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Date:	08 / 10 / 2014
From:	Ian Dalrymple, Statistical Consultant
To:	Acme Medical Devices Inc.
Re:	Statistical Consulting Center Identification Number S14-156 (Final Summary Report)

1.0 RESEARCH FIELD

Medical Device Manufacturing

2.0 TITLE

Characterization of Back Out Torque for Threaded Fasteners

3.0 EXECUTIVE SUMMARY

Several factors are involved in the torque process including the application of Loctite which serves as the threadlocking agent. The intent of this study was to study these factors in detail and if possible provide a 100% verification solution for ensuring Loctite is present.

A single joint was selected by the customer's engineering team as representative to serve as a pilot study for the experimental and analytical `methodology. The joint under study consisted of a stainless steel, 1/4 -20 fastener into an aluminum female substrate with Loctite 242 as the threadlocking agent. Back out torque was used as the response variable of interest for determining robustness of the torque operation.

A controlled experiment was performed with back out torque as the response. The experiment identified all factors as significant at the 0.10 significance level save one main effect and one interaction effect. A model was then constructed given these results and settings determined from the model for back out torque maximization. Using these settings a time vs. back out torque experiment was performed indicating a significant quadratic trend exists between time and back out torque. Finally, the sample groups from the time study were used to conclude there is no possibility of applying a torque check to this threadlocked joint in order to determine Loctite presence. Too much distributional overlap exists between the threadlocked and non-threadlocked devices to properly discern.

4.0 INTRODUCTION

Threaded fasteners are commonplace in the medical device, automotive and various other industries. The process is generally inexpensive from both a material and labor standpoint although the equipment can become elaborate and costly in some cases. Threaded fasteners are used to maintain the relative position of two or more components throughout life of the product. In the tightened state the fastener is stretched within its elastic region thereby providing clamping load to the components being held together. The higher the clamping load the more likely the relative positions will be maintained throughout life. Reference “Bolted Joint Design” by Fastenal Engineering and Design Support (Rev. 3-4-2009) for a comprehensive examination of threaded fastener mechanics.

When the device is subjected to vibration during use threadlocking agents are used to prevent back out. The threadlocker under consideration in this study was Loctite 242 which is manufactured by Henkel. Loctite 242 is a blue liquid that is applied to the bolt threads before insertion. In the tightened state, when no air is present, the threadlocking agent cures “locking” the joint together. The threadlocker in its cured state serves to prevent the bolt from backing out when subjected to vibration.

In some cases failure of a threaded joint can result in user injury or even death. Due to this criticality, verification of threadlocker presence in the proper amount is highly sought after. “Verification” has a very specific meaning in the medical device industry and defines a process or product characteristic that can be measured 100% of the time with an adequate gage.

The primary goal was to determine if a counter-clockwise torque exists that could be used to verify the presence of Loctite. The torque would be chosen such that no damage is done to “good” parts but parts with missing Loctite are caught. In order to achieve this goal several research questions were presented by the client. The questions are enumerated in the following section.

5.0 DATA SOURCES

All experimentation was conducted by the client. Consultation took place before commencement of the project and after the first experiment was conducted.

6.0 MATERIALS AND METHODS

The research questions presented by the client are listed below with the respective methods employed following each question.

i) *Which of the key factors for torque and Loctite application significantly affect the back out torque? Which set of factors provides the highest value of back out torque? Which the lowest? Can a realistic model be developed for the remaining significant factors? Use the model to predict the maximum back-out torque in the design space of the settings tested.*

The explanatory variables under study for the first research question are included in the table below. These settings were provided by the client as realistic ranges for analysis due to cycle time and equipment restrictions.

Variable Name	Quantitative / Categorical	Fixed / Random	Levels
Input Torque	Quantitative	Fixed	60 inch-pounds
			100 inch-pounds
Location of Loctite	Categorical	Fixed	Bottom 1/2 threads
			Top 1/2 of threads
Amount of Loctite	Quantitative	Fixed	1 drop
			3 drops
Oven Temp.	Quantitative	Fixed (Block)	80º Celsius (30 minutes)
			140º Celsius (30 minutes)

Table 1: Explanatory Variables – Research Question 1

The diagram below has been included to provide visual representation of the study performed. The experimental design was a 2 level full factorial with 3 factors and 5 replications. A randomization restriction was present for the oven temp variable since the oven is a batch process and only a single plate was available for testing. In order to minimize the number of exposures of the test block to elevated temperatures the oven temperature variable was treated as a blocking factor. Some consideration was given to a split plot design by the customer but was not chosen due to the effects of repeated exposure of the test block to the elevated temperatures.

The illustration below represents only a single replication, is not randomized and does not include the blocking factor. The full experimental matrix with randomization has been included as Appendix A.

	Predictor		
Run	**Input Torque**	**Loctite Location**	**Loctite Amount**
1	60	Bottom threads	3
2	100	Top Threads	3
3	60	Bottom threads	3
4	100	Top Threads	3
5	60	Bottom threads	1
6	100	Top Threads	1
7	60	Bottom threads	1
8	100	Top Threads	1

Table 2: Study Diagram – Research Question 1

ii) *How does the back out torque vary with respect to curing time when the maximum back out torque settings from the Question 1 model are used?*

The table below outlines the variables under investigation in this portion of the analysis.

Variable Name	Quantitative / Categorical	Levels
Back Out Torque	Quantitative	NA - Response Variable
Time in Oven	Quantitative	0 minutes = control
		10 minutes
		20 minutes
		30 minutes

Table 3: Explanatory Variables – Research Question 2

The diagram below outlines the experimental design strategy taken to answer the second research question. All samples were built using the maximum settings found upon answering the first research question (100 in-lbs, bottom of threads and 3 drops of Loctite). Since the oven temperature was not significant the existing setting of 121º C was used for the samples. The customer has advised that residence times above 30 minutes are not recommended as the device electronics can be damaged.

Run	Time in Oven	Number of Samples
1	0	30
2	10	30
3	20	30
4	30	30

Table 4: Study Diagram – Research Question 2

iii) *What back out torque could be used to perform a Pass / Fail test on 100% of the product to discern those units in which Loctite has NOT been applied? Does the test impact the back-out torque performance via pre-stress?*

Simple distributional analysis and parameter estimation was used to determine a threshold torque value sufficiently above the no Loctite. This choice of back out torque would ensure almost all of the devices missing Loctite would be caught. Similar methods were then used to determine the occurrences per million of “good” joints that would break free when subjected to this torque.

7.0 RESULTS - RESEARCH QUESTION 1

7.1 EXPLORATORY / PRELIMINARY DATA ANALYSIS (EDA)

In order to determine the required number of replicates for the designed experiment a preliminary assessment was performed to estimate the standard deviation for the response (back out torque). Thirty units were built with input torque of 64 in-lbs, leading thread Loctite application and 1 - 3 drops of Loctite.

The boxplot below has been presented to illustrate the general variation in the data set. The distribution is fairly symmetrical with median of approximately 80 in-lbs. The IQR spans from approximately 70 to 90 in-lbs.

