Research Report on

FALEX HEATER TUBE EQUIVALENCY STUDY

by

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for

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Approved by:

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Research Facility (SwRI®)

Falex Heater Tube Equivalency Study

Conducted in accordance with RR-D02:1550 "Test Program to Establish Equivalence of Heater Tubes in ASTM D3241".

June 2010

Introduction

In the last decade there has been interest in having additional suppliers of the consumables for ASTM D3241, the Standard Test Method for Thermal Oxidative Stability of Aviation Turbine Fuels. While many of the properties of the requisite heater tubes are reducible to standardized values the subjective nature of the test evaluation requires that any alternative be compatible. To address this need, Subcommittee D.02.J developed and approved a protocol that addresses the subjective nature of the test in an analytical fashion. This report covers the use of that protocol, RR-D02:1550, in the evaluation of a candidate alternative heater tube and filter kit supplier.

Summary

Falex Corporation (Sugar Grove, IL) is a well established supplier of test apparatus and consumables for ASTM methods. Falex engaged Southwest Research Institute (SwRI) to organize and conduct the equivalency study. The program was acknowledged by Subcommittee D.02.J at the Summer 2009 meeting and George Wilson, SwRI, was appointed as the Task Force Chair[1]. The testing and evaluation was conducted during the fall semester of 2009 and spring semester of 2010.

The protocol has four distinct components:

- Part 1: Tube Metallurgy and Dimensions
- Part 2: Program to Establish Equivalency in Pretest Rating
- Part 3: ASTM D3241 Performance Equivalence Testing
- Part 4: Determination of Equivalence

The discussion of these elements follows this summary and for convenience each section starts at the top of a page.

The testing was completed successfully and the recommendation is that method D3241 be modified to identify Falex as a recognized supplier of heater tube and filter kits.

[1] Subcommittee D.02.J policy is that all commercial equivalence efforts are the responsibility of the interested party. Task Force assignments for these activities are a pro forma reporting method.

Part 1: Tube Metallurgy and Dimensions

The tube manufacturer shall furnish evidence that the metallurgy and physical dimensions of the heater tubes meet the following requirements (from Table 2, ASTM D3241):

Table 1: Results of Physical Measurements

D3241 Table 2 Physical Measurement Requirements		
Tube Metallurgy		**Falex Results**
Magnesium content, %		0.95
Silicon content, %		0.59
a) Mg:Si Ratio <= 1.9:1		1.61
b) Mg_2Si Percentage <= 1.85%		1.54
Tube Dimensions	**D3241 Requirements**	**Falex Results**
	Target ± Tolerance	**Result ± StDev**
Tube Length, mm	161.925 ± 0.254	161.907 ± .036
Center Section, mm	60.325 ± 0.051	60.333 ± .012
Outside Diameter		
Shoulders, mm	4.724 ± 0.025	4.729 ± .005
Center Section, mm	3.175 ± 0.051	3.176 ± .005
Inside Diameter	1.651 ± 0.051	1.653 ± 0.008
Total Indicator Runout, mm, max	0.013	0.011 max, 0.009 ± 0.0013
Surface finish, nm	50 ± 20	40.3 ± 6.4

The purpose of this section is to ensure that the prospective D3241 heater tubes meet the basic physical requirements of the method. The metallurgy is limited as controlling the impact of magnesium migration is important for consistent results. Excess magnesium can move to the test surface of the heater tube and form gray, dull patches. The melt analysis for this batch of aluminum is included in Annex 1.

The tube dimensions describe the basic physical characteristic of a D3241 Heater Tube. The data was generated by measuring thirty (30) tubes selected at random from production. The complete analysis for these properties is included in Annex A1.

