculating the volume in mL.

Each of the 16 experiments was run with 3 repetitions giving a total of 48 data points. Each run was done in random order with the appropriate machine settings adjusted for the new run.

Data Analysis

Figures 31, 32, and 33 are effects plots for the experimental data. The estimated effects are in line with expectations. Blow Time (C) and Air Pressure (E) are the variables which have the most effect on bottle shrinkage. As blow time increases, bottle volume increases. This is due to the extended amount of time the plastic has to cool and therefore set to counteract shrinkage. As blow pressure increases, bottle volume also increases. This is due to the increased air flow created by the higher pressures. The more air that passes through the bottle, the faster the container will cool therefore setting the bottle shape and counteracting shrinkage.

It is also seen that Factors A, B, and D have small main effects on the bottle quality. The estimates of main effects and the interactions CD and CE discussed below suggest that Factors C and E should be set at their high values with Factors A, B and D set at their low values for the optimal setup (to maximize volume). With Fasti delay and Exhaust time set low, we are able to shave nearly 1 second off of the total cycle time. Also the lower back pressure allows more transfer of air inside the container allowing faster cooling.

The significance of the CD and CE interactions is unknown. These are small effects compared to the main effects of C. I believe that blow time may cause instability on the air pressure in the container. By rights exhaust time should have little effect on the bottle properties especially since the time is so short.

These interactions are likely magnified by the intensity of the effect that blow time has on container volume.