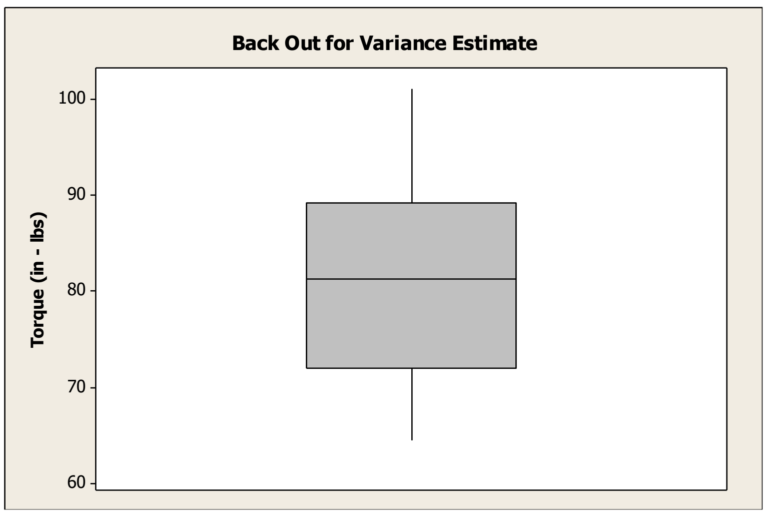


***Figure 1:** Boxplot for Preliminary Variance Estimate – Research Question 1*

The p-value for the Kolmogorov-Smirnov normality test is > 0.150 indicating there is not sufficient evidence present to reject the null of distributional normality assuming a significance level of 0.05. Therefore, the Chi-Square distribution was used to construct an upper bound for the standard deviation for the back out torque. The resulting 95% one sided confidence interval for the standard deviation using this method is 12.9 in-lbs.

An effect size of 15 in-lbs or less with power of 0.8 was the goal for the experiment. Practically, this means 80% of the time the experiment will name a factor significant if the effect is 15 in-lbs or greater. In order to calculate the required number of replicates given the effect size, power and standard deviation the power curve shown below was generated. The plot indicates only 3 replicates are required. Five were performed since extra material was available for experimentation.

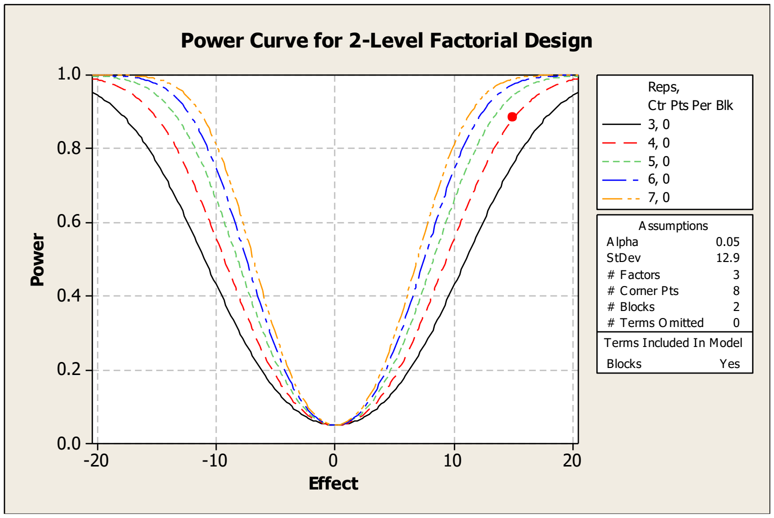


Figure 2: Power Curve for Replication Estimation – Research Question 1

The interaction plots generated from the experimental data are shown below and indicate the blocking factor (oven temp.) does not significantly interact with any of the other main factors. Intersecting lines in the plots with vastly different slopes suggests an interaction is present. In all of the plots the lines are overlaid indicating the effects can be ignored in further model development. In the plots block 1 is 80º C and block 2 140º C. Finally, the Minitab code for all EDA steps for this question has been provided as Appendix B.

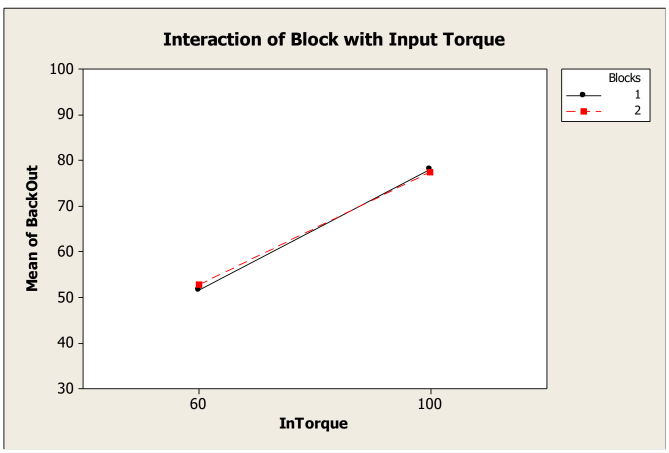


Figure 3.a: Block / Input Torque Interaction

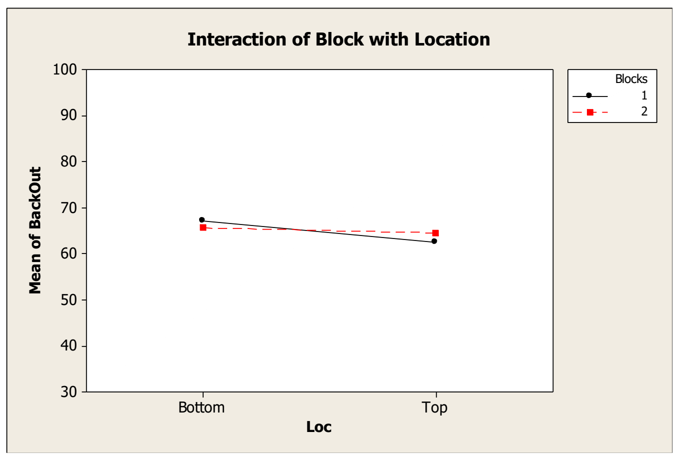


Figure 3.b: Block / Location Interaction

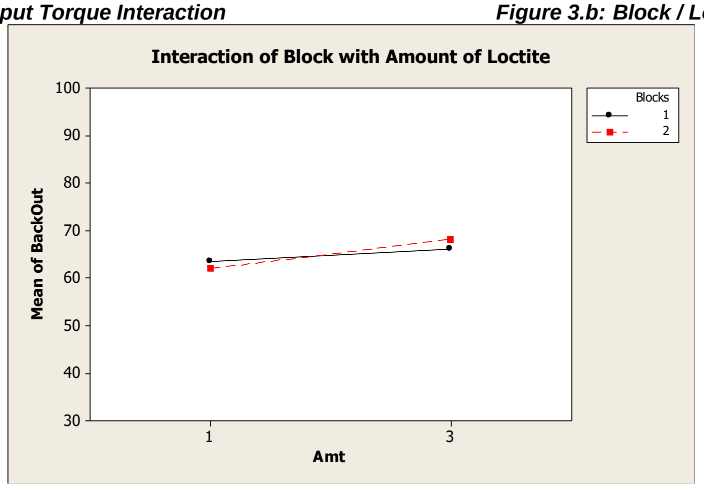


Figure 3.c: Block / Amount Interaction

7.2 STATISTICAL ANALYSIS

Minitab's "Analyze Factorial Design" functionality was utilized to test for significance of the factors. The testing is performed using the general linear model. The ANOVA table from this analysis has been included below. This model assumes the blocking interactions with the other factors are insignificant as shown in the EDA.

Analysis of Variance for BackOut (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Blocks	1	0.76	0.76	0.76	0.10	0.753
Main Effects	3	6837.60	6837.60	2279.20	303.31	0.000
InTorque	1	6556.16	6556.16	6556.16	872.47	0.000
Loc	1	82.08	82.08	82.08	10.92	0.002
Amt	1	199.36	199.36	199.36	26.53	0.000
2-Way Interactions	3	66.85	66.85	22.28	2.97	0.047
InTorque*Loc	1	28.39	28.39	28.39	3.78	0.061
InTorque*Amt	1	30.80	30.80	30.80	4.10	0.051
Loc*Amt	1	7.66	7.66	7.66	1.02	0.320
Residual Error	32	240.46	240.46	7.51		
Pure Error	32	240.46	240.46	7.51		
Total	39	7145.67				

Table 5: Analysis of Variance – Research Question 1

The table indicates the blocking factor is not significant at the 0.10 significance level as the p-value is 0.753. Similarly, the Location*Amount factor has a p-value of 0.320 and should not be considered in forthcoming models for back out torque. A significance level of 0.10 was chosen since the inclusion of additional factors is of no cost to the process and adds very little additional complexity. The adjusted R^2 from the reduced model is 96% meaning the model can explain that percent of the variation seen in the response. The adjusted R^2 accounts for the number of terms in the model such that erroneous terms can serve to reduce this metric.

