(CsEx-01)

Die-Casting Process Parameter Study

Reported by **Ranjit K. Roy**, Ph.D., P.E., **Nutek, Inc**.

In a die casting process, metal (generally alloys of Aluminum, Zinc & Magnesium) parts are formed by flowing molten metals (at 1200 – 1300 deg F) in the cavities of the dies made of steel. The dies are preformed to create cavities in the shape of the part. The key parameters that control the die casting process generally are, *Biscuit size, Shot speed, Metal temperature, Die temperature, Fill pressure*, *Cycle time,* to name a few. Typically these factors are susceptible to variation from day to day, or even cycle to cycle. The quality of the part produced is also affected by the design of the die, but is easier to control than the process variables mentioned before.

There are many types of observed defects that result in scrapped parts. The common defects observed are, *Surface abnormalities (Cold flaw, Cold lap, Chill swirls, Non-fill, etc.), Lamination (layers of metal on inside or outside surface), Gas Porosity, Blister, Shrinkage Porosity, Heat sinks, Crack & tears, Drags, Gate porosity, Driving ejector pins*, etc.

In a study to reduce the scrap rate of an aluminum die-cast bracket, an experiment was carried out. For the purposes of evaluation of the test samples four major types (evaluation criteria, see Table 1) of defects were monitored and recorded. The description of the evaluation criteria and the control & Noise factors (Table 2 & 3) included in the study are as described below.

Method of Evaluations)

#	Criteria Descriptions	Worst Reading	Best Reading	QC	Rel. Weighting %
1	Crack and Tear (length)	10 mm long	0 mm long	S	40
2	Heat Sinks (diameter)	15 mm	0 mm	S	25
3	Lamination (area)	5 sq.cm	0 sq.cm	S	20
4	Non-Fill (area of void)	2 sq.cm	0 sq.cm	S	15

Factor	Level 1	Level 2	Level 3	Level 4
A: Metal Flow Speed	1200 ips	1750 ips		
B: Metal Temperature	1220 deg F	1260 deg F		
C: Shot Speed	Current	15% higher		
D: Die Temperature (avg.)	550 deg F	600 deg F		
E: Biscuit Size	Smaller	Larger		
F: Ejection Stability	Straight	Wobbly		
G: Dwell Time	Shorter	Current Spec.		
H: Gate Design	Type 1	Type 2		
I: Shot Pressure	Standard	20% higher		
J: Closing Pressure	Lowest	Highest		

Noise Factor	Level 1	Level 2	Level 3	Level4
X: Die Spray	Present	Absent		
Y: Heat-Opst. Side of casting	Heat Applied	Heat absent		
Z: Lubrication	Regular	More Frequent		
U: Deposit Bu ilt-up	Uncleaned	Cleaned		
V: Uneven Die Temperature	Regular	Forced		
W: Foreign Matl. in Metal	Least Present	Added		

An L-12 orthogonal array was used to design the experiments to study ten 2-level factors described in Table 2. It was assumed that the large number of interactions between two factors is present, but not significant. Even if some interactions are present, because of the fact that L-12 array design distributes the effects to all columns, they are not expected to adversely affect conclusions about any single factor. The experiment design layout showing the appropriate column assignment and the modified orthogonal array are shown in Figures 1 and 2.

Three among the five identified noise factors are formally included in the study. Following the principle of robust design, the three noise factors (X, Y, & Z) were used to create the combination of the noise condition that the test samples were exposed to. An L-4 orthogonal array was used as the outer array to combine the noise factors. The experiments under this scheme require that four saples in each tria l conditions are tested by exposing them to the influence of the combined noise effects as prescribed by the outer array.

This experiment was designed and results were analyzed using the IBM/PC Compatible Widows software named Qualitek-4 (QT4).

Figure 1. Factor Description and their Column Assignment

Inner Array Design

Array Type: L-12

Use <ctrl> + <arrows> to move cursor.