Part 2: Program to Establish Equivalency in Pretest Rating

Part 2 is the visual appearance comparison of the candidate Falex tubes with the Alcor tubes. The authors of RR-D:1550 knew this would be problematic because of the existential challenge caused by asking people to compare two items. With no objective criteria on which to evaluate this, the raters are bound to find differences. This is why the protocol requested so many raters (minimum of 4 at 5 locations) and the results show the importance. The ratings were conducted at the following locations:

1. London, UK
2. Northern New Jersey, USA
3. Houston, Texas, USA
4. Southern New Jersey, USA
5. San Francisco Bay Area, California, USA

Each of these tests was conducted in the same fashion, a single person handled all the tubes and the raters placed their ratings on coded sheets. The results of this evaluation are seen in the following graph:

			Rater #																						
Test Pair	Tube A	Tube B	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Pair 1	21	22				1				1		1	1												
Pair 2	1	11	1		1			1	1	1		1	1									1			
Pair 3	2	12	1			1	1	1	1					1	1			1				1			
Pair 4	3	13	1	1	1		1	1	1			1	1		1	1									
Pair 5	23	24					1	1				1	1				1	1							
Pair 6	4	14		1		1	1			1			1			1	1								
Pair 7	5	15	1		1	1	1	1	1	1		1	1	1	1							1			
Pair 8	25	26					1	1		1			1		1							1			
Pair 9	6	16						1					1	1	1	1	1						1		1
Pair 10	7	17									1		1		1	1	1	1							
Pair 11	8	18			1	1	1	1		1		1	1	1	1										
Pair 12	27	28		1				1				1	1			1									
Pair 13	29	30	1			1							1		1						1	1			
Pair 14	9	19			1		1	1	1				1		1		1								
Pair 15	10	20			1			1				1	1	1	1		1	1	1				1		
Pair 16	A	B	1	1	1		1				1					1			1						
Pair 17	C	D							1									1							
Pair 18	E	F		1	1		1	1	1		1		1		1		1					1			
Pair 19	G	H											1									1			
Pair 20	I	J					1						1		1				1						

Graph 1: Equivalence Evaluation of Heater Tube Pairs

In the graph, the pairs (1, 5, 8, 12, 13, 16-20) with the white background are Alcor/Alcor pairs. The remaining pairs with the blue background are Alcor/Falex pairs. Pairs that the raters found non-equivalent are indicated by the numeral 1 and the yellow background. Among the raters we find a variation in non-equivalence finding from ‘none’ to ‘almost all’. Although in all there was a fairly normal distribution of results. There are more of these (39%) for the Alcor/Falex pairs than for the Alcor/Alcor pairs (23%).

At the start of this we realized that the tendency, even with significant Alcor/Alcor non-equivalent pairs, would be to ascribe the Alcor/Falex non matching pairs to ‘issues’ with the Falex tubes. So we added another analysis criterion, rejection. Kind of an extension of the method required for pre-screening for suitability test.

There can be four results for non-matching Alcor/Falex pairs:

1) Both useable, just not the same
2) Reject the Falex tube
3) Reject the Alcor tube
4) Reject both tubes

The results from that evaluation can be seen in following graph:

			Rater #																						
Test Pair	Tube A	Tube B	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Pair 1	21	22				A				1		A	1												
Pair 2	1	11	A		1			F	1	1		A	F									1			
Pair 3	2	12	F			A	A	A	1					1	1			AF				1			
Pair 4	3	13	A	A	A		A	A	1			A	1		1	A						A			
Pair 5	23	24					A	A				A	1				A	A							
Pair 6	4	14		1		F	A			A			A			A	A								
Pair 7	5	15	A		1	A	A	1	1	AF		A	1	1	1							1			
Pair 8	25	26					A	A		AA			1		1							1			
Pair 9	6	16						A		A			F	1	1	F	F						1		A
Pair 10	7	17									1		AF		F	F	F	1							
Pair 11	8	18			1	F	F	F		F		F	F	1	F										
Pair 12	27	28		1				A		AA		A	AA			AA						A			
Pair 13	29	30	A			A				AA			A		1						1	A			
Pair 14	9	19			1	AF	A	A	1	A			AF		AF		F					A			
Pair 15	10	20			A			A		F		A	AF	1	1		F	A	1			F	1		
Pair 16	A	B	A	1	A		A			A	1		A			A			1						
Pair 17	C	D							1	A			A					1				A			
Pair 18	E	F		1	1		A	A	1		1		AA		AA		A					A			
Pair 19	G	H								A			AA									A			
Pair 20	I	J					A						AA		1				1			A			

Alcor/Alcor
Alcor/Falex
Falex Reject
Alcor Reject
Both Reject

A/F Pairs: 93 of 240 Not Equivalent

Of Those 93, 39 Alcor Tubes Rejected

Of Those 93, 29 Falex Tubes Rejected

Graph 2: Rejection Evaluation of Heater Tube Pairs

Interestingly, among the Alcor/Falex pairs the Alcor tube was more likely to be rejected in a non-equivalent pair. Like before, we have created a second existential question. In reality, taken one at a time it is unlikely any of these tubes would be rejected from routine use.