The least squares means table shown below indicates the maximum average force was achieved for the 100 in-lbs, location bottom and 3 drop run with a value of 81.74 in-lbs. The minimum average back out torque value was for the 60 in-lbs, top and 1 drop run. These results make intuitive sense as more Loctite covering more threads with higher torque should result in higher back out torque.

Least Squares Means for BackOut

	Mean	SE Mean
InTorque		
60	52.14	0.6130
100	77.74	0.6130
Loc		
Bottom	66.37	0.6130
Top	63.51	0.6130
Amt		
1	62.70	0.6130
3	67.17	0.6130
InTorque*Amt		
60 1	50.78	0.8669
100 1	74.63	0.8669
60 3	53.49	0.8669
100 3	80.85	0.8669
Loc*Amt		
Bottom 1	63.70	0.8669
Top 1	61.71	0.8669
Bottom 3	69.04	0.8669
Top 3	65.30	0.8669
InTorque*Loc*Amt		
60 Bottom 1	52.48	1.2259
100 Bottom 1	74.92	1.2259
60 Top 1	**49.08**	**1.2259**
100 Top 1	74.34	1.2259
60 Bottom 3	56.34	1.2259
100 Bottom 3	**81.74**	**1.2259**
60 Top 3	50.64	1.2259
100 Top 3	79.96	1.2259

Table 6: Least Squares Means – Research Question 1

The residuals from the reduced model are well behaved as they are normally distributed, have homogeneity of variance across the fitted values and appear to be independent of one another. The figure below presents the Minitab generated four in one residual plots showing the residual assumptions have been met. This acceptable residual behavior coupled with the R^2 adjusted value of 96% further supports the omission of the blocking factor interactions from the model.

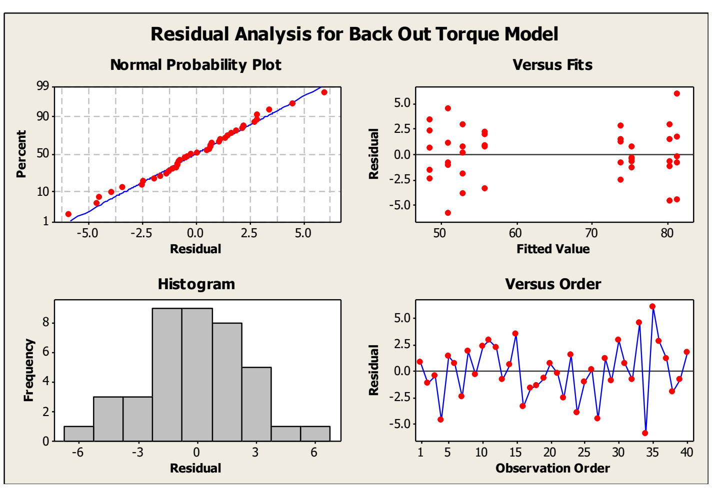


Figure 4: Residual Analysis – Research Question 1

The main and interaction effects plots below have been provided to illustrate the impact of each of the factors on the response, back out torque. In order to maximize back out torque one would maximize input torque and apply three drops of Loctite to the bottom of the fastener. This conclusion is clear from the plots shown below and aligns with the LS means.

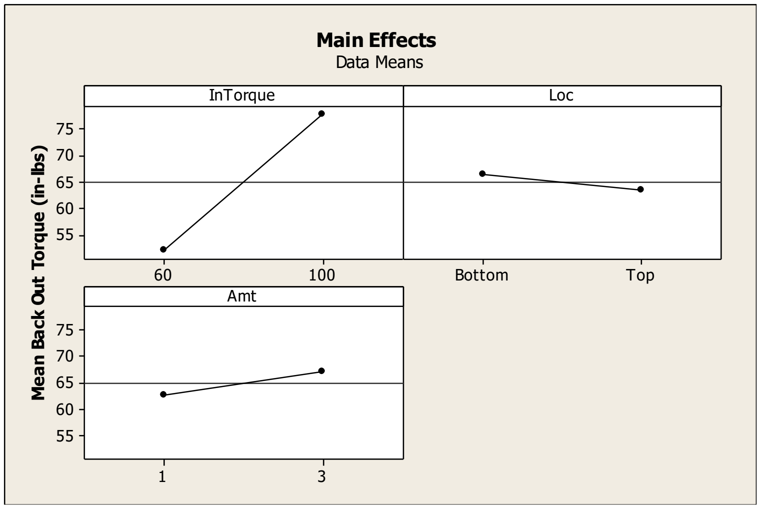


Figure 5.a: Main Effects Plots – Research Question 1

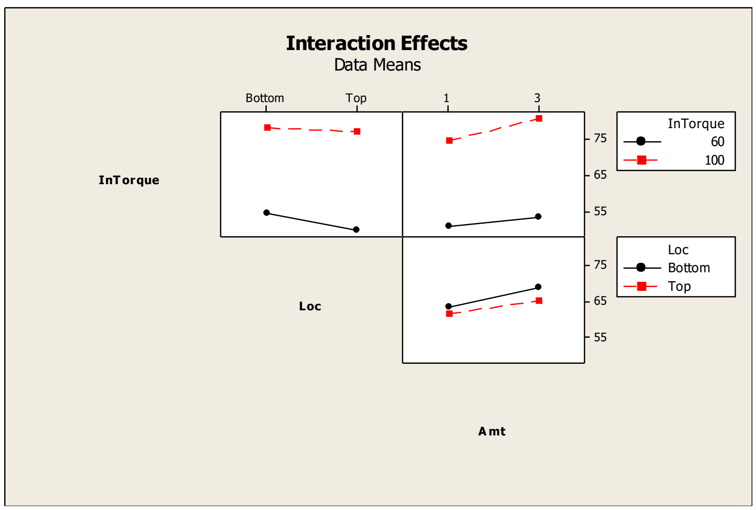


Figure 5.b: Interaction Effects – Research Question 1

The regression coefficients have been assembled below into a response equation for back out torque. This equation can be used to predict the value of back out torque in the design space. The insignificant factors have been removed in construction of the equation.

$$Back\ Out\ Torque = 16.28 + 0.55 * InTorque - 4.80 * Location - 1.28 * Amount + 0.042 * InTorque * Location + 0.044 * InTorque * Amount$$

Equation 1: Response Equation for Back Out Torque – Research Question 1

The equation results in a maximum when the input torque is set to 100 in-lbs, location to bottom and amount to 3 drops. These results are identical to what was seen from the effects plots and analysis of the LS means. The resultant maximum predicted value is 81.44 in-lbs. The comprehensive output from Minitab for the experimental analysis has been included as Appendix C.

8.0 RESULTS – RESEARCH QUESTION 2

8.1 EXPLORATORY / PRELIMINARY DATA ANALYSIS (EDA)

The boxplots below show the general increasing trend in back out torque with time. The profile has a higher slope between points 0 and 10 when compared to the remaining portion of the curve.