	Factors	Level 1	Level 2
1	A: Metal Flow Spd	1200 ips	1750 ips
2	B: Metal Temp.	1220 deg	1260 deg F
3	C: Shot Speed	Current	15% Higher
4	D: Die Temp.	550 deg F	6050 deg F
5	E: Biscuit Size	Smaller	Larger
6	F: Ejection Stb.	Straight	Wobbly
7	G: Dwell Time	Shorter	Current Spe
8	H: Gate Design	Type 1	Type
9	I: Shot Pressure	Standard	20% Higher
10	J: Closing Press.	Lowest	Highest
11	COLUMN UNUSED	UNUSED	------------

Figure 2. Inner Array (L-12) used for the Experiment Design

Edit Inner Array

Array Type: L - 12

	1	2	3	4	5	6	7	8	9	10	11
1	1	1	1	1	1	1	1	1	1	1	0
2	1	1	1	1	1	2	2	2	2	2	0
3	1	1	2	2	2	1	1	1	2	2	0
4	1	2	1	2	2	1	2	2	1	1	0
5	1	2	2	1	2	2	1	2	1	2	0
6	1	2	2	2	1	2	2	1	2	1	0
7	2	1	2	2	1	1	2	2	1	2	0
8	2	1	2	1	2	2	2	1	1	1	0
9	2	1	1	2	2	2	1	2	2	1	0
10	2	2	2	1	1	1	1	2	2	1	0
11	2	2	1	2	1	2	1	1	1	2	0
12	2	2	1	1	2	1	2	1	2	2	0

The layout of the experiment designed using the L-12 array calls for 12 separte experimental conditions called the trial conditions. Two among the 12 conditions are shown in Figure 3. All other trial conditions are easily obtained from QT4 on demand (not shown). These trial condition forms part of the recipe for carrying out the experiments.

Figure 3. Two (Trial# 1 & 2) among the 12 Trial Conditions

Descriptions Trial Conditions **Qualitek-4**

Trial Condition 1 (Random order for running this Trial is 9)

Factors	Level Description	Level #
A: Metal Flow Spd	1200 ips	1
B: Metal Temp.	1220 deg	1
C: Shot Speed	Current	1
D: Die Temp.	550 deg F	1
E: Biscuit Size	Smaller	1
F: Ejection Stb.	Straight	1
G: Dwell Time	Shorter	1
H: Gate Design	Type 1	1
I: Shot Pressure	Standard	1
J: Closing Press.	Lowest	1
COLUMN UNUSED		0

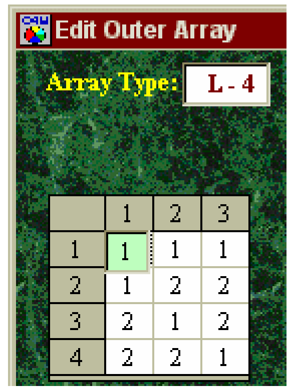
Descriptions Trial Conditions **Qualitek-4**

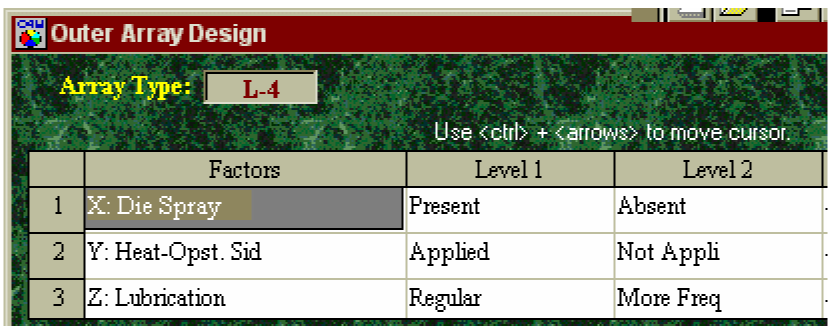
Trial Condition 2 (Random order for running this Trial is 1)

Factors	Level Description	Level #
A: Metal Flow Spd	1200 ips	1
B: Metal Temp.	1220 deg	1
C: Shot Speed	Current	1
D: Die Temp.	550 deg F	1
E: Biscuit Size	Smaller	1
F: Ejection Stb.	Wobbly	2
G: Dwell Time	Current Spe	2
H: Gate Design	Type	2
I: Shot Pressure	20% Higher	2
J: Closing Press.	Highest	2

Since it was desired to pursue robust design strategy in this study, the noise factors were included in the experiment by using an L-4 as the outer array. The L-4 outer array, in this experiment, combined the three 2-level noise factors to form four conditions of the noise. The noise factor description and the array are shown in Figure 4.

