Technical Paper

Current Problems In The Wax Room And How They Are Best Overcome

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Jeffrey Rich
MPI, Inc.

Aaron Phipps
MPI, Inc.

Andrew Miller
Tech Cast, LLC

Andrew Bomberger
Tech Cast, LLC

Abstract

MPI has conducted a customer survey to determine what problems investment casting foundries are experiencing in their wax rooms. This paper provides the details of that survey. We have analyzed the results to determine, by industry served, what are the most common defects in the wax room. Tech Cast, LLC was one of the foundries that responded to our survey and agreed to allow testing on their equipment to evaluate the defects, conduct troubleshooting (optimization) and ultimately mitigate the defect. The corrective action(s) necessary to resolve the issues are explained as well as the outcome of making the needed process changes. Where applicable, the ICI *Atlas of Wax Pattern Defects*, as well as the ICI *Process Control Course Materials* are referenced. MPI's *Wax-room Operator and Advanced Operator Training* also served as a guideline for the appropriate optimization theory.

It is our experience that the correct application of process controls and capable equipment addresses wax-room defects. High level control capabilities, combined with training on how to properly troubleshoot defects and a good understanding of how to modify current processes will mitigate or even eliminate the defects leading to increased productivity and decreased scrap.

Introduction

For this year's ICI show, we wanted to find a topic that has relevance to all investment casting foundries and may potentially help solve problems that they face on a daily basis. To do this, we needed to understand exactly what the foundries' issues are as they relate to the wax room. We had our thoughts, based on years of experience dealing with foundries, making wax injectors, using wax injectors and the generally accepted faults known to exist in the wax room. Our goal was to validate our beliefs in a manner that left no doubt that the issues found and described were true wax-room issues that cause defects. We did not want to rely solely on experience, supposition or theory. To do that, a foundry survey was conducted. The survey results were then used to determine the most common defects. One of the respondent foundries, Tech Cast, LLC volunteered to be part of the balance of the project and served as the test site whereby experiments were conducted to validate appropriate corrective actions to mitigate or eliminate the defects. The survey and experiment results are contained within this document. The results are analyzed and put to the test. Did we actually make any improvements? You will have to read the paper to find out.

The Survey

A web-based survey was conducted asking foundries to provide a listing of their top wax-room issues. Sixty-five foundries responded to the survey providing insight into their respective problem areas and the defects most experienced. While the survey provided no surprises, it was important to validate wax-room issues directly from the foundries actual experiences. The results, as shown in figure 1, were in line with what we had anticipated they would be. Overall, the top three issues were related to:

1) Flow or knit lines
2) Sink, Cavitation, Shrinkage
3) Trapped Air

Minor differences by industry were observed and below, in figure 1, are Pareto charts illustrating the various defects noted by the foundries. Each foundry was specifically asked, "What are the top 5 problems that you are facing in your wax room that you wish you had a solution for TODAY?" A checklist of 22 known issues was provided along with a space to write in any comments. The data was collated to determine the most prevalent issues.

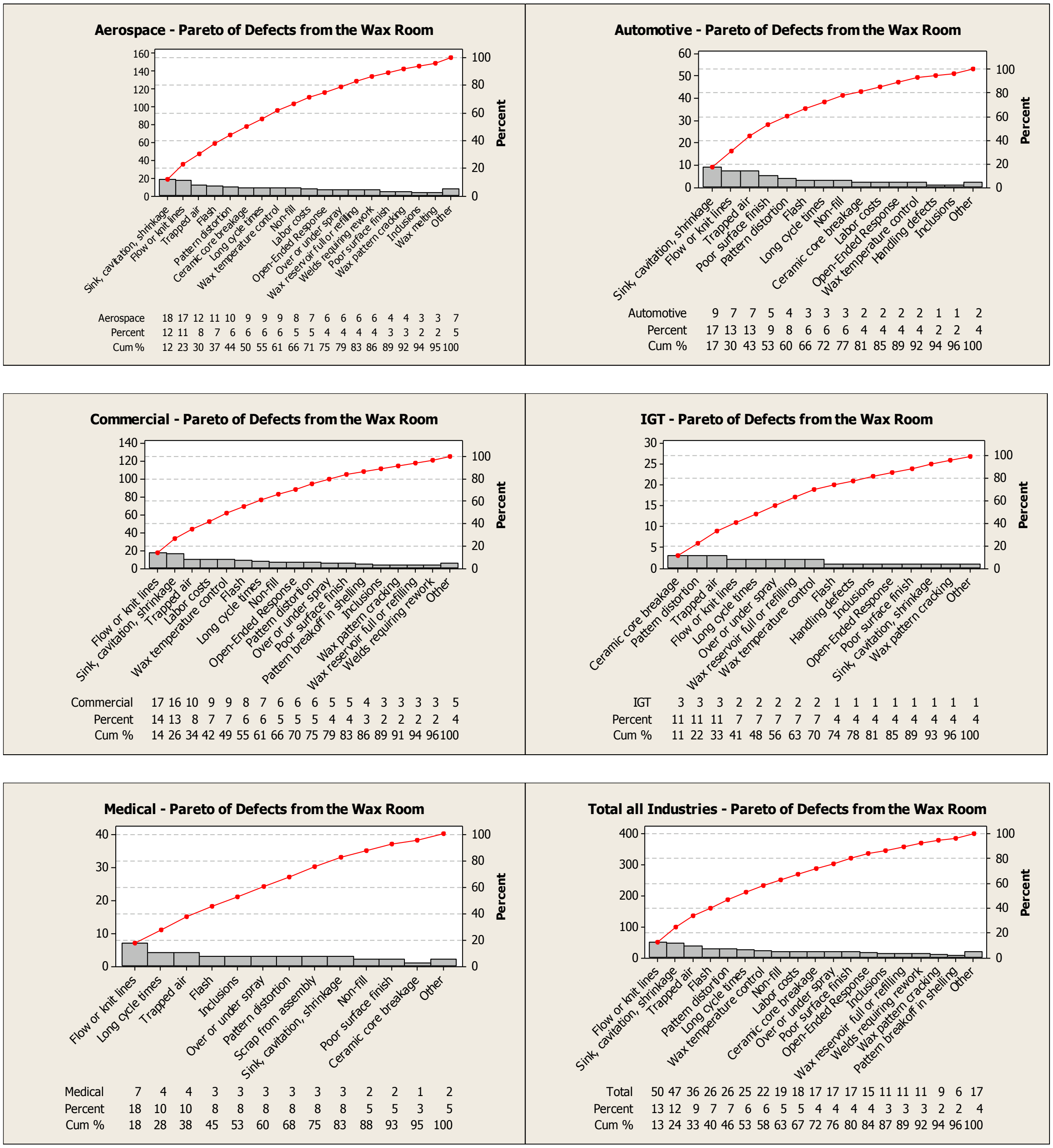


Figure 1: Industry Survey Results

Experiment Plan

With the survey results and a partner to move forward with, the next step was to design an experiment that could put the results to the test. The collaborative team had to determine an effective method to mitigate or eliminate the negative effects of the defects identified as the top offenders in the survey. It was determined that the foundry would select two problematic dies that exhibited at least one of the top three defects. The dies would be injected on the foundry's presses using the established recipe such as temperatures, pressure, flow and cycle time. Multiple injections would be conducted in a production manner with data from each injection being captured on a portable injection graphing unit. The injection graphing unit measures, records and displays real-time wax temperature, wax pressure and wax flow from any wax injector. The injection results are saved as CSV files for later analysis as well as graphed for real-time evaluation.

For each die/machine selected, the following experimental data would be collected and acted upon:

1) Conduct 40 injections using the foundry's selected die, machine, wax and recipe. Capture injection data on the injection graphing unit to help with item 3 below real-time evaluation of graphing and CSV files for later review.

2) Evaluate each pattern for quality and document the inspection results.

3) Make injection parameter adjustments to improve pattern quality using data obtained from the injection graphing unit, consulting the ICI *Atlas of Wax Pattern Defects* and practical experience.

4) Conduct die optimization based on item 3 above. After optimization, conduct another 40 injections collecting the injection data on the injection graphing unit.

5) Again, evaluate each pattern for quality and document the inspection results in the same manner as item 2 above.

The results of the experiment are then analyzed and the appropriate conclusions drawn and presented.

Conducting the Experiment

It was very interesting to find just how hard a simple test plan could be when conducted on old, modified and heavily used equipment. Issues we did not anticipate made the die optimization more complex, which lead to additional testing conducted on a new injection machine. More on that to follow.

The experiment was conducted with two different dies on two different machines. Die 1 is a six cavity automated die running pattern wax on an automatic horizontal four post machine. Die 2 is a two cavity manually operated soluble die with a manually operated ejector and pneumatic operated pulls on a vertical four-post machine. These dies were selected to test a variety of conditions in terms of equipment, tool design and wax type.

Additionally, our testing is considered short-term variation and does not include long-term variation. This affects the choice of certain statistical analysis during capability testing. Statistically the long-term variation can be anticipated to be 1.5 sigma worse than the short-term variation.