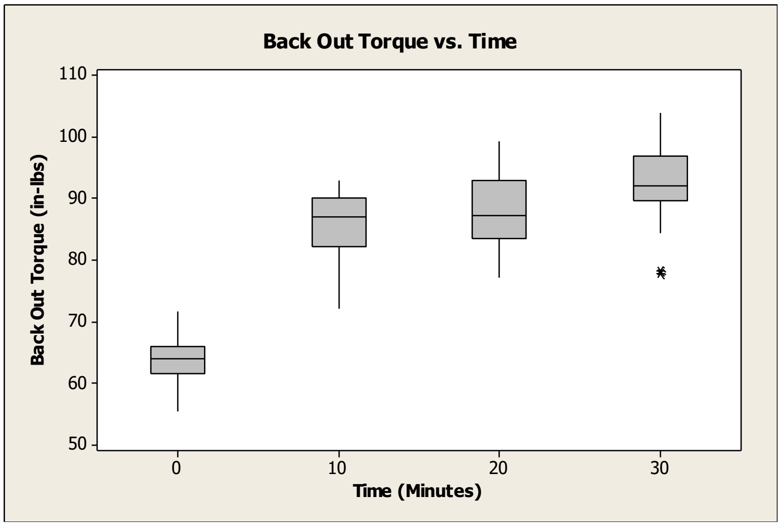


Figure 6: Boxplots of Back Out Torque vs. Time – Research Question 2

Each sample takes approximately 30 seconds to test so 15 minutes can elapse between the first sample tested and the last. Testing was performed to determine if a trend is present within the groups as a result of this additional ambient cure time. The figure below displays the run charts with the associated trend p-values. This trend test method uses the binomial probability distribution to determine the chance of each point lying above or below the median and aggregates these results from each point to form an overall test result. None of the groups exhibited a trend as the p-values are all much greater than the chosen significance level of 0.05.

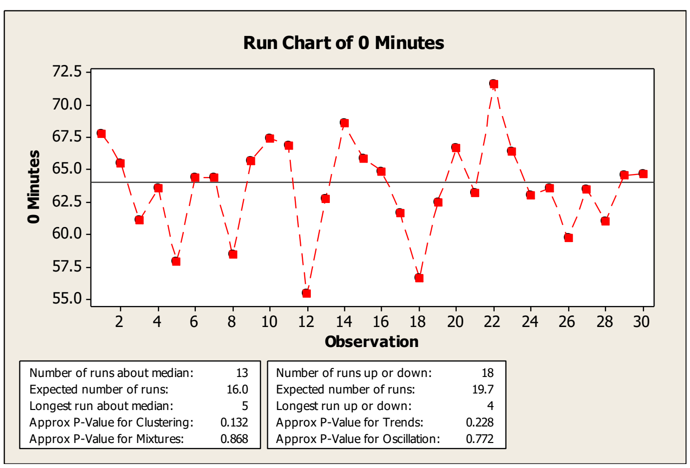


Figure 7.a: Run Charts for 0 Minute Group – Research Question 2

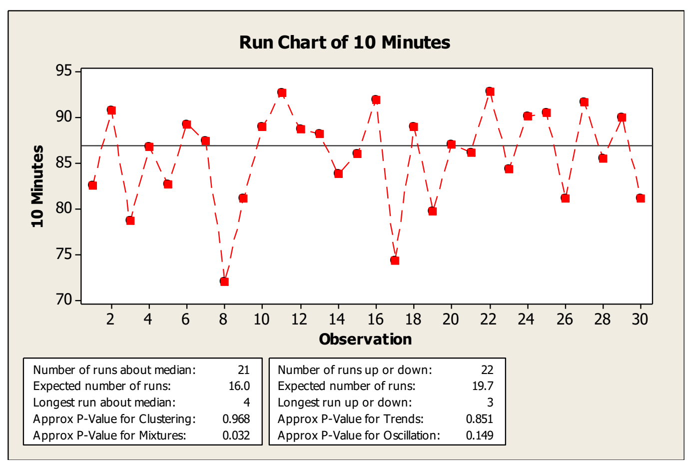


Figure 7.b: Run Charts for 10 Minute Group – Research Question 2

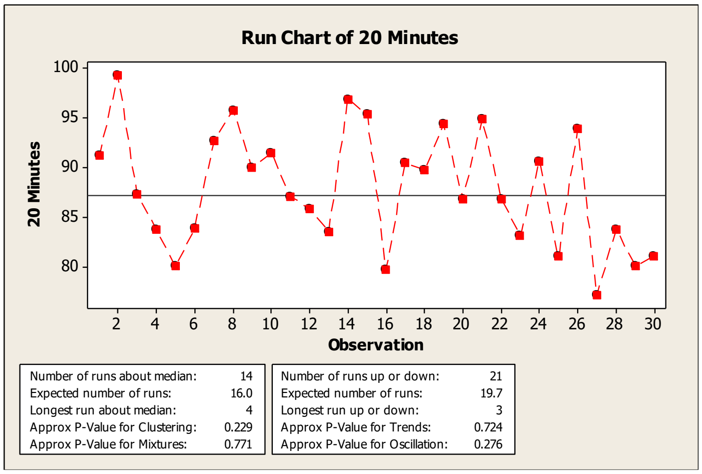


Figure 7.a: Run Charts for 20 Minute Group – Research Question 2

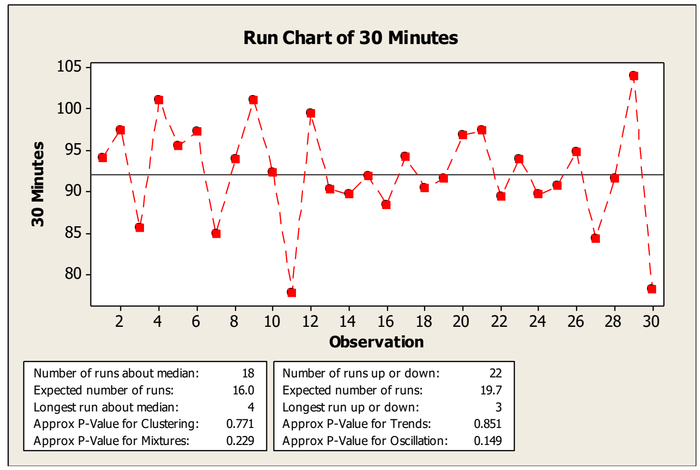


Figure 7.a: Run Charts for 30 Minute Group – Research Question 2

8.2 STATISTICAL ANALYSIS

Simple regression was originally used to model back out torque to curing time. This original model had rather significant curvature present in the residuals vs. fitted values indicating a higher term should be included. Using the Minitab Regression module a model with cure time and cure time squared was fit. The summary results and residual analysis for the regression has been included below. The results indicate all terms in the model are significant. The residuals are well behaved although a slight funnel shape is present in the fitted values plot. Transformation of the response was attempted but only made the residual plots worse so no transformative changes were made. The full Minitab analysis for this research question has been included as Appendix D.

```
The regression equation is
Out = 64.8 - 0.0447 Time^2 + 2.22 Time


Predictor        Coef    SE Coef       T      P
Constant       64.770      1.045   61.99  0.000
Time2       -0.044700   0.005360   -8.34  0.000
Time           2.2209     0.1678   13.24  0.000


S = 5.87111   R-Sq = 77.6%   R-Sq(adj) = 77.3%


Analysis of Variance

Source           DF       SS      MS       F      P
Regression        2  14010.2  7005.1  203.22  0.000
Residual Error  117   4033.0    34.5
Total           119  18043.2
```

Table 7: Regression of Back Out Torque on Time – Research Question 2

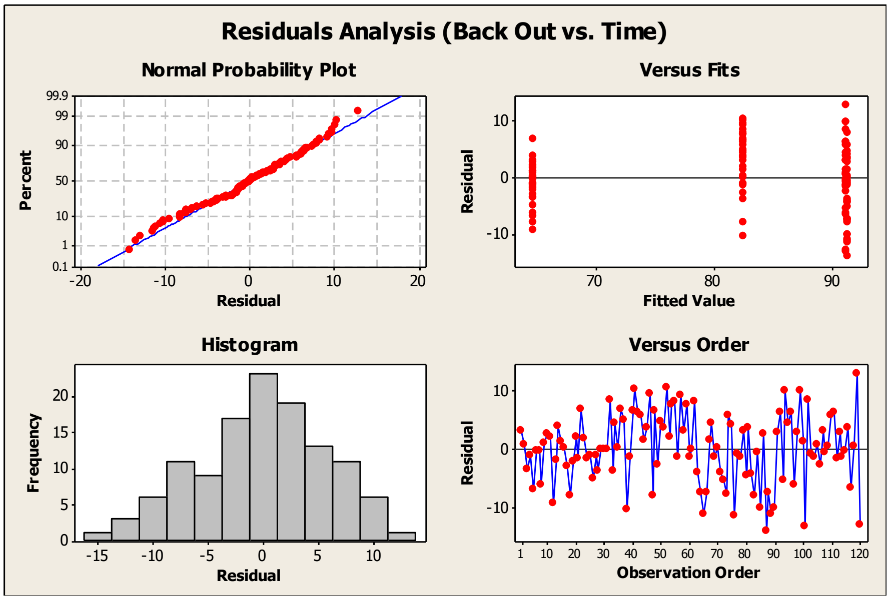


Figure 8: Residual Analysis – Research Question 2

9.0 RESULTS - RESEARCH QUESTION 3

9.1 STATISTICAL ANALYSIS

The summary statistics for each of the time groups has been provided below. All of the distributions can be considered normal since the KS p-values are all greater than 0.05 which is the client's procedurally defined alpha value for normality testing.