Figure 4. Outer Array (L-4) and the Noise Factor Descriptions





The outer array prescribes four distinct noise conditions under which one or more samples are to be tested in each trial condition. With one sample tested in each combination of the noise and trial condition (often refered as a *cell*), this scheme called for a total of 48 test samples (four in each trial condition. The noise conditions to which the trial samples were exposed while conducting the tests are shown in Figure 5. To save time, the prescribed randomly selected order, as indicated in the figure, was ignored for the noise condition, but the prescribed random order for the trial condition (with control factors) were followed.

Figure 5. Factor Description and their Column Assignment

Noise Condition 1 (Randomly selected order # 4)		
Factors	Level Description	Level #
X: Die Spray	Present	1
Y: Heat-Opst. Sid	Applied	1
Z: Lubrication	Regular	1

Noise Condition 2 (Randomly selected order # 3)		
Factors	Level Description	Level #
X: Die Spray	Present	1
Y: Heat-Opst. Sid	Not Appli	2
Z: Lubrication	More Freq	2

Noise Condition 3 (Randomly selected order # 2)		
Factors	Level Description	Level #
X: Die Spray	Absent	2
Y: Heat-Opst. Sid	Applied	1
Z: Lubrication	More Freq	2

Noise Condition 4 (Randomly selected order # 1)		
Factors	Level Description	Level #
X: Die Spray	Absent	2
Y: Heat-Opst. Sid	Not Appli	2
Z: Lubrication	Regular	1

The test results were evaluated by number of defective parts from a group of fixed number of samples (64). Defects were examined under four separate evaluation criteria (Table 1). Standard for identifying a sample as defective was determined by the project team and used to evaluate the results

The trial conditions along with the corresponding noise conditions form the recipe for carrying out the test samples under 48 unique conditions. For each trial condition (Figure 3) there are four noise conditions (Figure 5). Four samples in each trial condition were tested in sequence, by exposing each to the noise condition prescribed. The test was carried out by following the random order of selection of the trial condition and the results (no of defective parts) recorded. The experiment configuration with inner array, outer aray, and the results are shown in Figure 6.

Figure 6. Experiment Configuration with Inner and Outer Array

Review Noise Factors

Outer Array

	1	2	3	4
3	1	2	2	1
2	1	2	1	2
1	1	1	2	2

Review Control Factors

	1	2	3	4	5	6	7	Results 1	Results 2	Results 3	Results 4
1	1	1	1	1	1	1	1	12	11	13	10
2	1	1	1	1	1	2	2	15	12	14	12
3	1	1	2	2	2	1	1	15	11	10	19
4	1	2	1	2	2	1	2	5	7	8	9
5	1	2	2	1	2	2	1	5	4	5	6
6	1	2	2	2	1	2	2	6	8	8	9
7	2	1	2	2	1	1	2	13	16	12	21
8	2	1	2	1	2	2	2	14	12	14	10
9	2	1	1	2	2	2	1	12	11	12	14
10	2	2	2	1	1	1	1	13	11	12	12
11	2	2	1	2	1	2	1	12	15	16	11
12	2	2	1	1	2	1	2	18	17	19	17

Inner Array | Results

QT4 was used to perform most common analysis steps automatically without user inputs. Once quality characteristic, which is *smaller is better* in this experiment, with a few click of the mouse analysis was completed. The calculated values of the factor average effects are shown in Figure 7. The number corresponding to each factor represents the average of results containing the factor level. The difference columns indicates the difference in the average level effects and correspond to the influence of the factors to the variability.