Pattern quality was graded using the same inspector for all runs in the experiment. The inspector graded each pattern looking at flow lines, air entrapment and general visual pattern quality. A pattern was given a value of 1 if the pattern was deemed acceptable for the subsequent process. A value of 2 was assigned if the injection was usable but required repair. Finally, if the pattern was deemed unusable or scrap the pattern was given a value of 3.

Die 1 – Machine 1

Die 1 was a six-cavity tool, shown in figure 2, where one cavity is blocked off due to inability to produce good parts when all six cavities are used. The tool reportedly produces high scrap rates due to flow lines, knit lines and air representing two of the top defects from the survey.

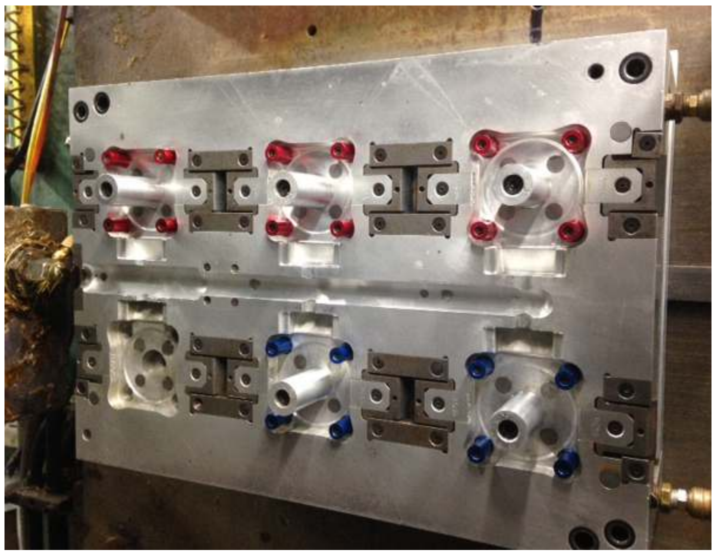


Figure 2: Die 1 Configuration

Examples of die 1 pattern grading are shown in figure 3. Typical grade 2 indications consist of knit lines around the outer holes of the pattern. Grade 3 indication were more severe in natural and consisted of significant flow lines throughout the pattern.

Figure 3: Die 1 Pattern Grading

After conducting the baseline injections, die optimization was attempted. Those injections are labeled as "improved" in the following analysis. Noted defects included, in order of criticality; flow lines, entrapped air and knit lines. As per the test plan, all available information was reviewed and adjustments were made to wax temperature, die temperature and wax flow in order to decrease the baseline scrap rate.

As the adjustment process began it was observed that the machine's wax temperatures were not set in an ideal manner to optimize process control. Table 1 summarizes the difference between the original baseline settings and the revised improved settings.

Table 1: Injection Temperature Settings

Control Area	Baseline, °F	Improved, °F
Reservoir Zone 1	145	155
Reservoir Zone 2	136	127
Injection Cylinder	145	127
Wax Hose	136	127
Injection Nozzle	141	127

The first item addressed was wax reservoir zone 1 temperature which was set to 145 degrees. This low temperature has two negative impacts. First, it does not allow an easy medium for any air that could be entrapped in the wax to escape. Zone 1 wax should be maintained at a temperature above the midpoint between the beginning of the wax paste range and the wax manufacturer's recommended melting temperature. Usually this is around 155 to 165 degrees. The baseline recipe had zone 1 at 145 degrees so it was agreed to raise the temperature to 155 degrees. The machine manufacturer recommends that reservoir zone 2, injection cylinder, wax hose and wax nozzle all be set to the same temperature. The original settings for each area of temperature control were from 136 to 145 degrees. The temperature for all control areas after zone 1 should be the desired injection temperature, which was 127 degrees. Failure to do so only induces variability into the process by subjecting the wax to different temperatures as it flows through the injection system.

In addition to the temperature settings above there were a number of mechanical problems discovered during the optimization phase of die 1 that limited the effectiveness of the optimization. First, the automatic fill valves controlling the wax additions to the conditioning reservoir from a central distribution system were bypassed and manually controlled. This led to inconsistent volumes of wax in the conditioning reservoir as well as proved to be problematic in maintaining temperature control. Second, it was found that the water temperature control on the reservoir zone 2 was not cooling properly and required maintenance that was not completed during our testing.

Given the defects of flow lines and knit lines it was believed we could overcome the pattern quality issues in other ways while decreasing the cycle time. Machine 1 was set-up with the flow at maximum, setting of 10 or 100%. This high flow rate, combined with liquid wax injections may contribute to air being trapped in the parts. Flow was reduced to a setting of 5. Wax injection pressure was originally at 625 psi and no change was made.

Die temperature was the area we thought we could get the most benefit so this was increased from 60 to 65 degrees. The five degree increase in die temperature required an increase in cycle time from 75 to 85 seconds in order to prevent the ejector pins from damaging the patterns. The positive of these changes came in reduction of scrap from 30% to 8%.

Die 2 – Machine 2

The wax used in machine 2 was a soluble pattern wax. The wax was added to the reservoir via buckets from a melting/holding vessel located near machine 2. This bucketing, much like adding wax manually via the central line on machine 1, is performed on an irregular basis and may add significant variability to the process.

The die on machine 2 was a two-cavity tool with one manually actuated pneumatic slide and manually actuated ejection. The defect noted on these parts was poor surface finish.

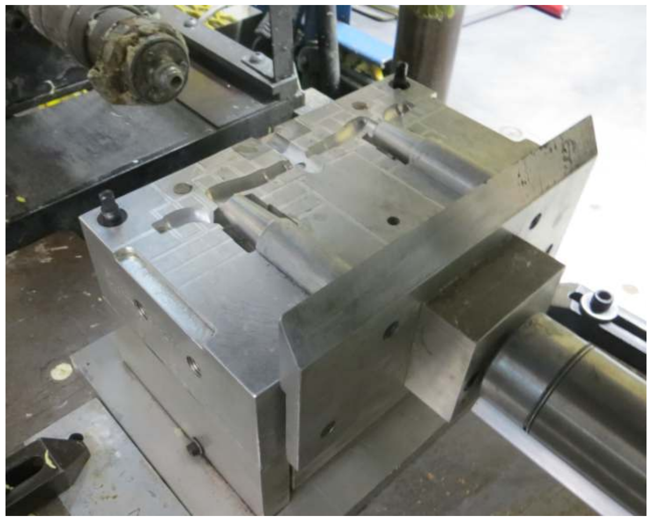


Figure 4: Die 2 Configuration

As previously described for Die 1, the experiment was conducted on Die 2 per the experiment plan. Die 2 was set up according to the original die recipe and the 40 initial injections were produced. Per the experiment plan, the patterns were evaluated and the injection data collected on the injection graphing unit. The primary defect for this part was surface finish blemishes in the form of surface negatives. A blue dye was applied to the soluble patterns after injection to aid in visual detection of the negatives. Examples of die 2 pattern grading are show in figure 5.

Figure 5: Die 2 Pattern Grading

As with Die 1, the baseline injections on Die 2 found issues with the machine that hampered our ability to optimize the die. The first issue was with wax temperature. The set point was 140 degrees and the machine was reporting actual temperature of 140 degrees. Using the injection graphing unit to collect wax temperatures was very problematic. We attempted to use a nozzle tip extension with a thermocouple probe in the wax stream. Unfortunately, the die cooled the extension so effectively that we repeatedly stopped the injection process with frozen wax in the nozzle extension. We did manage to capture five injections where the actual temperature was measured. The injection graphing unit indicated an initial spike of temperature as high as 180 degrees followed by injection temperatures around 148 degrees. Two decisions were made at this point. First to remove the nozzle extension and not take further temperature readings and second that we would not attempt to change the temperature for the optimization process. The second decision being driven by the fact that Machine 2 could not accurately control the wax temperature being injected.

The wax flow was controlled by a needle valve. The baseline setting was maximum flow with a black ring visible on the needle valve screw. It was quickly determined that the injection parameters had the machine in pressure control. Injection machine manufacturers recommend using flow control. The difference is understanding how the flow rate is being controlled. Pressure is a tool to do two things: achieve the desired flow and to pack the die after the die is full. Flow control is achieved when the pressure is sufficient to obtain the desired flow rate set on the machine. The correct method is to adjust the flow rate to the desired flow and ensure the pressure is sufficient to achieve that flow rate. This can be verified on a manual machine by nozzle purging and increasing pressure while purging. If the flow rate increases as pressure is increased, the machine is in pressure control. For the optimization of this part, we wanted to ensure the machine was operating in flow control. As such, the flow rate was decreased to a setting that allowed for flow control.

Wax pressure was initially set to 120 psi. Again, to ensure we had sufficient pressure to put the machine into flow control as well as increase the packing out of the part, we set the machine to 250 psi.

Table 2: Die 2 Parameters

Machine 2		
Injection Parameters:	Baseline	Improved
Dwell Time (seconds)	90	45
Wax Inj. Pressure (PSI)	120	250
Flow	100% (Black Ring)	3/8 turn (Green Ring)
Zone 1 (degrees F)	140	140
Injection Unit (degrees F)	140	140
Nozzle (degrees F)	140	140
Stationary Platen (degrees F)	58	58
Moving Platen (degrees F)	58	58

Die 1 - Machine 3

It was determined during the Die 1 – Machine 1 experiment that complete optimization would not be possible due to the condition on the foundry's injection machine. To further illustrate the optimization potential, the die was transported to another facility and injected using a modern automatic horizontal c-frame injection press hereafter referred to simply as machine 3. The same tests were run on machine 3 and all data analyzed.