Descriptive Statistics: Back Out Torque Time Groups

Variable	Time	Total Count	Mean	StDev	Minimum	Median	Maximum	IQR	Skewness	KS p-value
Out	0	30	63.653	3.604	55.400	64.000	71.600	4.475	-0.38	> 0.150
	10	30	85.860	5.273	72.000	86.950	92.900	7.875	-0.89	> 0.150
	20	30	87.96	5.92	77.20	87.20	99.30	9.50	0.06	> 0.150
	30	30	92.28	6.12	77.80	92.15	104.00	7.38	-0.53	> 0.150

Table 8: Summary Statistics for Time Groups – Research Question 3

Since it is imperative to ensure all product with missing Loctite can be discerned (consumer risk) the check torque value must be set sufficiently far from the mean of the control group (time = 0 minutes). Setting the value at 4 standard deviations above the mean results in 78.07 in-lbs. Four standard deviations above the mean equates to approximately 30 parts per million without Loctite being identified as having Loctite.

The table below summarizes the number of standard deviations the means for each of the cure groups is from 78.07 in-lbs. These values represent the number of parts with Loctite that would identified as not having Loctite.

Group	Standard Deviations Between Mean and 78.07	False Positives per Million
10 minutes	1.47	71000
20 minutes	1.67	47460
30 minutes	2.32	10170

Table 9: Check Torque Summary Table – Research Question 3

As can be seen above the rate of false positives for all groups is unacceptable. The false positive rates can be obtained directly from a standard normal table. Since the false positive rates are so high no further analysis will be performed. This test method is not recommended as a viable option for determining if Loctite is present on this joint with these settings. The full Minitab analysis has been included as Appendix E.

10.0 DISCUSSION

The research questions have been reproduced here with the condensed conclusions:

i) *Which of the key factors for torque and Loctite application significantly affect the back-out torque? Which set of factors provides the highest value of back out torque? Which the lowest? Can a realistic model be developed for the remaining significant factors? Use the model to predict the maximum back-out torque in the design space of the settings tested.*

- The input torque, location of Loctite, amount of Loctite, input torque / location interaction and input torque / amount of Loctite interaction are all significant at the 0.10 significance level.
- The highest back out torque results from input torque equal to 100 in-lbs, amount of Loctite of 3 drops and location at the bottom of the threads.
- The lowest back out torque results from 60 in-lbs input torque, 1 drop of Loctite and application of Loctite to the top of the threads.
- The resulting model is presented in its entirety as Equation 1 which has been reproduced below. The model indicates the maximum back out torque will result from 100 in-lbs input torque, 3 drops of Loctite and application to the bottom of the threads. The oven temperature was not significant so shall be maintained at the current temperature of 121^{O} C. The interactions with the oven temperature were not included in the analysis since the interaction plots showed no interaction.

$$Back\ Out\ Torque = 16.28 + 0.55 * InTorque - 4.80 * Location - 1.28 * Amount + 0.042 * InTorque * Location + 0.044 * InTorque * Amount$$

Equation 1: Response Equation for Back Out Torque

ii) *How does the back-out torque vary with respect to curing time when the maximum back out torque settings from the Question 1 model are used?*

Back out torque increases with increasing residence time in the oven as to be expected. A second order model has been fit with a resulting R^2 of 77.6%. It appears the majority of the curing occurs within the first ten minutes as the plot levels out significantly between 10 and 30 minutes.

iii) *What back-out torque could be used to perform an Pass / Fail test on 100% of the product to discern those units in which Loctite has NOT been applied? Does the test impact the back-out torque performance via pre-stress?*

The false positive rates are unacceptable for all cure times up to 30 minutes. Therefore, a 100% pass / fail test cannot be used to discern product with Loctite from product without Loctite. The impact of a back out pass / fail test on the ultimate back out strength was not evaluated since the test is not recommended.

11.0 ACKNOWLEDGEMENTS

No additional acknowledgements are appropriate.

12.0 REFERENCES

Minitab version 16 was used for all statistical analysis performed in this summary report. Minitab 16 is the standard software package used for statistical analysis by the client.

The code used has been included in the appropriate appendix as referenced in the respective section of the report. An electronic copy of the Minitab working project will be included on the project flash drive with the working copy of the report.

Finally, an electronic copy of “Bolted Joint Design” by Fastenal Engineering and Design Support (Rev. 3-4-2009) has been included on the project flash drive.

13.0 FINAL CONSIDERATIONS

The primary goal of 100 % verification cannot be achieved for times less than or equal to 30 minutes with this Loctite formulation at 121º C. The following two options exist to further pursue the goal of 100% inspection for this specific application:

1) Perform the same experimentation with a different threadlocking formulation such as Loctite 271.

2) Investigate the strength profile with times greater than 30 minutes for much cooler temperatures.

It has been a pleasure working with you on this project. If you have any questions with the summary report please feel free to call me anytime.

Regards,

Ian Dalrymple
586-703-8134

Appendix A

(Full Experimental Matrix – Research Question 1)

StdOrder	RunOrder	CenterPt	Blocks	InTorque	Loc	Amt	BackOut
31	1	1	2	60	Bottom	3	56.7
40	2	1	2	100	Top	3	79.2
37	3	1	2	100	Bottom	1	74.9
32	4	1	2	100	Top	3	75.8
36	5	1	2	100	Top	3	81.8
25	6	1	2	100	Bottom	1	76.1
34	7	1	2	60	Top	1	46.2
23	8	1	2	60	Bottom	3	57.8
21	9	1	2	100	Bottom	1	75
38	10	1	2	60	Top	1	50.9
28	11	1	2	100	Top	3	83.3
35	12	1	2	60	Bottom	3	58.1
33	13	1	2	100	Bottom	1	74.6
22	14	1	2	60	Top	1	49.2
26	15	1	2	60	Top	1	52.1
27	16	1	2	60	Bottom	3	52.5
30	17	1	2	60	Top	1	47
29	18	1	2	100	Bottom	1	74
24	19	1	2	100	Top	3	79.7
39	20	1	2	60	Bottom	3	56.6
11	21	1	1	100	Bottom	3	81.1
10	22	1	1	100	Top	1	71.4
14	23	1	1	100	Top	1	75.4
13	24	1	1	60	Bottom	1	49
4	25	1	1	60	Top	3	50
17	26	1	1	60	Bottom	1	53
7	27	1	1	100	Bottom	3	76.8
6	28	1	1	100	Top	1	75.1
16	29	1	1	60	Top	3	50.2
9	30	1	1	60	Bottom	1	55.8
5	31	1	1	60	Bottom	1	53.6
19	32	1	1	100	Bottom	3	80.5
20	33	1	1	60	Top	3	55.6
8	34	1	1	60	Top	3	45.2
3	35	1	1	100	Bottom	3	87.3
2	36	1	1	100	Top	1	76.7
12	37	1	1	60	Top	3	52.2
1	38	1	1	60	Bottom	1	51
18	39	1	1	100	Top	1	73.1
15	40	1	1	100	Bottom	3	83