Figure 7. Factor Average Effects and their Level-Effects Differences

Main Effects (Average Effects of Factors and Interactions) Qualitek-4

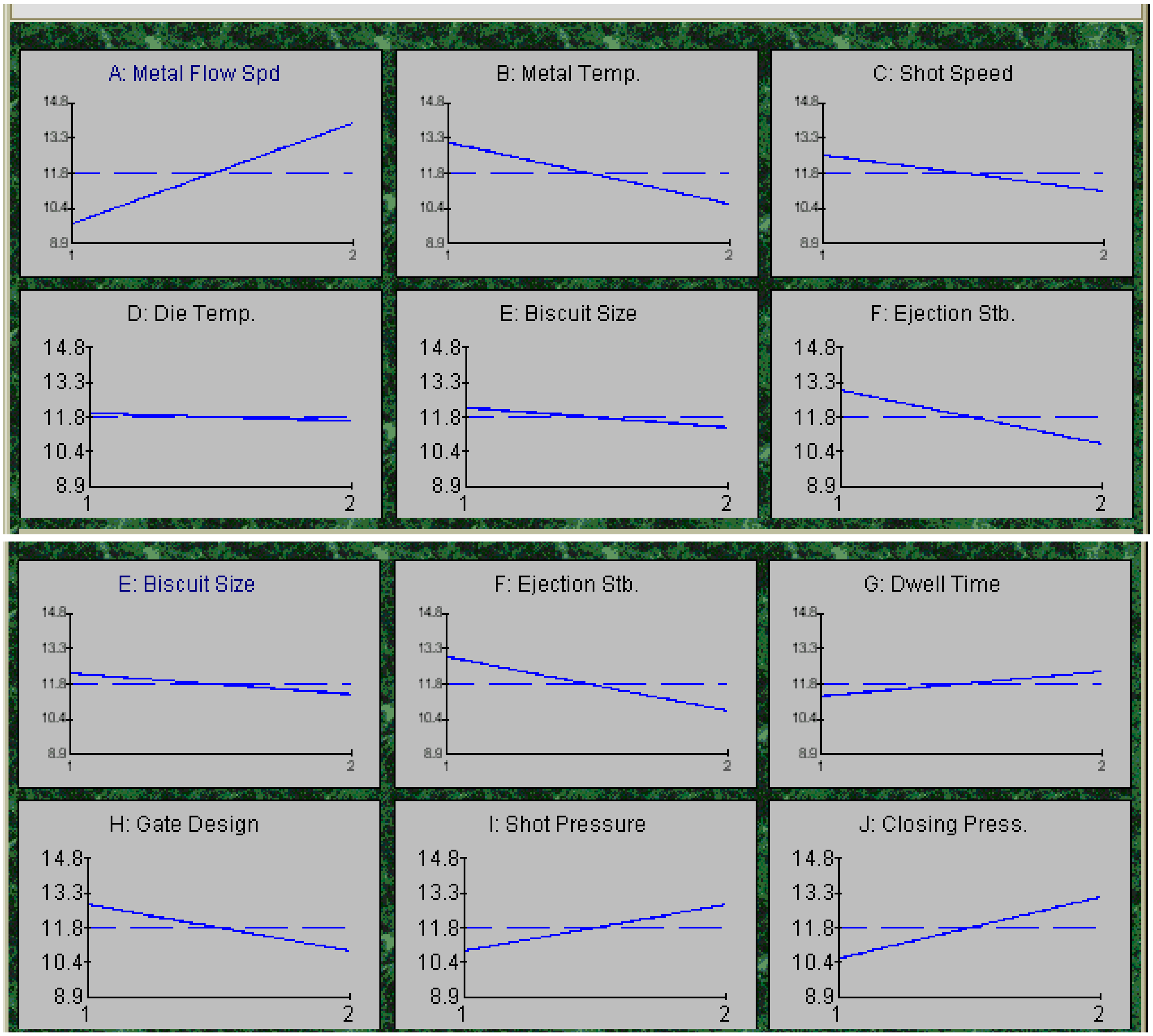
Expt. File: CSEX-101.Q4W Data Type: Average Values

QC Type: Smaller is Better

Column # / Factors	Level 1	Level 2	L2 - L1
1 A: Metal Flow Spd	9.75	13.916	4.166
2 B: Metal Temp.	13.125	10.541	-2.584
3 C: Shot Speed	12.583	11.083	-1.5
4 D: Die Temp.	12	11.666	-.334
5 E: Biscuit Size	12.25	11.416	-.834
6 F: Ejection Stb.	12.958	10.708	-2.25
7 G: Dwell Time	11.333	12.333	1
8 H: Gate Design	12.791	10.875	-1.917
9 I: Shot Pressure	10.875	12.791	1.916
10 J: Closing Press.	10.541	13.125	2.583

A better representation of the factor influence is obtained by plotting the factor influence graphs generally referred as the main effect plots. The main effects (Figure 8) show the trend of influence of the factor influence. The slopes of the lines also show the relative influence of the factor to the variability of results. The main effects of all the factors included in the study are shown in Figure 8. (Biscuit Size and Ejection Pressure plots are repeated in the Figure). Based on the quality characteristic, the desirable design condition was readily determined from this plot.