It has been established from previous experimentation that batch to batch variability can have a significant effect on pattern quality as the characteristics of the wax drift within the manufacturer's tolerances. To eliminate that variable, wax from three different batches was sent out for viscosity testing. Below are the viscosity curves for all three samples. Based on the similarities among the curves the batch to batch viscosity variation was deemed acceptable for the purposes of the experiment. To further reduce variation, the foundry provided the alternate test facility with wax from the same vintage as tested on Machine 1.

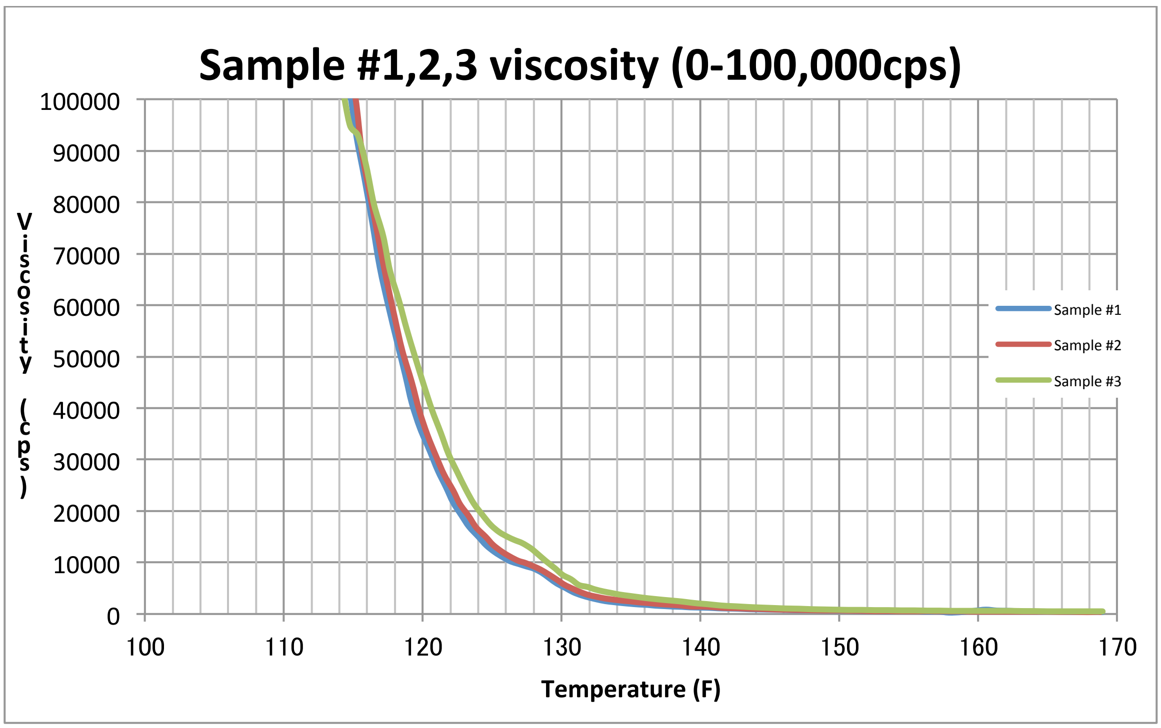


Figure 6: Wax Viscosity Curve

The wax was conditioned and the minimum injectable temperature was determined to be 126 degrees. The wax reservoir was continuously fed newly melted wax via an on-machine wax melter relying on the reservoir level control to keep the conditioning reservoir at the optimal level, always near full.

By adjusting the recipe parameters, we were able to find an optimized recipe that we agreed provided repeatable, quality patterns. Data from 40 replications using the optimized parameters was collected using the injection graphing unit followed by pattern evaluation.

The differences between the Baseline, Improved and Optimized parameters are displayed in table 3 below.

Table 3: Die 1 Parameters

	Machine 1		Machine 3
Injection Parameters:	Baseline	Improved	Optimized
Dwell Time (seconds)	75	85	50
Wax Inj. Pressure (PSI)	625	625	500
Flow	10.0 (# setting)	5.0 (# setting)	6.0 (in^3/sec)
Zone 1 (degrees F)	145	155	150
Zone 2 (degrees F)	136	127	127
Injection Unit (degrees F)	145	127	127
Wax Hose (degrees F)	136	127	127
Nozzle (degrees F)	141	127	127
Stationary Platen (degrees F)	60	65	70
Moving Platen (degrees F)	60	65	70

To better understand the requirement for process control and how it affects the outcome of an injected pattern we turned to both qualitative and quantitative analysis tools. Next, we will explore the tools used and the results of that analysis.

Analysis of Results

Viewing figure 6 illustrates the effect of the wax parameters and machine capability on the quality of the injected patterns. Scrap rates reduced from a baseline of 30% to 8.5% at the improved parameters. The optimized parameters removed all scrap observations from the sample set. Even better, the yield rate of good parts requiring no rework went from 22% to 35% to 75% when comparing baseline, improved and optimized runs respectively.

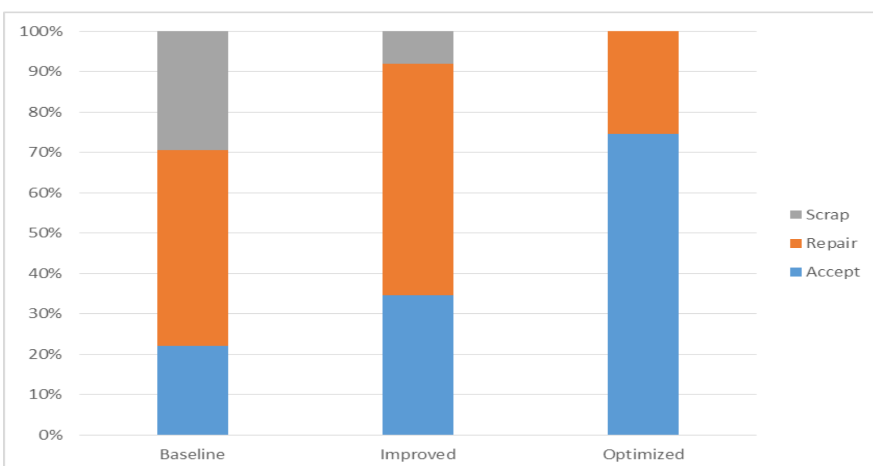


Figure 7: Die 1 Pattern Quality

The scrap and rework reduction is significant in itself, but while doing this we initially increased cycle time for the improved injections on Machine 1. However, with a fully functioning, high process control Machine 3 we cut the cycle time by 42.2% over the improved injections and 33.3% over the baseline injections. An unforeseen element of this improved cycle time was an elevated throughput of wax exceeding the cooling capability of the chiller connected to the conditioning reservoir. This manifested itself in wax injection temperature gradually increasing as is seen in the Machine 3 Mini-tab Quality Six Pack chart for temperature between injections later in this paper. This special cause variation was tracked down to the root cause, which was insufficient chilled water flow.

Regarding Die 2 on Machine 2, the minor changes made to this recipe we did see an improvement in the parts which netted scrap reduction from 8% to 4% and a yield rate increase of good parts (no rework required) from 44% to 61%.