Appendix B

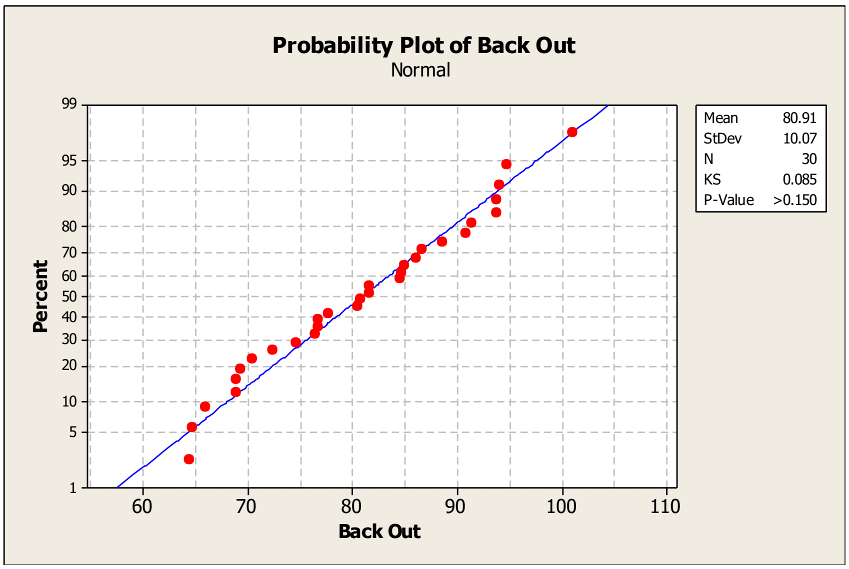
(EDA Minitab Output – Research Question 1)

Boxplot for Standard Deviation Estimate

```
MTB > Boxplot 'Back Out';
SUBC>   IQRBox;
SUBC>   Outlier.
```

Normality Test for Standard Deviation Estimate

```
MTB > NormTest 'Back Out';
SUBC>   KSTest.
```



Confidence Limit for Standard Deviation

```
MTB > OneVariance 'Back Out';
SUBC>   Confidence 95.0;
SUBC>   Alternative -1.
```

Test and CI for One Variance: Back Out

```
Method

The chi-square method is only for the normal distribution.
The Bonett method is for any continuous distribution.


Statistics

Variable   N  StDev  Variance
Back Out  30   10.1       101


95% One-Sided Confidence Intervals

                      Upper
                      Bound
                        for   Upper Bound
Variable  Method      StDev  for Variance
Back Out  Chi-Square   12.9           166
          Bonett       12.3           151
```

Power Curve Generation

```
MTB > Power;
SUBC>   FFDesign 3 8;
SUBC>     Effect 15;
SUBC>     Power 0.8;
SUBC>     CPBlock 0;
SUBC>     Sigma 12.9;
SUBC>     Blocks 2;
SUBC>     FitC;
SUBC>     FitB;
SUBC>   GPCurve;
SUBC>     NSize 3 4 5 6 7.
```

Power and Sample Size

```
2-Level Factorial Design

Alpha = 0.05  Assumed standard deviation = 12.9

Factors: 3   Base Design: 3, 8
Blocks:  2

Including blocks in model.
```

Center Points Per Block	Effect	Reps	Total Runs	Target Power	Actual Power
0	15	4	32	0.8	0.882745

Power Curve for 2-Level Factorial Design

<u>Interaction with Blocking Factor</u>

```
MTB > LPlot Mean( 'BackOut' ) * 'InTorque';
SUBC>   Group 'Blocks';
SUBC>   Symbol 'Blocks';
SUBC>   Connect 'Blocks'.
```

Line Plot of Mean(BackOut)

```
MTB > LPlot Mean( 'BackOut' ) * 'Loc';
SUBC>   Group 'Blocks';
SUBC>   Symbol 'Blocks';
SUBC>   Connect 'Blocks'.
```

Line Plot of Mean(BackOut)

```
MTB > LPlot Mean( 'BackOut' ) * 'Amt';
SUBC>   Group 'Blocks';
SUBC>   Symbol 'Blocks';
SUBC>   Connect 'Blocks'.
```

Line Plot of Mean(BackOut)

Appendix C

(Experimental Analysis Minitab Output – Research Question 1)

Analyze Factorial Design for Model Generation (First pass with all terms included save third order)

Factorial Fit: BackOut versus Block, InTorque, Loc, Amt

Estimated Effects and Coefficients for BackOut (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		64.938	0.4334	149.82	0.000
Block		-0.138	0.4334	-0.32	0.753
InTorque	25.605	12.802	0.4334	29.54	0.000
Loc	-2.865	-1.432	0.4334	-3.31	0.002
Amt	4.465	2.233	0.4334	5.15	0.000
InTorque*Loc	1.685	0.843	0.4334	1.94	0.061
InTorque*Amt	1.755	0.877	0.4334	2.02	0.051
Loc*Amt	-0.875	-0.438	0.4334	-1.01	0.320

S = 2.74126 PRESS = 375.725
R-Sq = 96.63% R-Sq(pred) = 94.74% R-Sq(adj) = 95.90%

Analysis of Variance for BackOut (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Blocks	1	0.76	0.76	0.76	0.10	0.753
Main Effects	3	6837.60	6837.60	2279.20	303.31	0.000
InTorque	1	6556.16	6556.16	6556.16	872.47	0.000
Loc	1	82.08	82.08	82.08	10.92	0.002
Amt	1	199.36	199.36	199.36	26.53	0.000
2-Way Interactions	3	66.85	66.85	22.28	2.97	0.047
InTorque*Loc	1	28.39	28.39	28.39	3.78	0.061
InTorque*Amt	1	30.80	30.80	30.80	4.10	0.051
Loc*Amt	1	7.66	7.66	7.66	1.02	0.320
Residual Error	32	240.46	240.46	7.51		
Pure Error	32	240.46	240.46	7.51		
Total	39	7145.67				

Unusual Observations for BackOut

Obs	StdOrder	BackOut	Fit	SE Fit	Residual	St Resid
27	7	76.8000	81.7400	1.2259	-4.9400	-2.01R
33	20	55.6000	50.6400	1.2259	4.9600	2.02R
34	8	45.2000	50.6400	1.2259	-5.4400	-2.22R
35	3	87.3000	81.7400	1.2259	5.5600	2.27R

R denotes an observation with a large standardized residual.

Estimated Coefficients for BackOut using data in uncoded units

Term	Coef
Constant	16.2825
Block	-0.137500
InTorque	0.552375
Loc	-3.92750
Amt	-1.27750
InTorque*Loc	0.0421250
InTorque*Amt	0.0438750

```
Loc*Amt        -0.437500


Least Squares Means for BackOut

               Mean  SE Mean
InTorque
  60          52.14   0.6130
 100          77.74   0.6130
Loc
 Bottom       66.37   0.6130
 Top          63.51   0.6130
Amt
 1            62.70   0.6130
 3            67.17   0.6130
InTorque*Amt
  60 1        50.78   0.8669
 100 1        74.63   0.8669
  60 3        53.49   0.8669
 100 3        80.85   0.8669
Loc*Amt
 Bottom 1     63.70   0.8669
 Top 1        61.71   0.8669
 Bottom 3     69.04   0.8669
 Top 3        65.30   0.8669


Alias Structure
I
Blocks = InTorque*Loc*Amt
InTorque
Loc
Amt
InTorque*Loc
InTorque*Amt
Loc*Amt
```