Figure 8. Plot factor Average Influences (Main Effects)



Analysis of variance (ANOVA) is mainly performed to identify significant factors for the design and information for statistical controls. The ANOVA table in Figure 9 shows the significant factors and their relative influence to the variation of results. The numbers in the right column of the table represents the breakdown of the total influence (100%) to the results in terms of the individual share of the factors. Although, in proportion to the slopes of the main effects of the factors shown earlier, these are better indicators of the relative influence in discrete numbers. The factors that were found insignificant are ignored (POOLED) and offers opportunities for cost savings, as they can be set to any level in the final design.

Figure 9. ANOVA Showing Significant Factors and their Relative Influences

ANOVA Table — Qualitek-4

Expt. File: CSEX-101.Q4W Data Type: Average Value QC Type: Smaller is Better

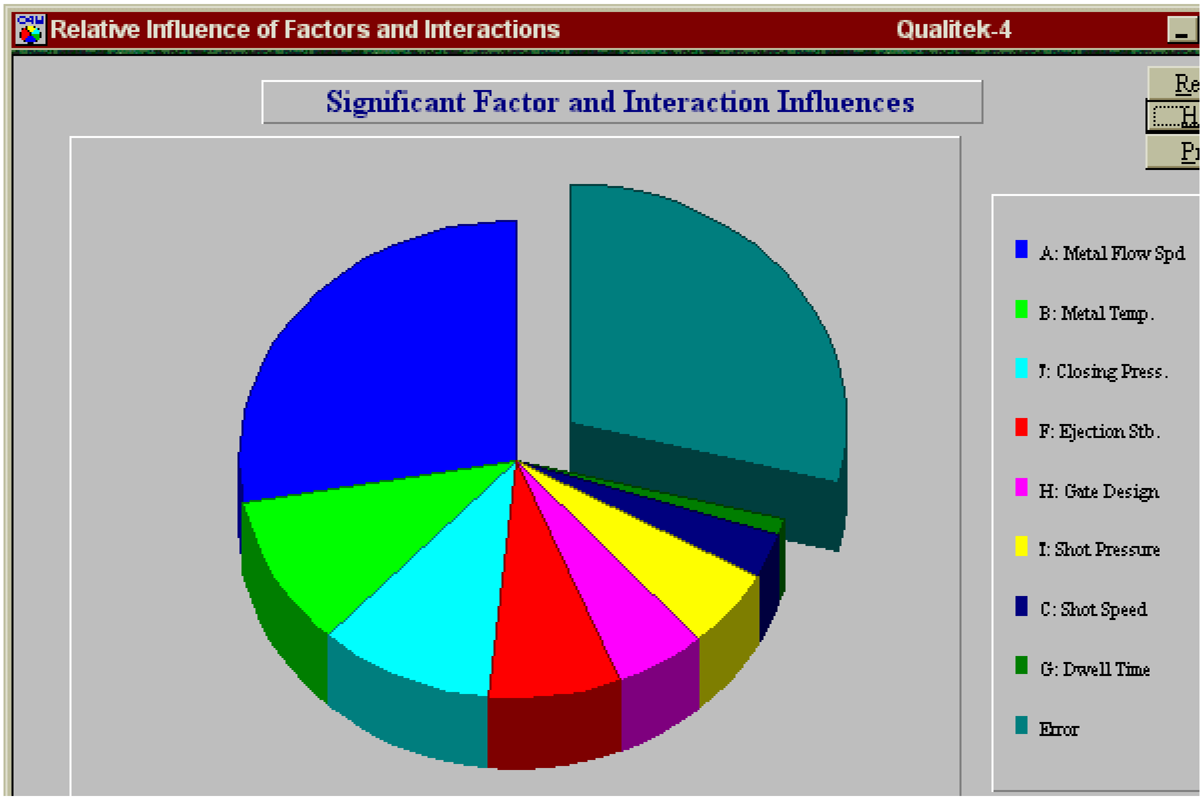
Print | Ok | Help | Cance

Col # / Factor	DOF (f)	Sum of Sqrs. (S)	Variance (V)	F - Ratio (F)	Pure Sum (S')	Percent P(%)
1 A: Metal Flow Spd	1	208.333	208.333	46.099	203.814	27.818
2 B: Metal Temp.	1	80.083	80.083	17.72	75.564	10.313
3 C: Shot Speed	1	26.999	26.999	5.974	22.48	3.068
4 D: Die Temp.	(1)	(1.333)		POOLED	(CL= *NC*)	
5 E: Biscuit Size	(1)	(8.333)		POOLED	(CL=85.14%)	
6 F: Ejection Stb.	1	60.749	60.749	13.442	56.23	7.674
7 G: Dwell Time	1	11.999	11.999	2.655	7.48	1.02