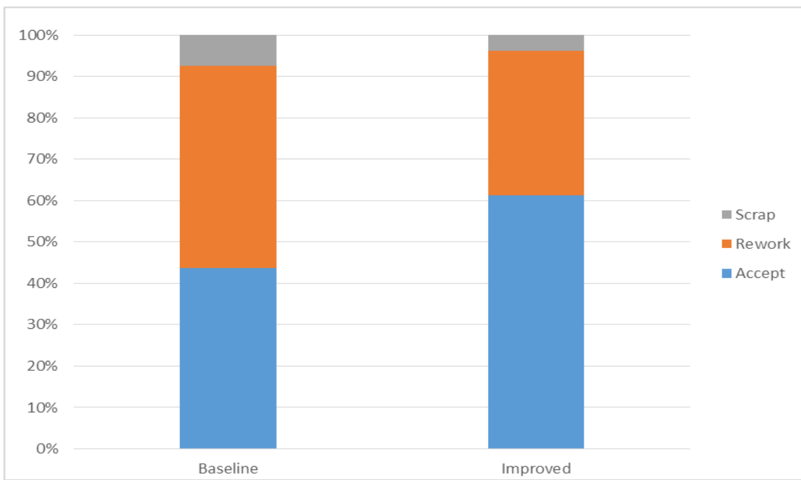
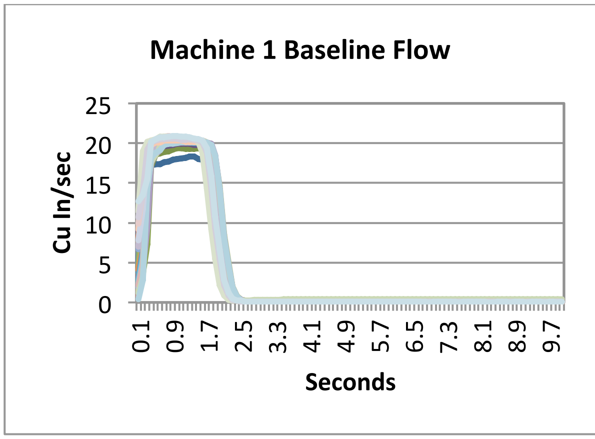
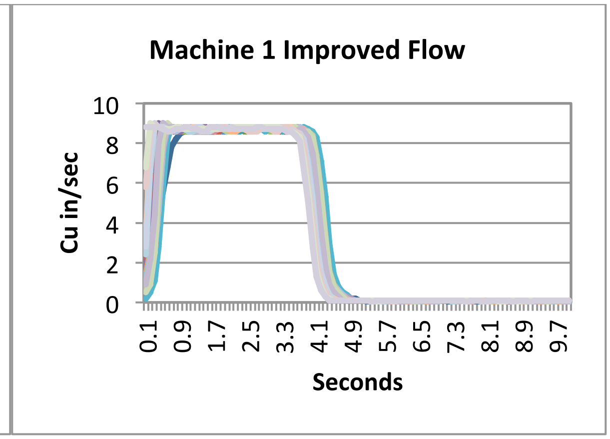
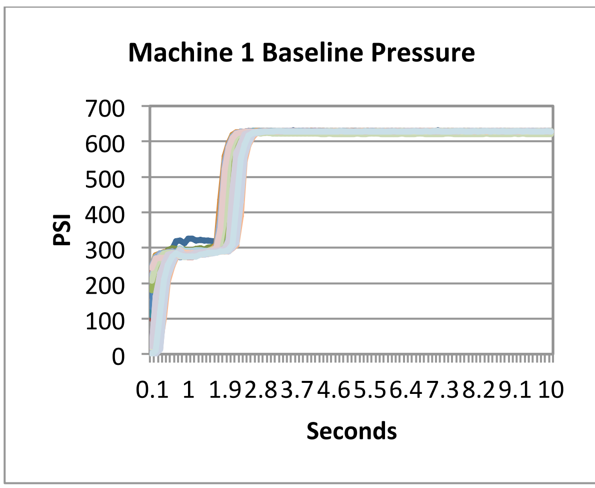


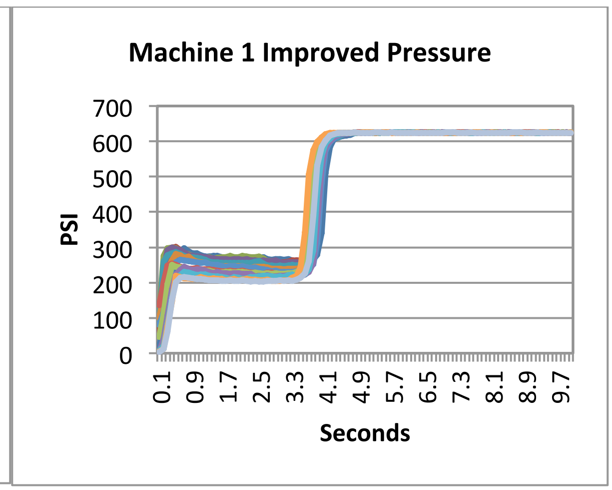
Figure 8: Die 2 Pattern Quality

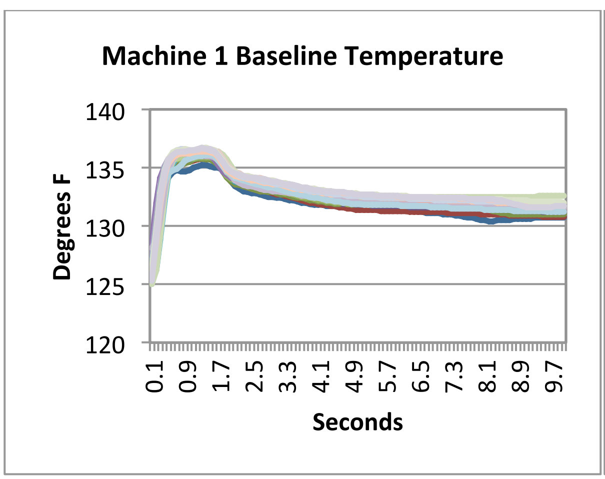
The following graphs represent the data collected using the portable injection graphing unit from each injection by machine.