Residual Plots for BackOut

Analyze Factorial Design for Model Generation (Insignificant Removed)

```
MTB > FFactorial 'BackOut' = C5 C6 C7 C5*C6 C5*C7;
SUBC>   Design C5 C6 C7 C4;
SUBC>   Order C1;
SUBC>   InUnit 1;
SUBC>   Levels 60 100 "Bottom" "Top" 1 3;
SUBC>   CTPT C3;
SUBC>   GFourpack C2;
SUBC>   Brief 2;
SUBC>   Alias;
SUBC>   Means C5 C6 C7 C5*C7.
```

Factorial Fit: BackOut versus InTorque, Loc, Amt

Estimated Effects and Coefficients for BackOut (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		64.938	0.4278	151.80	0.000
InTorque	25.605	12.802	0.4278	29.93	0.000
Loc	-2.865	-1.432	0.4278	-3.35	0.002
Amt	4.465	2.232	0.4278	5.22	0.000
InTorque*Loc	1.685	0.842	0.4278	1.97	0.057
InTorque*Amt	1.755	0.877	0.4278	2.05	0.048

```
S = 2.70553      PRESS = 344.466
R-Sq = 96.52%   R-Sq(pred) = 95.18%   R-Sq(adj) = 96.00%
```

Analysis of Variance for BackOut (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	6837.60	6837.60	2279.20	311.37	0.000
InTorque	1	6556.16	6556.16	6556.16	895.66	0.000
Loc	1	82.08	82.08	82.08	11.21	0.002
Amt	1	199.36	199.36	199.36	27.24	0.000
2-Way Interactions	2	59.19	59.19	29.60	4.04	0.027
InTorque*Loc	1	28.39	28.39	28.39	3.88	0.057
InTorque*Amt	1	30.80	30.80	30.80	4.21	0.048
Residual Error	34	248.88	248.88	7.32		
Lack of Fit	2	8.41	8.41	4.21	0.56	0.577
Pure Error	32	240.46	240.46	7.51		
Total	39	7145.67				

Unusual Observations for BackOut

Obs	StdOrder	BackOut	Fit	SE Fit	Residual	St Resid
34	8	45.2000	51.2150	1.0478	-6.0150	-2.41R
35	3	87.3000	81.4400	1.0478	5.8600	2.35R

R denotes an observation with a large standardized residual.

Estimated Coefficients for BackOut using data in uncoded units

Term	Coef
Constant	16.2825
InTorque	0.552375
Loc	-4.80250
Amt	-1.27750
InTorque*Loc	0.0421250

```
InTorque*Amt  0.0438750


Least Squares Means for BackOut

               Mean  SE Mean
InTorque
  60          52.14   0.6050
 100          77.74   0.6050
Loc
 Bottom       66.37   0.6050
 Top          63.51   0.6050
Amt
 1            62.70   0.6050
 3            67.17   0.6050
InTorque*Amt
  60 1        50.78   0.8556
 100 1        74.63   0.8556
  60 3        53.49   0.8556
 100 3        80.85   0.8556


Alias Structure
I
InTorque
Loc
Amt
InTorque*Loc
InTorque*Amt
```

Residual Plots for BackOut

Analyze Factorial Design for Least Squares Means

```
MTB > FFactorial 'BackOut' = C5 C6 C7 C5*C6 C5*C7 C6*C7 C5*C6*C7;
SUBC>   Design C5 C6 C7 C4;
SUBC>   Order C1;
SUBC>   InUnit 1;
SUBC>   Levels 60 100 "Bottom" "Top" 1 3;
SUBC>   CTPT C3;
SUBC>   GFourpack C2;
SUBC>   Brief 2;
SUBC>   Alias;
SUBC>   Means C5 C6 C7 C5*C7 C6*C7 C5*C6*C7.
```

Factorial Fit: BackOut versus InTorque, Loc, Amt

Estimated Effects and Coefficients for BackOut (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		64.938	0.4334	149.82	0.000
InTorque	25.605	12.802	0.4334	29.54	0.000
Loc	-2.865	-1.432	0.4334	-3.31	0.002
Amt	4.465	2.232	0.4334	5.15	0.000
InTorque*Loc	1.685	0.842	0.4334	1.94	0.061
InTorque*Amt	1.755	0.877	0.4334	2.02	0.051
Loc*Amt	-0.875	-0.438	0.4334	-1.01	0.320
InTorque*Loc*Amt	0.275	0.138	0.4334	0.32	0.753

S = 2.74126   PRESS = 375.725
R-Sq = 96.63%   R-Sq(pred) = 94.74%   R-Sq(adj) = 95.90%

Analysis of Variance for BackOut (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	6837.60	6837.60	2279.20	303.31	0.000
InTorque	1	6556.16	6556.16	6556.16	872.47	0.000
Loc	1	82.08	82.08	82.08	10.92	0.002
Amt	1	199.36	199.36	199.36	26.53	0.000
2-Way Interactions	3	66.85	66.85	22.28	2.97	0.047
InTorque*Loc	1	28.39	28.39	28.39	3.78	0.061
InTorque*Amt	1	30.80	30.80	30.80	4.10	0.051
Loc*Amt	1	7.66	7.66	7.66	1.02	0.320
3-Way Interactions	1	0.76	0.76	0.76	0.10	0.753
InTorque*Loc*Amt	1	0.76	0.76	0.76	0.10	0.753
Residual Error	32	240.46	240.46	7.51		
Pure Error	32	240.46	240.46	7.51		
Total	39	7145.67				

Unusual Observations for BackOut

Obs	StdOrder	BackOut	Fit	SE Fit	Residual	St Resid
27	7	76.8000	81.7400	1.2259	-4.9400	-2.01R
33	20	55.6000	50.6400	1.2259	4.9600	2.02R
34	8	45.2000	50.6400	1.2259	-5.4400	-2.22R
35	3	87.3000	81.7400	1.2259	5.5600	2.27R

R denotes an observation with a large standardized residual.

Estimated Coefficients for BackOut using data in uncoded units

```
Term                 Coef
Constant          16.2825
InTorque         0.552375
Loc              -2.82750
Amt              -1.27750
InTorque*Loc    0.0283750
InTorque*Amt    0.0438750
Loc*Amt          -0.98750
InTorque*Loc*Amt 0.0068750

Least Squares Means for BackOut

                   Mean  SE Mean
InTorque
  60              52.14   0.6130
 100              77.74   0.6130
Loc
 Bottom           66.37   0.6130
 Top              63.51   0.6130
Amt
 1                62.70   0.6130
 3                67.17   0.6130
InTorque*Amt
  60 1            50.78   0.8669
 100 1            74.63   0.8669
  60 3            53.49   0.8669
 100 3            80.85   0.8669
Loc*Amt
 Bottom 1         63.70   0.8669
 Top 1            61.71   0.8669
 Bottom 3         69.04   0.8669
 Top 3            65.30   0.8669
InTorque*Loc*Amt
  60 Bottom 1     52.48   1.2259
 100 Bottom 1     74.92   1.2259
  60 Top 1        49.08   1.2259
 100 Top 1        74.34   1.2259
  60 Bottom 3     56.34   1.2259
 100 Bottom 3     81.74   1.2259
  60 Top 3        50.64   1.2259
 100 Top 3        79.96   1.2259

Alias Structure
I
InTorque
Loc
Amt
InTorque*Loc
InTorque*Amt
Loc*Amt
InTorque*Loc*Amt
```

Residual Plots for BackOut

Main and Interaction Effects Plots

```
MTB > FFMain C5 C6 C7;
SUBC>   Resp 'BackOut';
SUBC>   InUnit 1;
SUBC>   Levels 60 100 "Bottom" "Top" 1 3;
SUBC>   CTPT C3.
```

Main Effects Plot for BackOut

```
MTB > FFInt C5 C6 C7;
SUBC>   Resp 'BackOut';
SUBC>   InUnit 1;
SUBC>   Levels 60 100 "Bottom" "Top" 1 3;
SUBC>   CTPT C3.
```