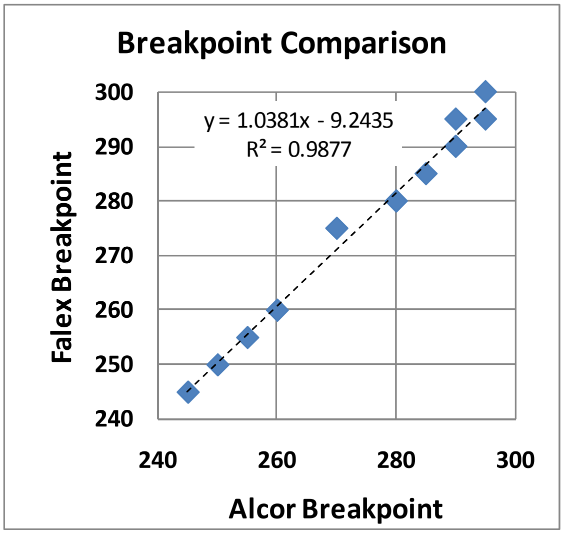
Overall, we believe this confirms what most knowledgeable people would notice – there is a slight difference in appearance. Heater tubes that were very different in appearance would likely have a much more definitive result.

Part 3: ASTM D3241 Performance Equivalence Testing

The Protocol requires a minimum of 9 Breakpoint/Fuel pairs at a minimum of five labs. We have twelve fuels tested at six labs. Paired Breakpoint pairs on five fuels at Southwest Research Institute, two pairs at ITC London (for Air BP), two pairs at Chevron Research and one pair each at ExxonMobil, Flint Hills and SGS Houston.

Table 2: Breakpoint Results

	Tube Source		
Breakpoint	Alcor	Falex	Fuel
Fuel #1	255	255	SwRI - 1
Fuel #2	290	290	ITC - Jet 'A'
Fuel #3	295	295	ITC - Jet 'B'
Fuel #4	245	245	SwRI - 2
Fuel #5	250	250	SwRI - 3
Fuel #6	280	280	SwRI - 4
Fuel #7	290	295	Chevron #1
Fuel #8	290	290	SwRI - 5
Fuel #9	260	260	Chevron #2
Fuel #10	285	285	SGS Houston
Fuel #11	295	300	Flint Hills
Fuel #12	270	275	ExxonMobil



Graph 3: Breakpoint Comparison

The data covers Breakpoint results from 245°C to 300°C. It would be hard to have better data than this, with a correlation coefficient of 0.9938. Not all the data is from deposition, Fuel #4 failed on differential pressure. Historically, we have considered a Breakpoint difference of less than 10°C to be insignificant (which is consistent with the fact that the standard minimum test increment is 5°C). The complete test results and data are in Annex A2.

Part 4: Determination of Equivalence

The following four points are as stated in RR-D.02:1550. The required analysis was conducted by Dr. William F. (Bill) Taylor who was one of the original authors of the protocol. (Dr. Taylor has been the primary statistician for Subcommittee D.02.J for many years.) His analysis follows each point.

1. Proof of equivalence shall require that the tubes tested with the same fuel produce the same breakpoint temperature on a statistically significant basis. Any differences in breakpoint temperature between the two tubes shall be tested by comparing average differences for all fuels to the breakpoint temperature standard deviation using the appropriate breakpoint temperature standard deviation, as discussed in Section 3. A statistical t-test based on a 95% confidence level criteria may be used.

   The t-test of the breakpoint temperature clearly shows that there is no statistical significant difference between the two tubes. (Calculation in Annex A3)

2. The breakpoint temperature difference data shall be examined for any sign of bias as a function of breakpoint temperature level, fuel type or fuel processing method. Results of these breakpoint temperature data analyses shall be a factor in determining the overall judgment of equivalence.