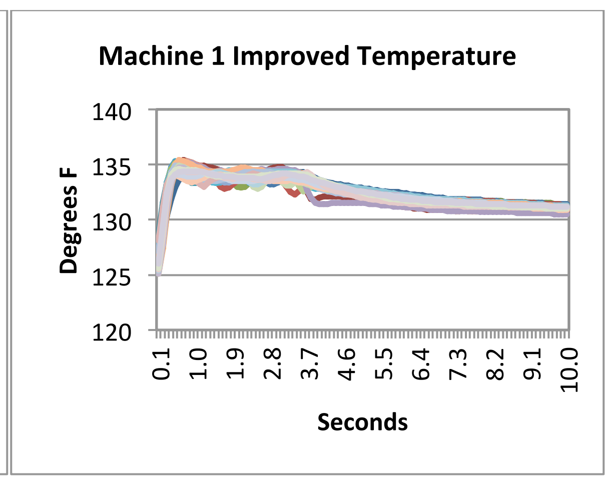


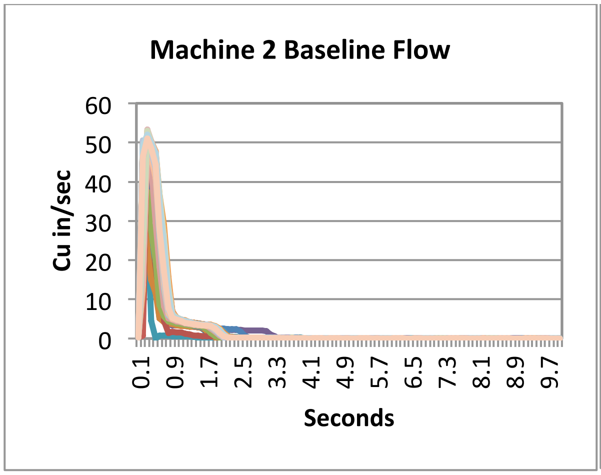


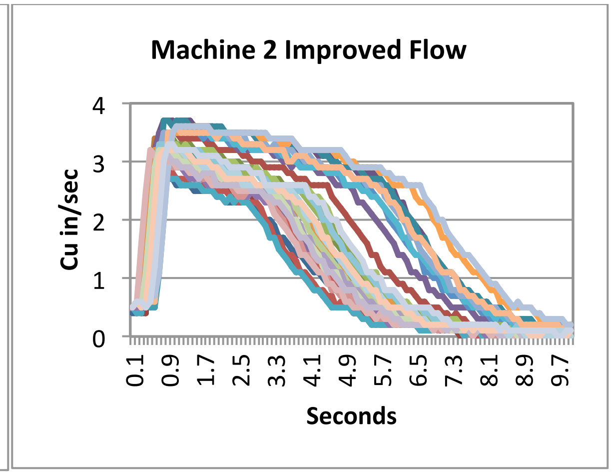


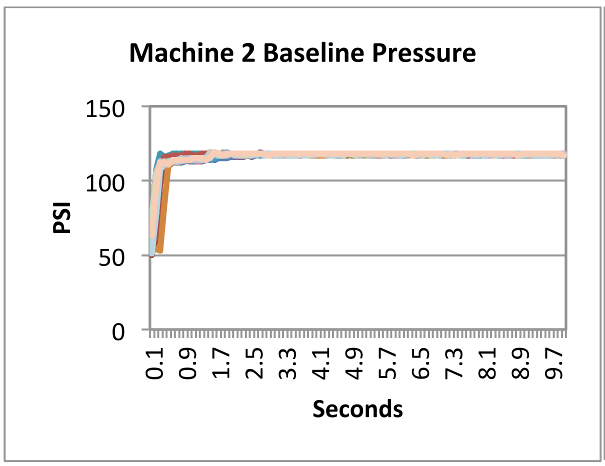


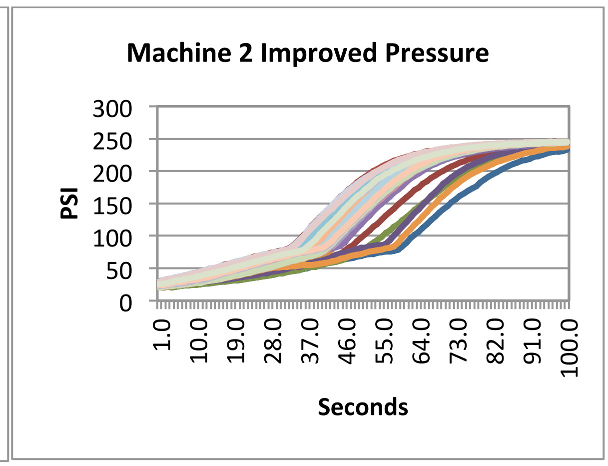


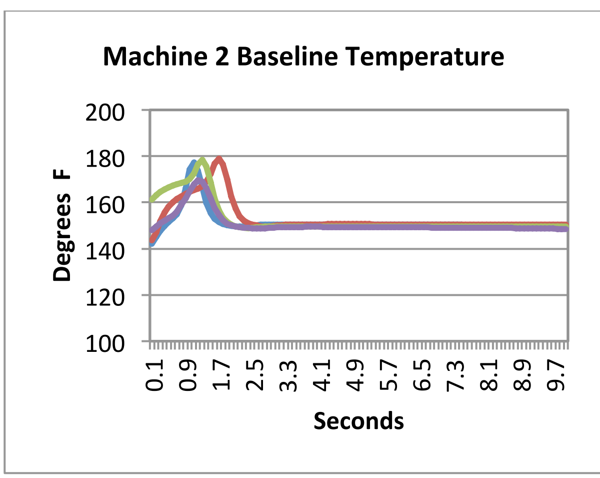


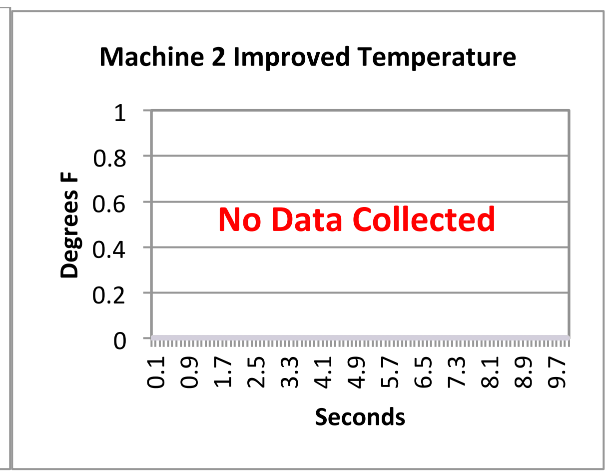

Machine 2 Baseline Flow
Cu in/sec
60
50
40
30
20
10
0
0.1 0.9 1.7 2.5 3.3 4.1 4.9 5.7 6.5 7.3 8.1 8.9 9.7
Seconds

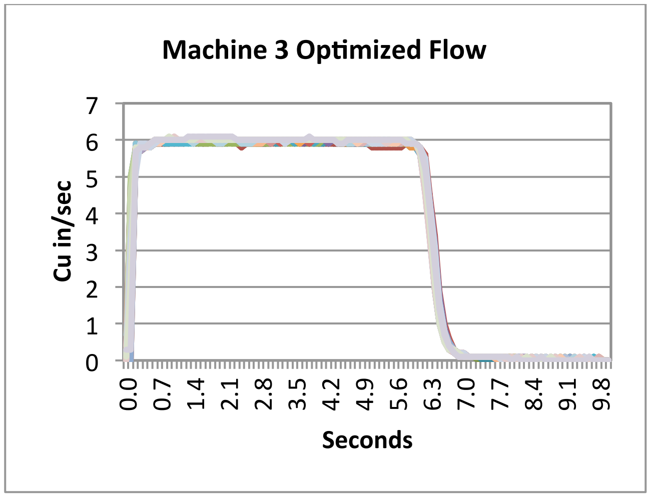

Machine 2 Improved Flow
Cu in/sec
4
3
2
1
0
0.1 0.9 1.7 2.5 3.3 4.1 4.9 5.7 6.5 7.3 8.1 8.9 9.7
Seconds

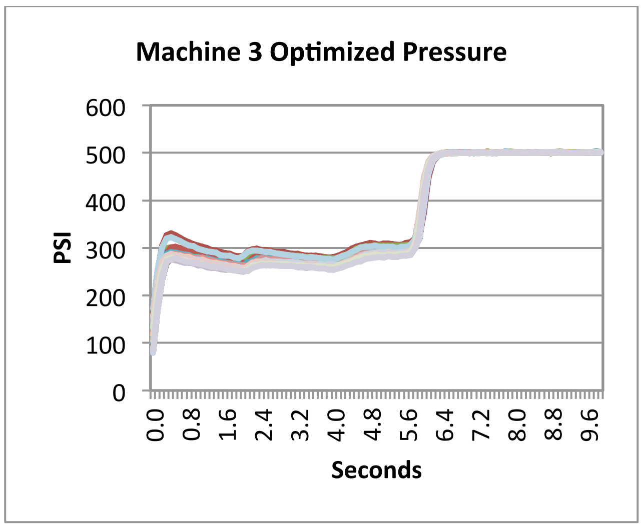

Machine 2 Baseline Pressure
PSI
150
100
50
0
0.1 0.9 1.7 2.5 3.3 4.1 4.9 5.7 6.5 7.3 8.1 8.9 9.7
Seconds

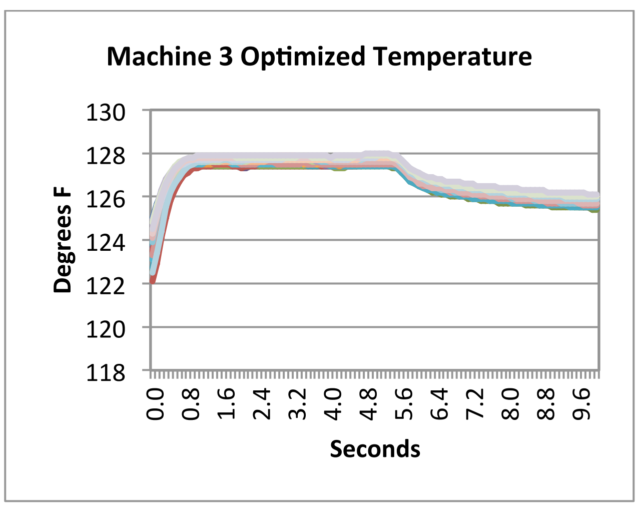

Machine 2 Improved Pressure
PSI
300
250
200
150
100
50
0
1.0 10.0 19.0 28.0 37.0 46.0 55.0 64.0 73.0 82.0 91.0 100.0
Seconds


Machine 2 Baseline Temperature
Degrees F
200
180
160
140
120
100
0.1 0.9 1.7 2.5 3.3 4.1 4.9 5.7 6.5 7.3 8.1 8.9 9.7
Seconds


Machine 2 Improved Temperature
Degrees F
1
0.8
0.6
0.4
0.2
0
No Data Collected
0.1 0.9 1.7 2.5 3.3 4.1 4.9 5.7 6.5 7.3 8.1 8.9 9.7
Seconds



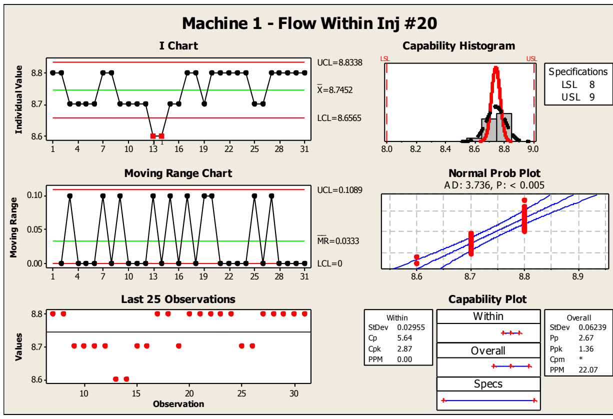


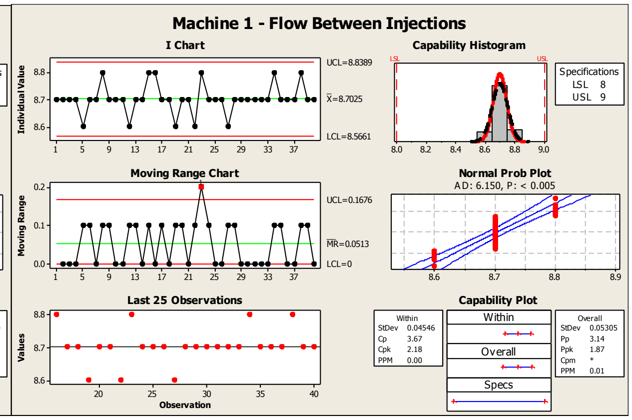


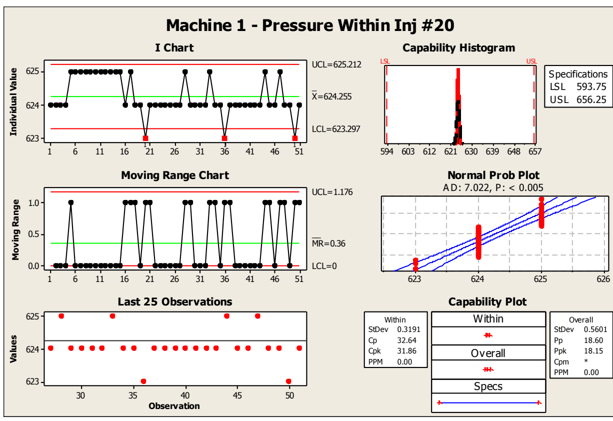
To determine statistical capability of each machine, the improved and optimized data was used to run SPC and Capability Analysis. An exception is on Machine 2 temperatures where the only data collected was during the baseline injections. This data is graphically illustrated using Mini-tab's Quality Six-Pack tool. One set of graphs is used to look at capability within a single injection, while another set of graphs is used to compare one injection to the next covering all 40 injections. Each metric is analyzed during a part of the injection cycle when the process should be controlled by the machine set point. As an example, within an injection on Machine 1, flow is analyzed while the wax is flowing from 1 second to 3.5 seconds, temperature is analyzed in the same time period and wax pressure is looked at after the flow stops and the die is packing. For all analysis within an injection, we chose to use injection number 20 data. To analyze from one injection to the next an appropriate point in the injection was selected where for each criterion the machine should be providing the same output. For example, when comparing the flow for machine 1 between all injections we used the data recorded by the injection graphing unit at 2 seconds, temperature was looked at for the same time and pressure was analyzed at 9.9 seconds. There are six, Six-Pack charts for each machine. One set of three dedicated to within an injection for temperature, pressure and flow and another set of three for between injections for the same criterion. The set point was used as the target value for each criterion and where no set point is easily discernable (i.e. manually set control with no feedback) the actual mean as produced and recorded by the injection graphing unit is used. The specification limits are established as plus or minus two degrees F for temperature, 5% for pressure and .5 in^3/sec for flow.