Interaction Plot for BackOut

Appendix D
(Experimental Analysis Minitab Output – Research Question 2)

Boxplots of Back Out Torque vs. Time

```
MTB > Boxplot ( 'Out' ) * 'Time';
SUBC>   IQRBox;
SUBC>   Outlier.
```

Boxplot of Out

Run Charts for Back Out Torque within Time Groupings

```
MTB > RunChart '0 Minutes' 1.
```

Run Chart of 0 Minutes

```
MTB > RunChart '10 Minutes' 1.
```

Run Chart of 10 Minutes

```
MTB > RunChart '20 Minutes' 1.
```

Run Chart of 20 Minutes

```
MTB > RunChart '30 Minutes' 1.
```

Run Chart of 30 Minutes

Back Out vs. Time Regression Analysis

```
MTB > Regress 'Out' 2 'Time2' 'Time';
SUBC>   GFourpack;
SUBC>   RType 1;
SUBC>   Constant;
SUBC>   Brief 2.
```

Regression Analysis: Out versus Time2, Time

```
The regression equation is
Out = 64.8 - 0.0447 Time2 + 2.22 Time


Predictor        Coef   SE Coef      T      P
Constant       64.770     1.045  61.99  0.000
Time2       -0.044700  0.005360  -8.34  0.000
Time           2.2209    0.1678  13.24  0.000


S = 5.87111   R-Sq = 77.6%   R-Sq(adj) = 77.3%


Analysis of Variance

Source           DF       SS      MS       F      P
Regression        2  14010.2  7005.1  203.22  0.000
Residual Error  117   4033.0    34.5
Total           119  18043.2


Source  DF  Seq SS
Time2    1  7970.7
Time     1  6039.5


Unusual Observations

Obs  Time2      Out     Fit  SE Fit  Residual  St Resid
 87    400   77.200  91.308   0.795   -14.108     -2.43R
101    900   77.800  91.166   1.045   -13.366     -2.31R
119    900  104.000  91.166   1.045    12.834      2.22R
120    900   78.200  91.166   1.045   -12.966     -2.24R

R denotes an observation with a large standardized residual.
```

Residual Plots for Out

Appendix E
(Experimental Analysis Minitab Output – Research Question 3)

Descriptive Statistics for Time Groupings

```
MTB > Describe 'Out';
SUBC>   By 'Time';
SUBC>   Mean;
SUBC>   StDeviation;
SUBC>   Median;
SUBC>   IQRange;
SUBC>   Minimum;
SUBC>   Maximum;
SUBC>   Skewness;
SUBC>   Kurtosis;
SUBC>   Count.
```

Descriptive Statistics: Out

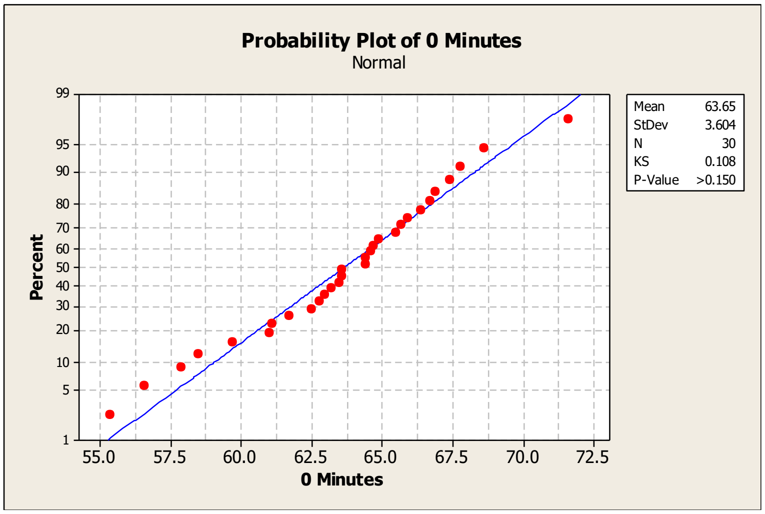
Variable	Time	Total Count	Mean	StDev	Minimum	Median	Maximum	IQR	Skewness
Out	0	30	63.653	3.604	55.400	64.000	71.600	4.475	-0.38
	10	30	85.860	5.273	72.000	86.950	92.900	7.875	-0.89
	20	30	87.96	5.92	77.20	87.20	99.30	9.50	0.06
	30	30	92.28	6.12	77.80	92.15	104.00	7.38	-0.53

Variable	Time	Kurtosis
Out	0	0.35
	10	0.47
	20	-1.01
	30	0.55

Normality Testing for Time Groupings

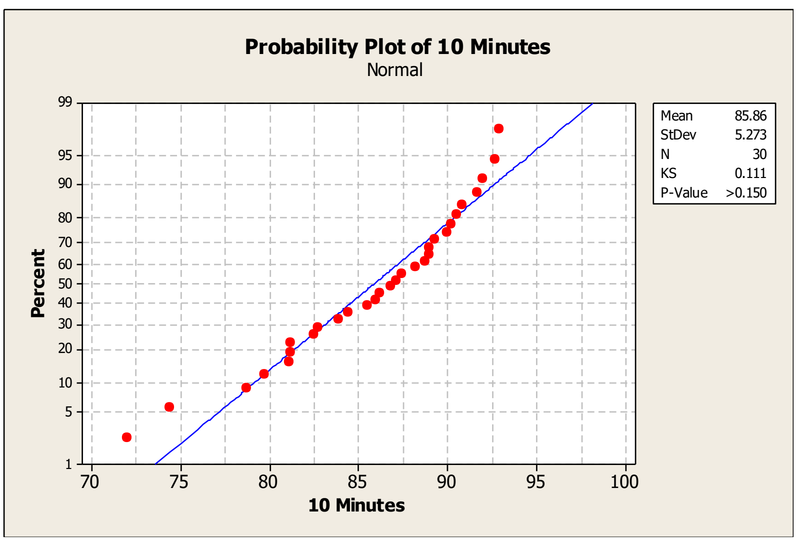
```
MTB > NormTest '0 Minutes';
SUBC>   KSTest.
```

Probability Plot of 0 Minutes



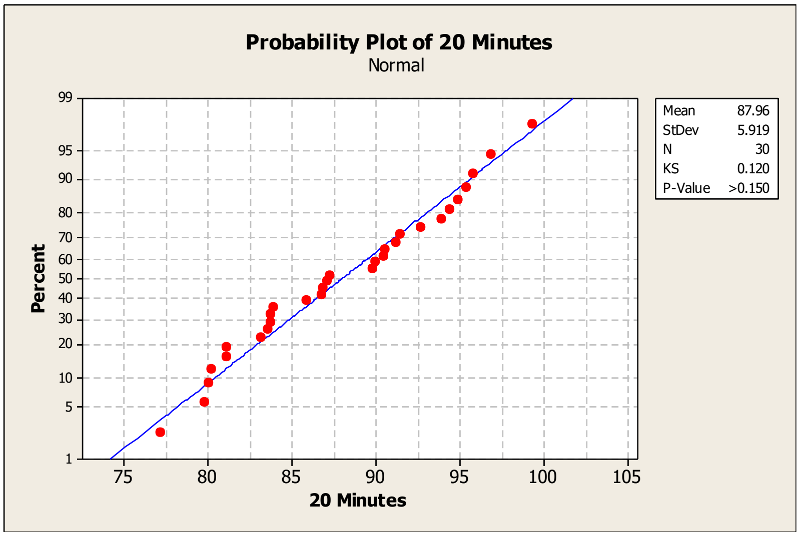

```
MTB > NormTest '10 Minutes';
SUBC>   KSTest.
```

Probability Plot of 10 Minutes



```
MTB > NormTest '20 Minutes';
SUBC>   KSTest.
```

Probability Plot of 20 Minutes




```
MTB > NormTest '30 Minutes';
SUBC>   KSTest.
```

Probability Plot of 30 Minutes