   There is no significant evidence of bias. Nine (9) of the twelve (12) data pairs are identical, and the other three pairs show only a small 5 degree difference which does not show any strong effect of level etc and thus appears to be random. The excellent regression analysis correlation which was obtained demonstrates the high quality of the data.

3. For JFTOT runs where the same fuel samples are run at the same temperature the results for the "Proposed Heater Tube" and "ALCOR Heater Tube" shall be compared to see if they produce the same failure mode and if the visual tube rating results are equivalent. The number of cases where equivalency occurs versus the number of cases where equivalency does not occur shall be a factor in determining the overall judgment of equivalence.

   Failure mode was the same in practically all of the data. Tube rating visual data is good considering the natural scatter.

4. Results of Section 2, Pretest Rating studies, shall be a factor in determining the overall judgment of equivalence.

   Pretest results show these visual ratings are highly subjective as would be expected from any rating of this type (as shown by all the problems we had with D1094 ratings before we dropped the test from the spec). Clearly, the Breakpoint data is more reliable and should be the basis for the overall conclusion.

Conclusion

In addition to the specific point analysis required by the protocol, Dr. Taylor added the following concluding remark:

> Overall, the results demonstrate that the Falex and Alcor tubes are equivalent in performance.

Based on the cumulative evidence it is clear that the Falex Heater Tubes are suitable for use in ASTM D3241, the Standard Test Method for Thermal Oxidation Stability of Aviation Turbine Fuels.

Recommendation

Based on the successful completion of RR:D02-1550, the Falex Equivalency Task Force recommends adding a new footnote and reference to Table 2 of ASTM D3241[2].

In Table 2:

Heater tube[A,B,C]

In the Table 2 footnotes

[C]The following equipment, heater tube and filter kits, manufactured by Falex Corporation, 1020 Airpark Dr., Sugar Grove, IL, 60554-9585, was run through the test protocol in RR:D02-1550 and established as equivalent. This test is detailed in RR:D02-XXXX.

[2] The Falex Equivalency Task Force and Subcommittee D.02.J are aware that the ASTM Form and Style Manual says suppliers should not be referenced if more than one is available. In the interest of flight safety, it is Subcommittee D.02.J practice to include all suppliers that have been established as equivalent, by research report, in methods the Subcommittee holds.

Annex A1

Tube Metallurgy and Dimensions

Melt Analysis

Redacted for Confidentiality

PAGE 1

SOLD TO	PURCHASE ORDER	08/23/07 DATE PRINTED
SOLD TO	PURCHASE ORDER	DATE PRINT [redacted]

1.66X.140/60610 — CUSTOMER PART NUMBER

1.66 OD X .140 WALL X 17.5 LBS/PC — DESCRIPTION

305986-001	50042 081	6061-O
RELEASE-ITEM	LOT	ALLOY/TEMPER

===

MECHANICAL PROPERTY RESULTS

DIE	LOT	SAMPLE#	UTS(KSI)	YTS(KSI)	ELONG%	HARDNESS	CONDUCT.	BEND
50042	081	0001 001	16.8	5.7	28.8	NA	N/A	N/A
50042	081	0001 002	17.1	6.1	26.3	NA	N/A	N/A
50042	081	0001 003	16.9	5.8	28.4	NA	N/A	N/A
50042	081	0001 004	17.0	6.1	26.9	NA	N/A	N/A
50042	081	0001 005	16.9	5.7	29.1	NA	N/A	N/A

CHEMICAL COMPOSITION (WT%), ALUMINUM REMAINDER

6061 LMT	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Pb	Bi	Zr	Ga	Others Ea	Others Tot
Max	.80	.70	.40	.15	1.20	.35	.25	.15	NA	NA	NA	NA	.05	.15
Min	.40	.00	.15	.00	.80	.04	.00	.00	NA	NA	NA	NA	.00	.00

Heat#	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Pb	Bi	Zr	Ga	Others Ea	Others Tot
022505	.590	.300	.21	.040	.950	.050	.020	.020	.000	.010	.000	.000	.000	.000

Domestic Melt Source

===

APPLICABLE REQUIREMENTS:

ASTMB-241 & ACTUAL CHEMISTRY

[redacted]

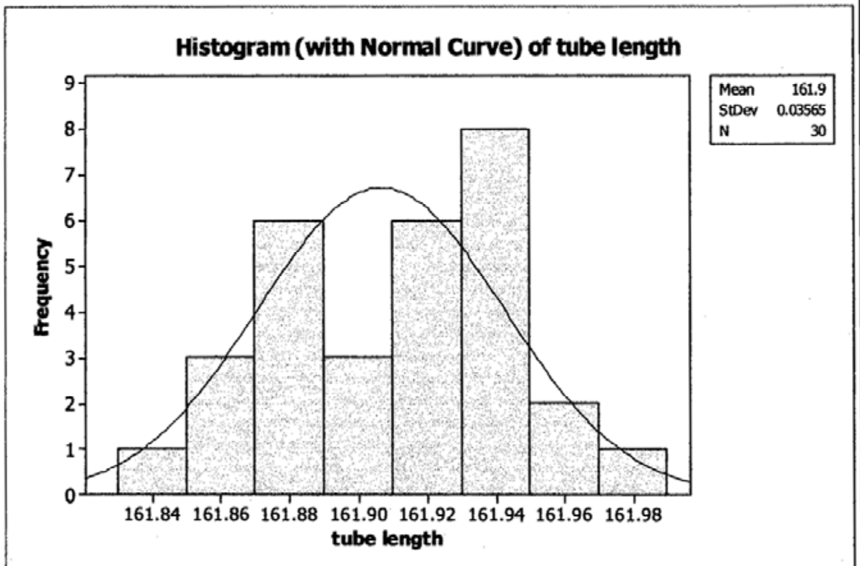
[redacted] hereby certifies that metal shipped under this order has been inspected and tested and found in conformance with the applicable specifications forming a part of the description set forth in [redacted] sales acknowledgement form. Any warranty is limited to that shown on [redacted] general terms & conditions of sale. Test reports are on file, subject to examination.

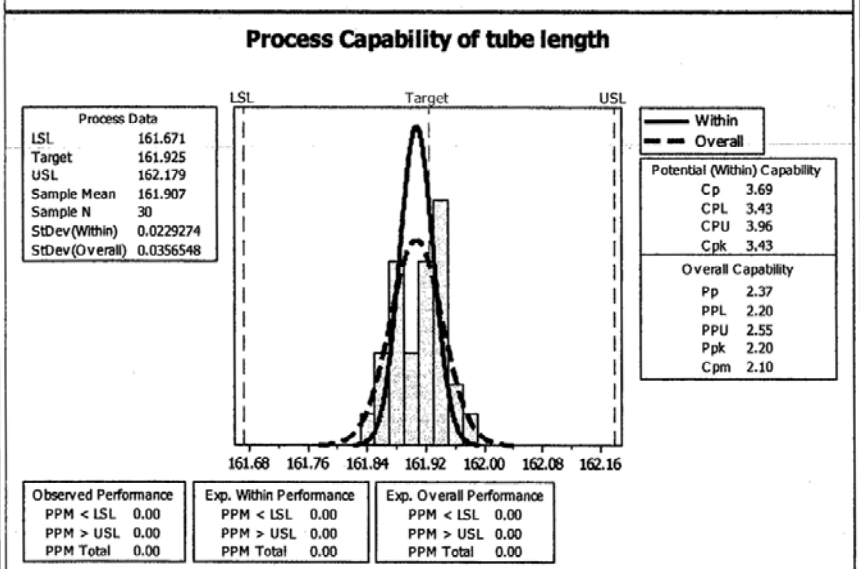
Tube Length

Minitab Project Report

Tube Length P/N 400-500-001   161.925 +/- .254mm

Variable	Mean	StDev	Minimum	Median	Maximum	Range
tube length	161.91	0.0357	161.84	161.91	161.98	0.140