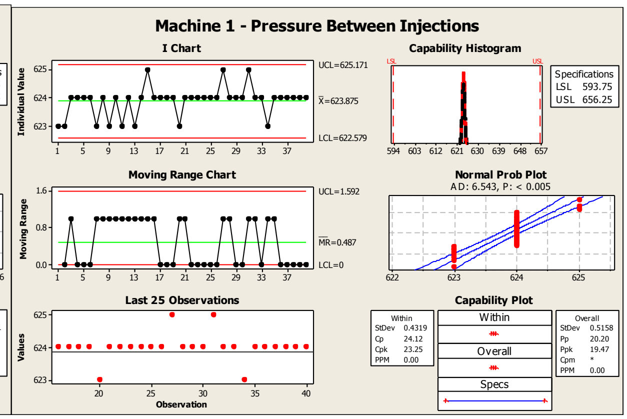
Analyzing this data tells us if the machine is statistically capable. Statistical capability includes determination of three questions: is the machine in control, is the machine stable and is the machine capable? To analyze the first two questions we review the results of Statistical Process Control (SPC) charts. To answer the third question we use standard capability matrices Cp and Cpk. This information is located on the below Mini-tab Quality Six-Pack charts.

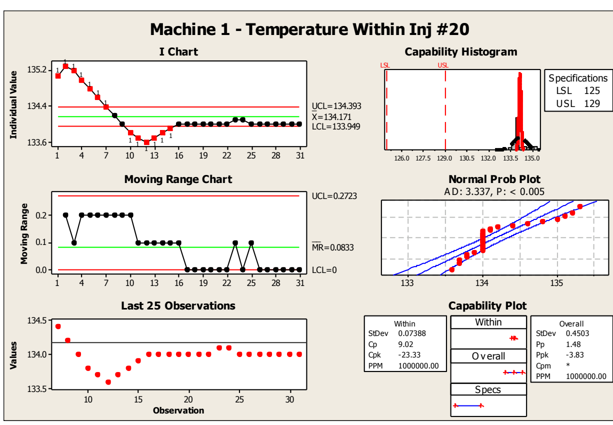
Machine 1:

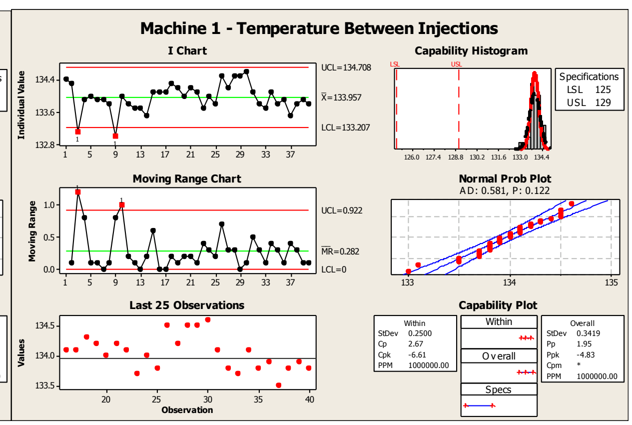

Machine 1 - Flow Within Inj #20
I Chart
UCL=8.8338
X̄=8.7452
LCL=8.6565
Individual Value
Capability Histogram
LSL
USL
Specifications
LSL 8
USL 9
Moving Range Chart
UCL=0.1089
MR̄=0.0333
LCL=0
Moving Range
Normal Prob Plot
AD: 3.736, P: < 0.005
Last 25 Observations
Values
Observation
Capability Plot
Within
StDev 0.02955
Cp 5.64
Cpk 2.87
PPM 0.00
Overall
StDev 0.06239
Pp 2.67
Ppk 1.36
Cpm *
PPM 22.07
Specs


Machine 1 - Flow Between Injections
I Chart
UCL=8.8389
X̄=8.7025
LCL=8.5661
Individual Value
Capability Histogram
LSL
USL
Specifications
LSL 8
USL 9
Moving Range Chart
UCL=0.1676
MR̄=0.0513
LCL=0
Moving Range
Normal Prob Plot
AD: 6.150, P: < 0.005
Last 25 Observations
Values
Observation
Capability Plot
Within
StDev 0.04546
Cp 3.67
Cpk 2.18
PPM 0.00
Overall
StDev 0.05305
Pp 3.14
Ppk 1.87
Cpm *
PPM 0.01
Specs

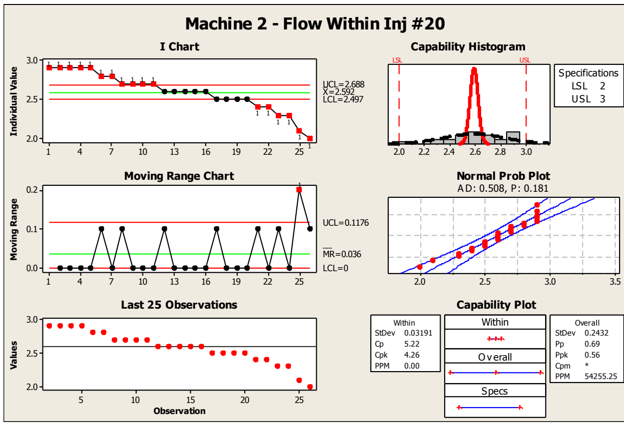

Machine 1 - Pressure Within Inj #20
I Chart
UCL=625.212
X̄=624.255
LCL=623.297
Individual Value
Capability Histogram
LSL
USL
Specifications
LSL 593.75
USL 656.25
Moving Range Chart
UCL=1.176
MR̄=0.36
LCL=0
Moving Range
Normal Prob Plot
AD: 7.022, P: < 0.005
Last 25 Observations
Values
Observation
Capability Plot
Within
StDev 0.3191
Cp 32.64
Cpk 31.86
PPM 0.00
Overall
StDev 0.5601
Pp 18.60
Ppk 18.15
Cpm *
PPM 0.00
Specs

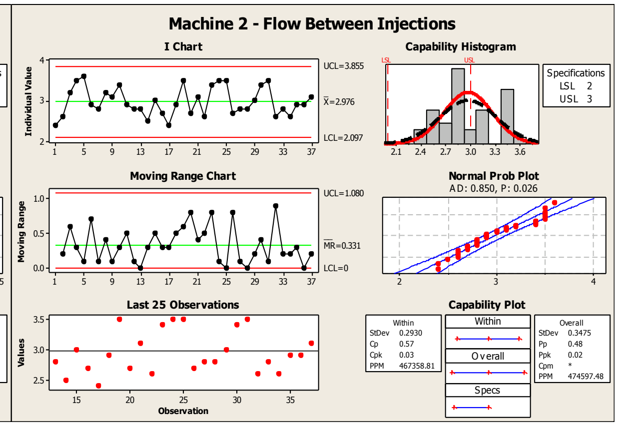

Machine 1 - Pressure Between Injections
I Chart
UCL=625.171
X̄=623.875
LCL=622.579
Individual Value
Capability Histogram
LSL
USL
Specifications
LSL 593.75
USL 656.25
Moving Range Chart
UCL=1.592
MR̄=0.487
LCL=0
Moving Range
Normal Prob Plot
AD: 6.543, P: < 0.005
Last 25 Observations
Values
Observation
Capability Plot
Within
StDev 0.4319
Cp 24.12
Cpk 23.25
PPM 0.00
Overall
StDev 0.5158
Pp 20.20
Ppk 19.47
Cpm *
PPM 0.00
Specs

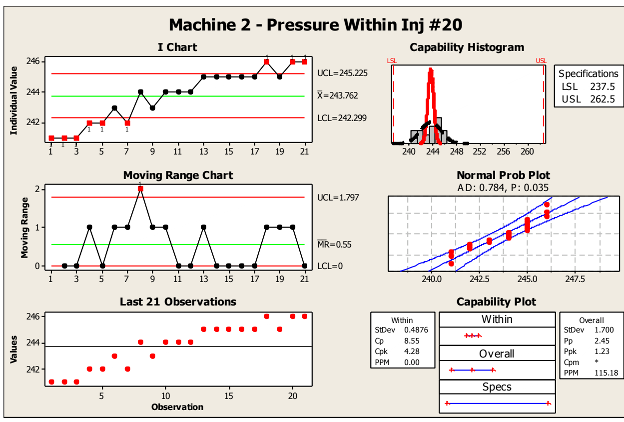

Machine 1 - Temperature Within Inj #20
I Chart
UCL=134.393
X̄=134.171
LCL=133.949
Individual Value
Capability Histogram
LSL
USL
Specifications
LSL 125
USL 129
Moving Range Chart
UCL=0.2723
MR̄=0.0833
LCL=0
Moving Range
Normal Prob Plot
AD: 3.337, P: < 0.005
Last 25 Observations
Values
Observation
Capability Plot
Within
StDev 0.07388
Cp 9.02
Cpk -23.33
PPM 1000000.00
Overall
StDev 0.4503
Pp 1.48
Ppk -3.83
Cpm *
PPM 1000000.00
Specs