Figure 31. Main Effects Plot for Factors

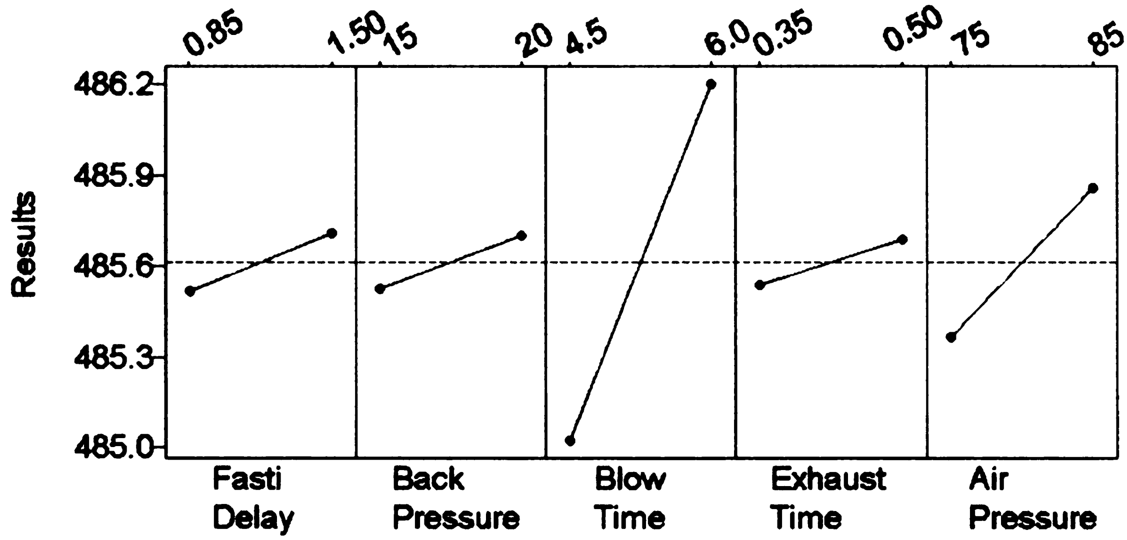


Figure 32. Normal Probability of Factors

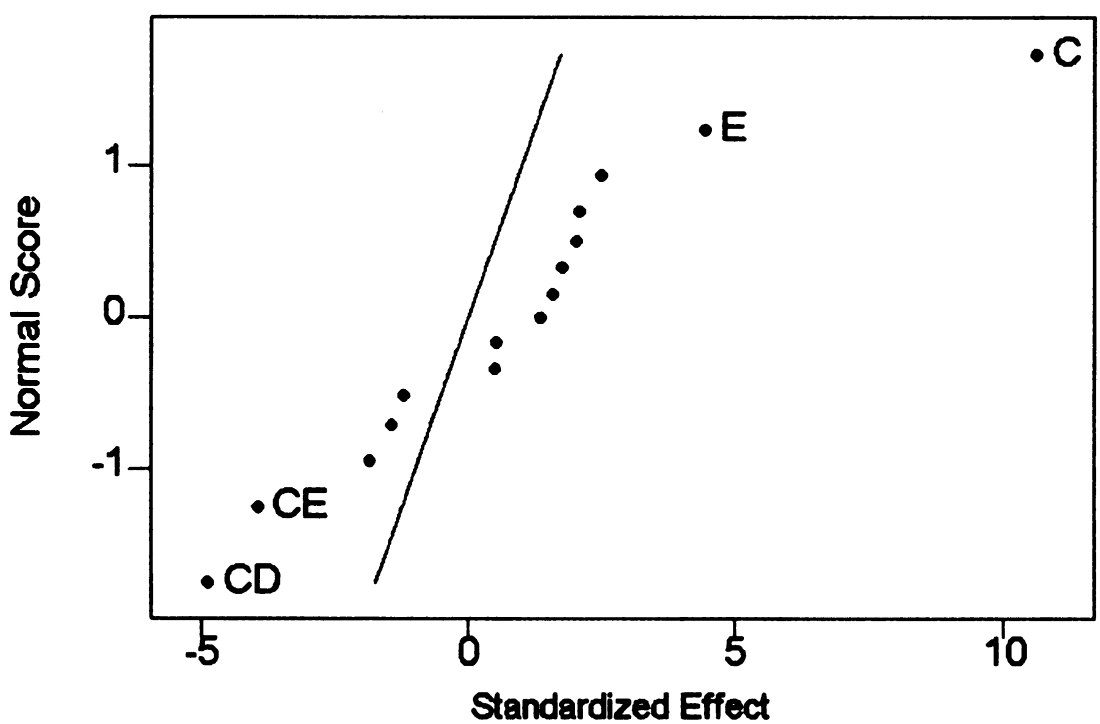
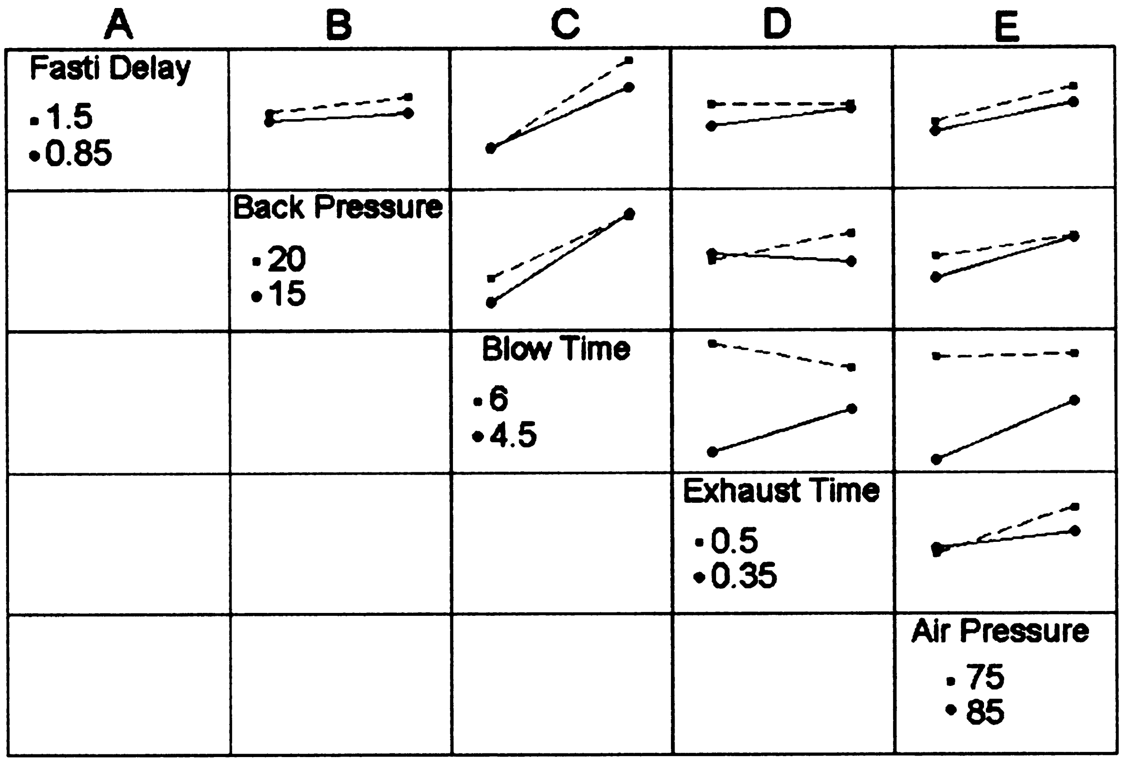