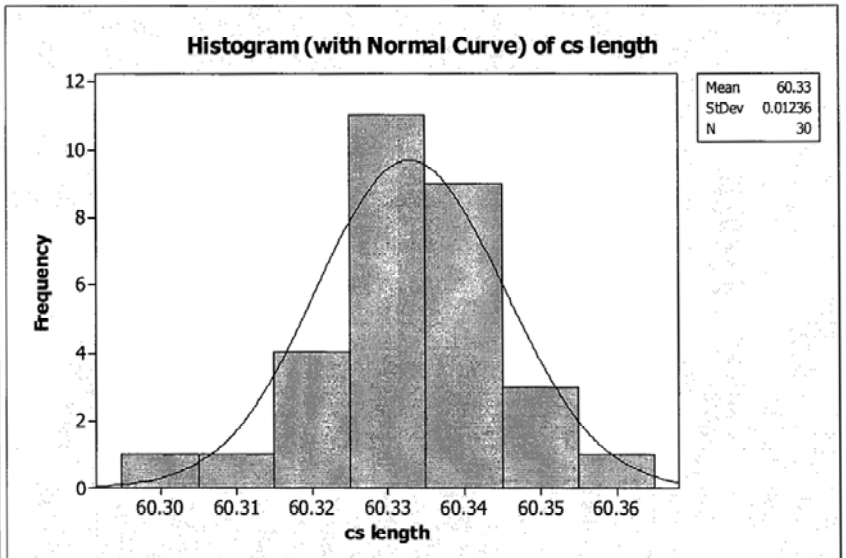


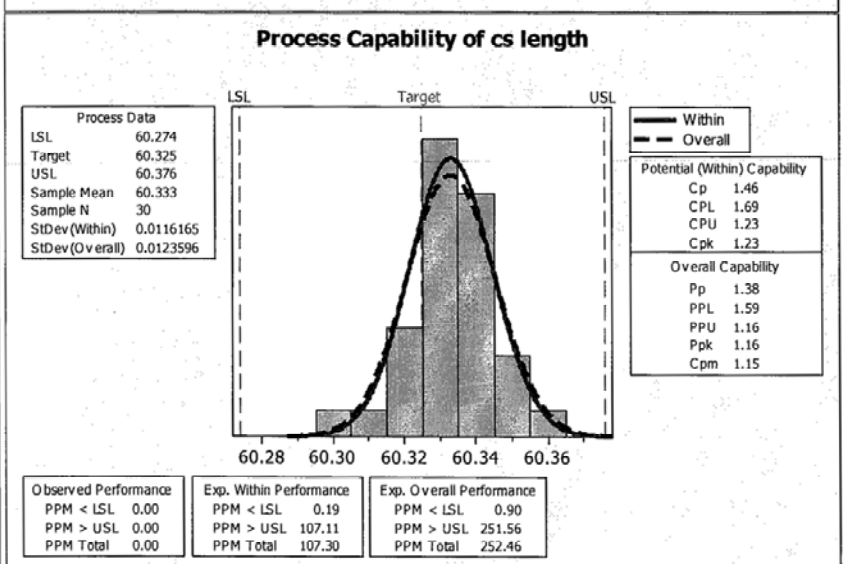
Center Section Length

Minitab Project Report

Center Section Length P/N 400-500-001 60.325 +/ .051mm

Variable	Mean	StDev	Minimum	Maximum
cs length	60.333	0.0124	60.300	60.360



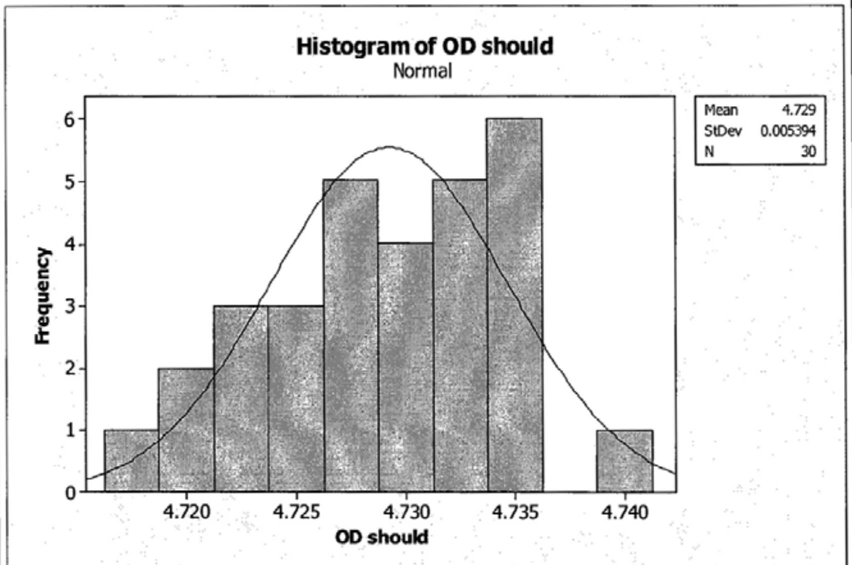