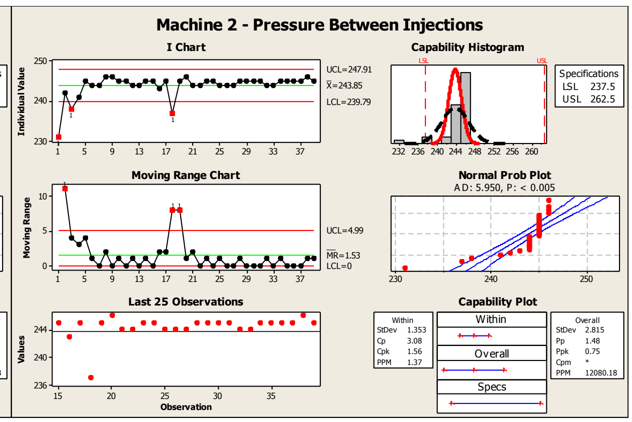

Machine 1 - Temperature Between Injections
I Chart
UCL=134.708
X̄=133.957
LCL=133.207
Individual Value
Capability Histogram
LSL
USL
Specifications
LSL 125
USL 129
Moving Range Chart
UCL=0.922
MR̄=0.282
LCL=0
Moving Range
Normal Prob Plot
AD: 0.581, P: 0.122
Last 25 Observations
Values
Observation
Capability Plot
Within
StDev 0.2500
Cp 2.67
Cpk -6.61
PPM 1000000.00
Overall
StDev 0.3419
Pp 1.95
Ppk -4.83
Cpm *
PPM 1000000.00
Specs

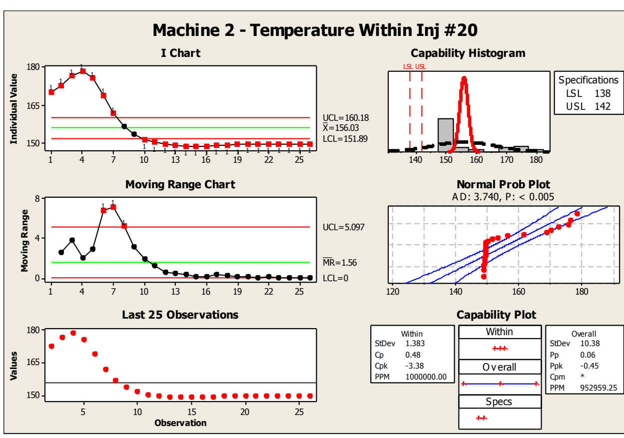
Machine 2:

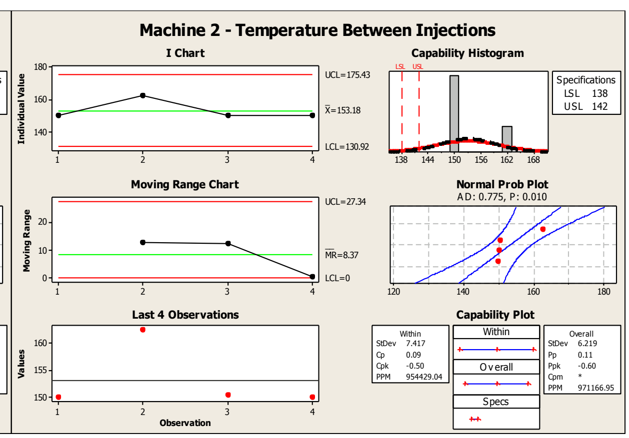

Machine 2 - Flow Within Inj #20
I Chart
Capability Histogram
Specifications LSL 2 USL 3
UCL=2.688
X̄=2.592
LCL=2.497
Moving Range Chart
UCL=0.1176
MR̄=0.036
LCL=0
Normal Prob Plot
AD: 0.508, P: 0.181
Last 25 Observations
Capability Plot
Within StDev 0.03191 Cp 5.22 Cpk 4.26 PPM 0.00
Overall StDev 0.2432 Pp 0.69 Ppk 0.56 Cpm * PPM 54255.25
Specs


Machine 2 - Flow Between Injections
I Chart
Capability Histogram
Specifications LSL 2 USL 3
UCL=3.855
X̄=2.976
LCL=2.097
Moving Range Chart
UCL=1.080
MR̄=0.331
LCL=0
Normal Prob Plot
AD: 0.850, P: 0.026
Last 25 Observations
Capability Plot
Within StDev 0.2930 Cp 0.57 Cpk 0.03 PPM 467358.81
Overall StDev 0.3475 Pp 0.48 Ppk 0.02 Cpm * PPM 474597.48
Specs

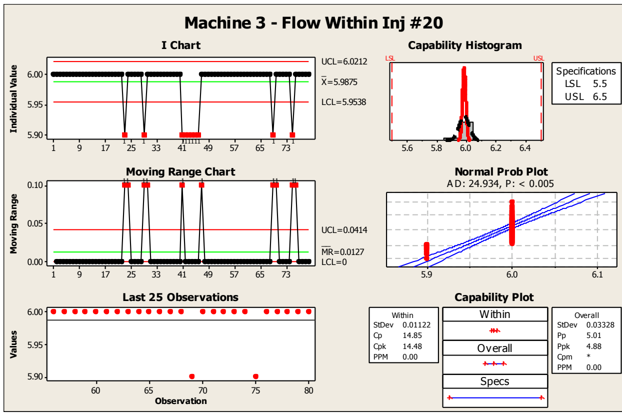

Machine 2 - Pressure Within Inj #20
I Chart
Capability Histogram
Specifications LSL 237.5 USL 262.5
UCL=245.225
X̄=243.762
LCL=242.299
Moving Range Chart
UCL=1.797
MR̄=0.55
LCL=0
Normal Prob Plot
AD: 0.784, P: 0.035
Last 21 Observations
Capability Plot
Within StDev 0.4876 Cp 8.55 Cpk 4.28 PPM 0.00
Overall StDev 1.700 Pp 2.45 Ppk 1.23 Cpm * PPM 115.18
Specs

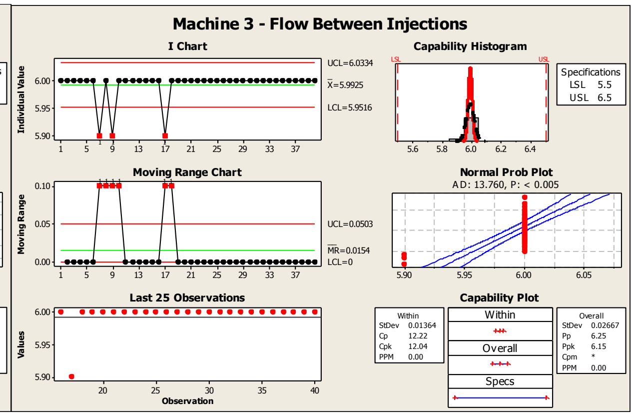

Machine 2 - Pressure Between Injections
I Chart
Capability Histogram
Specifications LSL 237.5 USL 262.5
UCL=247.91
X̄=243.85
LCL=239.79
Moving Range Chart
UCL=4.99
MR̄=1.53
LCL=0
Normal Prob Plot
AD: 5.950, P: < 0.005
Last 25 Observations
Capability Plot
Within StDev 1.353 Cp 3.08 Cpk 1.56 PPM 1.37
Overall StDev 2.815 Pp 1.48 Ppk 0.75 Cpm * PPM 12080.18
Specs

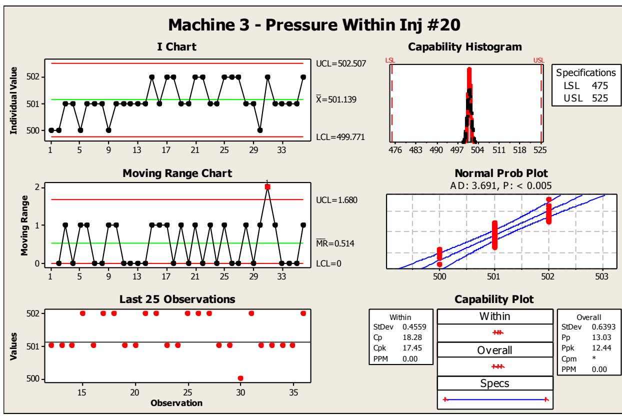

Machine 2 - Temperature Within Inj #20
I Chart
Capability Histogram
Specifications LSL 138 USL 142
UCL=160.18
X̄=156.03
LCL=151.89
Moving Range Chart
UCL=5.097
MR̄=1.56
LCL=0
Normal Prob Plot
AD: 3.740, P: < 0.005
Last 25 Observations
Capability Plot
Within StDev 1.383 Cp 0.48 Cpk -3.38 PPM 1000000.00
Overall StDev 10.38 Pp 0.06 Ppk -0.45 Cpm * PPM 952959.25
Specs