8 H: Gate Design	1	44.083	44.083	9.754	39.564	5.4
9 I: Shot Pressure	1	44.083	44.083	9.754	39.564	5.4
10 J: Closing Press.	1	80.083	80.083	17.72	75.564	10.313
Other/Error	39	176.249	4.519			28.994
Total:	47	732.666				100.00%

The relative influence of the factors to the variation of results is better presented in the form of a pie diagram as shown in Figure 10. The ANOVA shows that the four influential factors, in order of their influence, are factors A, B, J and F. In statistical process control studies the levels of these factors must be carefully held. Factors D & E were found insignificant (less than 90% confidence level). For statistical controls, tolerances for these two factors can be removed. As far as the objective of the experiment is concerned, these factors can be allowed to be uncontrollable (like the noise factors)

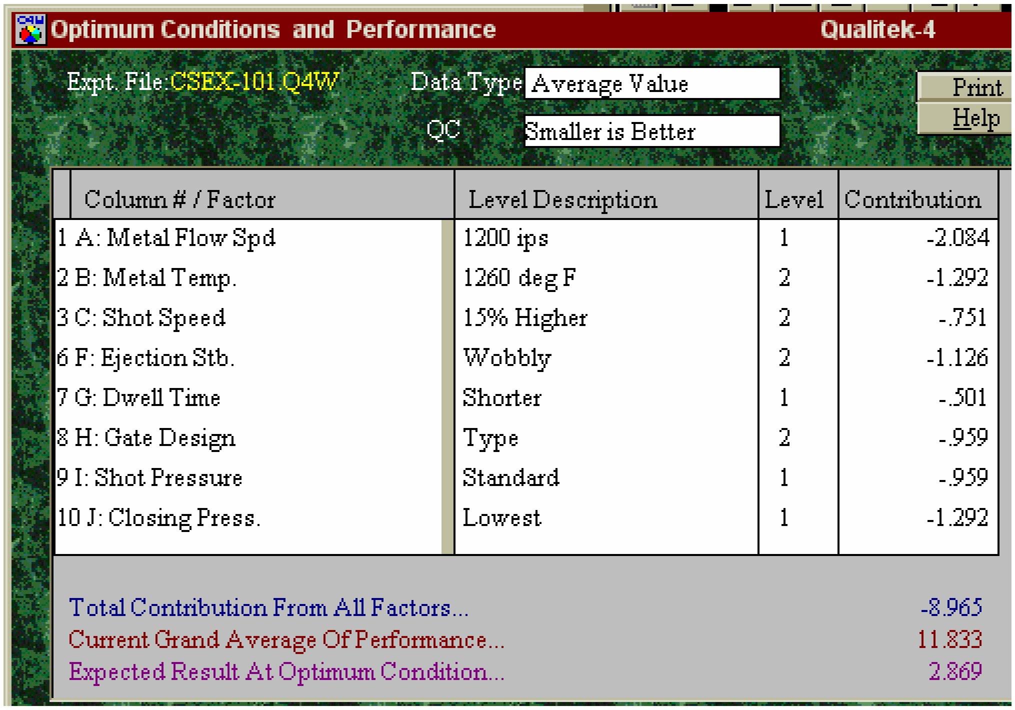
ANOVA also shows that 28.9% of the influence is due to factors not included in the study. The probable source of this influence could be from control factors not included (identified or not) in the experiments, noise factors not included in the experiment, and as always, the ever-present experimental error. (This number by its magnitude, large or small, alone does not necessarily have any reflection on the manner in which the experiment was carried out. Often it presents a better insight into the nature of the project. No matter the magnitude of the influence of the *error term*, the factor relative influence numbers are always meaningful.)