Figure 33. Plots of Interactions Between Factors



BIBLIOGRAPHY

ASTM Standard D2463-95. (1995). Standard Test Method for Drop Impact Resistance of Blow-Molded Thermoplastic Containers. Annual Book of ASTM Standards. vol 8.02. West Conshohocken, PA: ASTM International.

ASTM Standard D2659-95. (1995). Standard Test Method for Column Crush Properties of Blown Thermoplastic Containers," Annual Book of ASTM Standards. vol 8.02. West Conshohocken, PA: ASTM International.

ASTM Standard D2911-94. (1994). Standard Specification for Dimensions and Tolerances for Plastic Bottles. Annual Book of ASTM Standards. vol 8.02. West Conshohocken, PA: ASTM International.

ASTM Standard D3417-99. (1999). Standard Test Method for Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimetry (DSC). Annual Book of ASTM Standards. vol 8.02. West Conshohocken, PA: ASTM International.

Belcher, Samuel L. (1999). Practical Extrusion Blow Molding. NY: Marcel Dekker, Inc.

Ernst and Young. (2002). 2002 Global Packaging Report – The Top 100 Players.

Fasti USA Website. (2004). Internal Cooling for the Blow Molding Industry. <http://www.fastiusa.com/product3.php>

Freedonia Group. (2002). U.S. Plastic Container Demand. Plastics News.

Hernandez, Selke, and Culter. (2000). Plastics Packaging: Properties, Processing, Applications, and Regulations. Cincinnati, OH: Hanser Gardner Publications.

Lee, Norman C. (1990). Plastic Blow Molding Handbook. NY: Van Nostrand Reinhold.

Packaging Manufacturing Machinery Institute. (2003). 2003 U.S. Productivity & Profitability Trends Indicator Study Executive Summary. PMMI Publishing.

Rosato, Rosato, and DiMattia. (2004). Blow Molding Handbook. Cincinnati, OH: Hanser Gardner Publications.

Selke, S. and Xiong, L. (2003) PKG 829 Lab 3 Determination of Percent Crystallinity of Polyethylene by the Density Gradient and Differential Scanning Calorimetry.

Sichina, W.J. (2000). DSC as Problem Solving Tool: Measurement of Percent Crystallinity of Thermoplastics. <www.perkinelmer.com>

Sichina, W.J. (2000). Application of DSC to Injection Molding. <www.perkinelmer.com>

Society of Plastics Industry. (2003). U.S. blow molding equipment sales (2002-1Q 2003). Plastics News.