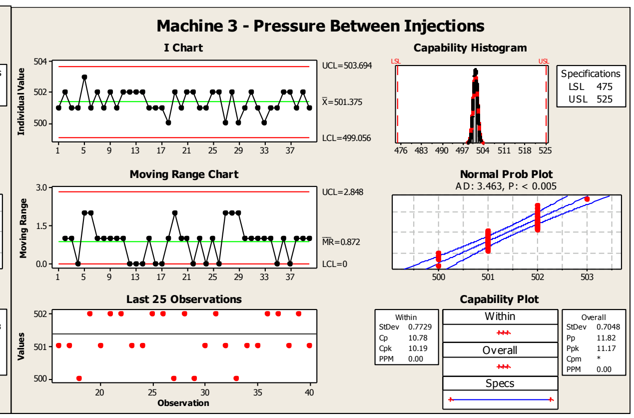

Machine 2 - Temperature Between Injections
I Chart
Capability Histogram
Specifications LSL 138 USL 142
UCL=175.43
X̄=153.18
LCL=130.92
Moving Range Chart
UCL=27.34
MR̄=8.37
LCL=0
Normal Prob Plot
AD: 0.775, P: 0.010
Last 4 Observations
Capability Plot
Within StDev 7.417 Cp 0.09 Cpk -0.50 PPM 954429.04
Overall StDev 6.219 Pp 0.11 Ppk -0.60 Cpm * PPM 971166.95
Specs

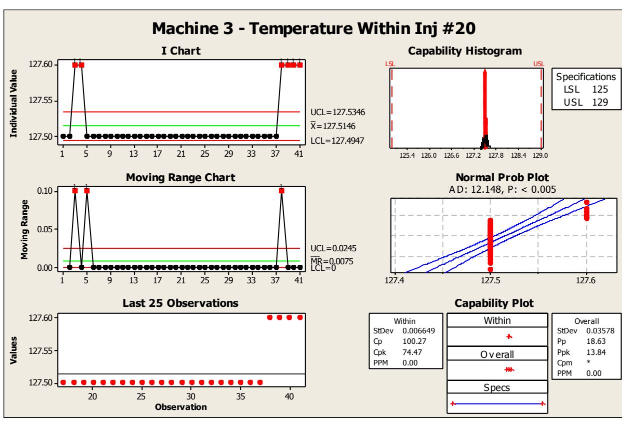
Machine 3:

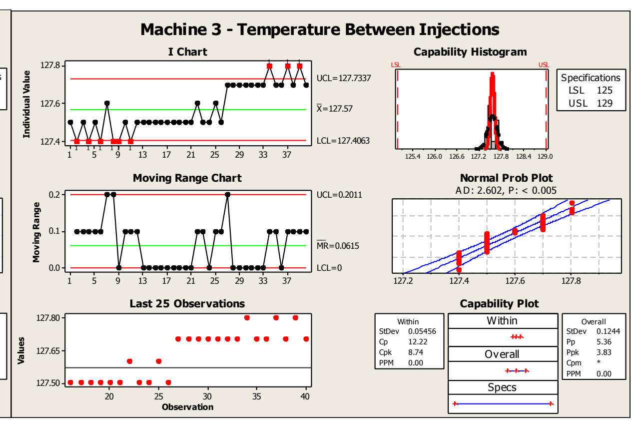

Machine 3 - Flow Within Inj #20
I Chart
Capability Histogram
Moving Range Chart
Normal Prob Plot
AD: 24.934, P: < 0.005
Last 25 Observations
Capability Plot
Specifications
LSL 5.5
USL 6.5
UCL=6.0212
LCL=5.9538
UCL=0.0414
LCL=0
Within
Overall
Specs


Machine 3 - Flow Between Injections
I Chart
Capability Histogram
Moving Range Chart
Normal Prob Plot
AD: 13.760, P: < 0.005
Last 25 Observations
Capability Plot
Specifications
LSL 5.5
USL 6.5
UCL=6.0334
LCL=5.9516
UCL=0.0503
LCL=0
Within
Overall
Specs


Machine 3 - Pressure Within Inj #20
I Chart
Capability Histogram
Moving Range Chart
Normal Prob Plot
AD: 3.691, P: < 0.005
Last 25 Observations
Capability Plot
Specifications
LSL 475
USL 525
UCL=502.507
LCL=499.771
UCL=1.680
LCL=0
Within
Overall
Specs


Machine 3 - Pressure Between Injections
I Chart
Capability Histogram
Moving Range Chart
Normal Prob Plot
AD: 3.463, P: < 0.005
Last 25 Observations
Capability Plot
Specifications
LSL 475
USL 525
UCL=503.694
LCL=499.056
UCL=2.848
LCL=0
Within
Overall
Specs


Machine 3 - Temperature Within Inj #20
I Chart
Capability Histogram
Moving Range Chart
Normal Prob Plot
AD: 12.148, P: < 0.005
Last 25 Observations
Capability Plot
Specifications
LSL 125
USL 129
UCL=127.5346
LCL=127.4947
UCL=0.0245
Within
Overall
Specs


Machine 3 - Temperature Between Injections
I Chart
Capability Histogram
Moving Range Chart
Normal Prob Plot
AD: 2.602, P: < 0.005
Last 25 Observations
Capability Plot
Specifications
LSL 125
USL 129
UCL=127.7337
LCL=127.4063
UCL=0.2011
LCL=0
Within
Overall
Specs

Putting it all together, table 4 summarized the machine capability.

Table 4: Machine Capability Analysis

Capability Analysis							
		Within Injection #20			Between Injections		
		Flow	Pressure	Temp	Flow	Pressure	Temp
In Control?	Machine 1	* Yes	Yes	No	Yes	Yes	* Yes
Stable?	Machine 1	Yes	Yes	Yes	* Yes	Yes	* Yes
Capable?	Machine 1	Yes	Yes	No	Yes	Yes	No
In Control?	Machine 2	No	No	No	Yes	* Yes	Yes
Stable?	Machine 2	* Yes	* Yes	No	Yes	* Yes	Yes
Capable?	Machine 2	Yes	Yes	No	No	Yes	No
In Control?	Machine 3	* Yes	Yes	* Yes	* Yes	Yes	** Yes
Stable?	Machine 3	* Yes	* Yes	* Yes	Yes	Yes	Yes
Capable?	Machine 3	Yes	Yes	Yes	Yes	Yes	Yes
* Items indicate some special cause variation that when reviewed is insignificant							
** Special Cause Variation due to external problem - Chiller flow not adequate for demand							

Conclusions

There are many conclusions to be drawn from this experiment. The most obvious is that process control is important and machine maintenance is the first line of defense in keeping a process in control. Operators often make adjustments to the machines in order to compensate for equipment that is not working properly. Those adjustments may allow production to continue, but the cost of lost efficiency and scrap may quickly become more than the cost to fix or even replace the equipment.

Understanding what a process is actually doing will lead to better decision making when it comes to improving a process. We often think we know what a process is doing and with this experiment, it was demonstrated that the lack of process feedback available on manual machines only contributes to variation. Operators may believe they know what is happening when in fact they know little about the true process taking place. You should not believe the machine's set point matches the actual output.

Flow control verses pressure control is an important concept to understand and apply correctly. As previously stated, pressure is a tool to do two things: achieve the desired flow and to pack the die after the die is full. The preferred method of machine control is flow control. Flow control is achieved when the pressure is sufficient to obtain the desired flow rate set on the machine. Flow will have a significant effect on the quality of your wax patterns and is often overlooked when making adjustments to optimize a specific die.

This experiment demonstrated the optimization of a die is achievable if your equipment is capable and you apply the principles outlined in the ICI *Atlas of Wax Pattern Defects*. The key is an understanding of how each process variable will interact on other variables so that the outcome of changing one variable can be predicted. As an example, a change in wax temperature has a significant role in cycle time as well as dimensional and visual characteristics.

When a machine is statistically capable and provides appropriate feedback, it is possible to significantly improve the wax-room efficiencies. Using the methods described in the *Atlas of Wax Pattern Defects* and from MPI's Operator Training, optimizing Die 1 has improved throughput by 281%. This is calculated by determining patterns per hour throughput. Grade 2 patterns were given a 50% "good" rating in order to make the comparison and machine cycle time was used as total cycle time just for the comparison. Actual throughput will be less given any manual operations that add to cycle time (i.e. mold release application). Using this method, Die 1 baseline throughput was 111 patterns per hour, improved was 133 patterns per hour and Die 1 on Machine 3 optimized was 312 patterns per hour. On Die 2, the improvement was an even more dramatic yielding a 458% increase in throughput. Baseline injection parameters were producing 27 acceptable patterns per hour and the improved parameters resulted in 125 acceptable patterns per hour.

References:

ICI *Atlas of Wax Pattern Defects*

ICI *Process Control Course Documentation*

MPI *Wax Injection Operation and Advanced Operation Training*