Figure 10. Graphical Display of Relative Influences of the Factors



The most desirable design condition (optimum) is generally determined by selecting the desirable levels of significant factors only. Since we are after smaller result in this project, the factor level that displays smaller average effect (see Figure 8) are selected as the desirable levels of the factor. The optimum condition and the expected performance at the optimum condition are shown in Figure 11. The optimum condition shown is the recommended design combination for best performance. This design condition is expected to lower the defective parts from 12 (average of all tests = 11.833) to about 3 parts (2.869).

Figure 11. Optimum Condition and the Expected performance


Optimum Conditions and Performance — Qualitek-4

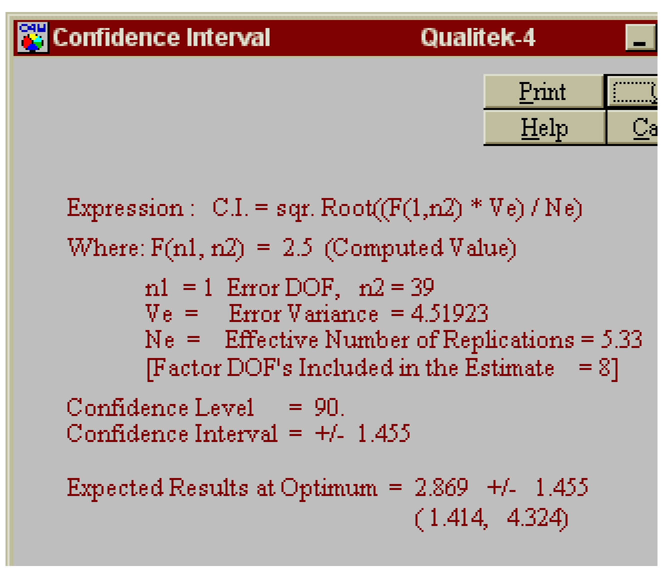
Expt. File: CSEX-101.Q4W — Data Type: Average Value — QC: Smaller is Better

Column # / Factor	Level Description	Level	Contribution
1 A: Metal Flow Spd	1200 ips	1	-2.084
2 B: Metal Temp.	1260 deg F	2	-1.292
3 C: Shot Speed	15% Higher	2	-.751
6 F: Ejection Stb.	Wobbly	2	-1.126
7 G: Dwell Time	Shorter	1	-.501
8 H: Gate Design	Type	2	-.959
9 I: Shot Pressure	Standard	1	-.959
10 J: Closing Press.	Lowest	1	-1.292

Total Contribution From All Factors... -8.965
Current Grand Average Of Performance... 11.833
Expected Result At Optimum Condition... 2.869

ANOVA calculation also provides boundaries of expected performance. The confidence interval (C. I.) on the expected performance at the optimum condition at 90% confidence interval is found to be between 1.4 and 4.3. This means that if 10 sets of samples were tested at the optimum condition, 9 out 10 such sets are expected to produce the mean results between 1.4 and 4.3.

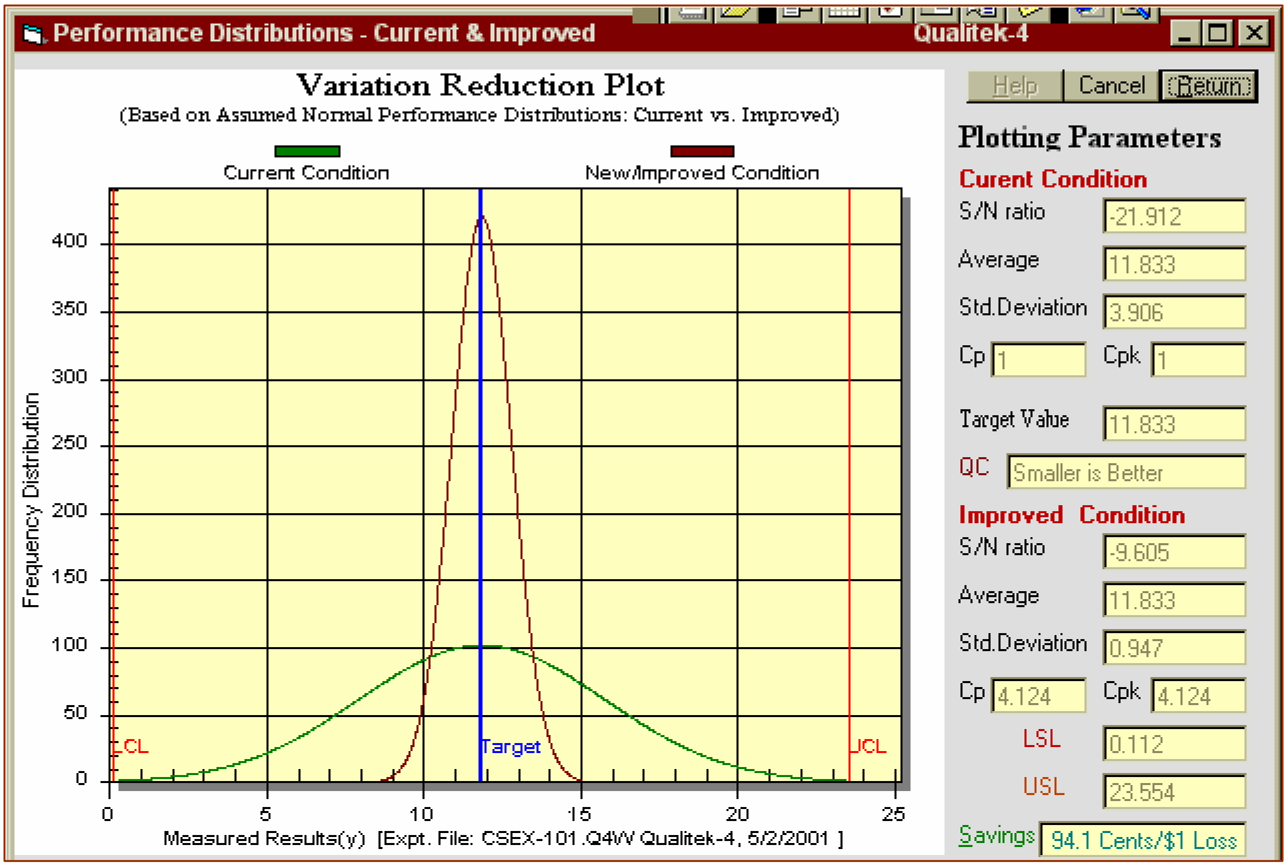
Figure 12. Confidence Interval on the Estimated Performance at the Optimum Condition



In addition to the analyses of results shown above, QT4 automatically presents single plot of performance distributions of current and new designs. From the expected performance improvement data, and some standard assumption, the software can quickly generate some estimate of a few other performance indices like, Cp, Cpk, Loss, etc. as shown Figure 12. Estimate of savings and variation reduction has also been confirmed by analyzing the signal-to-noise (S/N) ratios of the results.

- Factors A: Metal Flow Speed, B: Metal Temperature, J: Closing Pressure and F: Ejection Stability are found to be most significant.
- The new design condition determined from the experimental results is expected to reduce defective parts by 75% (from 12 to 3).
- Factors D: Die Temperature and E: Biscuit Size have the least influence on variability of results. These two factors should be set at levels of least cost.
- When the optimum design condition is incorporated in the production process, it is expected to reduce 94 cents out of every dollar currently spent on rework and rejects.

Figure 12. Variation Reduction and Savings Expected from the Improved Design



References

1. **Genichi Taguchi**. 1987. System of Experimental Design, UNIPUB, Kraus International Publications, New York.
2. **Ranjit K. Roy**. 2001. Design of Experiments Using the Taguchi Approach : 16 Steps to Product and Process Improvement, Hardcover (January 2001) John Wiley & Sons; ISBN: 0471361011 (Available from WWW.AMAZON.COM)
3. **Ranjit K. Roy**. 1990. A Primer on the Taguchi method, Society of Manufacturing Engineers, Dearborn, Michigan, USA. ISBN: 0-87263-468-X Fax: 1-313-240-8252 or 1-313-271-2861 (Also available from WWW.AMAZON.COM)
4. **Ranjit K. Roy, 1996, QUALITEK-4** (for Windows): Software for Automatic Design of Experiment Using Taguchi Approach, IBM or Compatible computer, Nutek, Inc. 3829 Quarton Road, Bloomfield Hills, MI 48302 USA. Tel & Fax: 1-248-540-3212 . Free DEMO from http://www.Nutek-us.com .