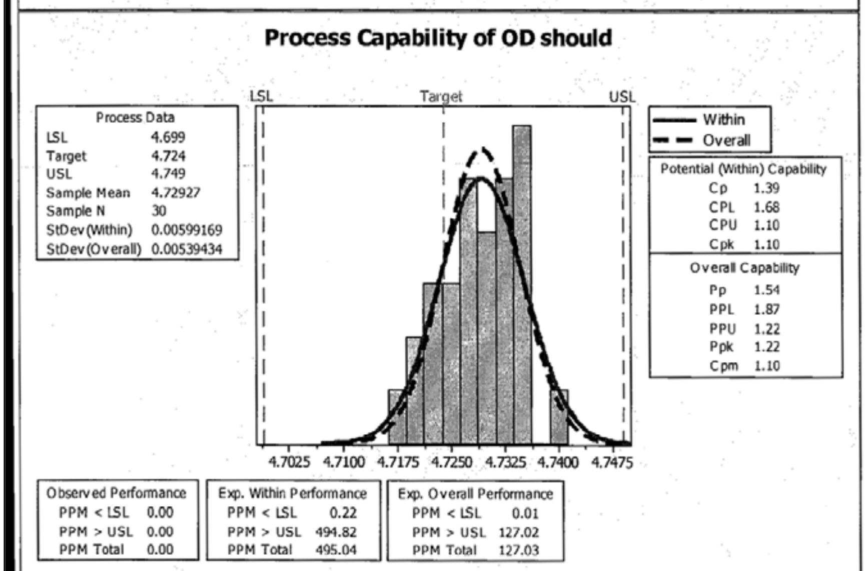
Outside Diameter - Shoulder

Minitab Project Report

Outside Diameter – Shoulder P/N 400-500-001 4.724 +/-.025mm

Variable	Mean	StDev	Minimum	Maximum	Range
OD should	4.7293	0.00539	4.7180	4.7390	0.0210



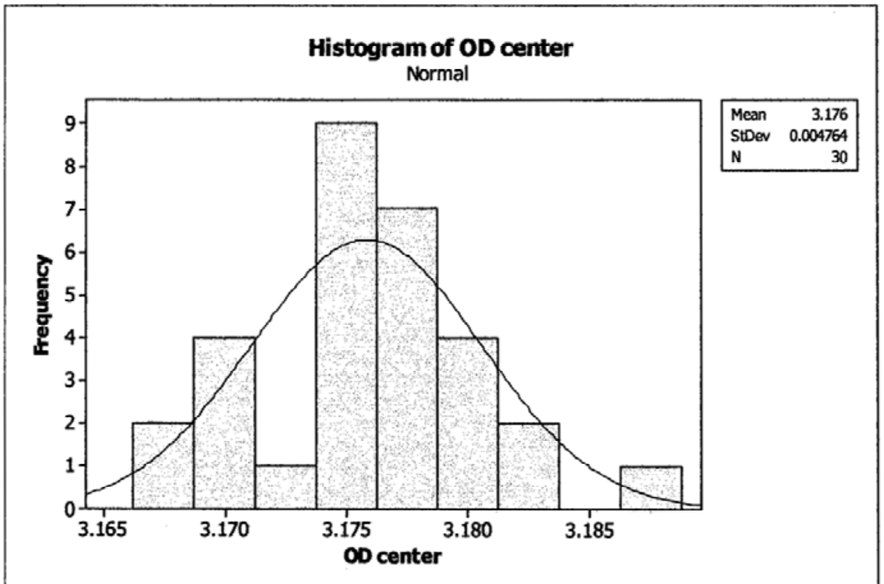


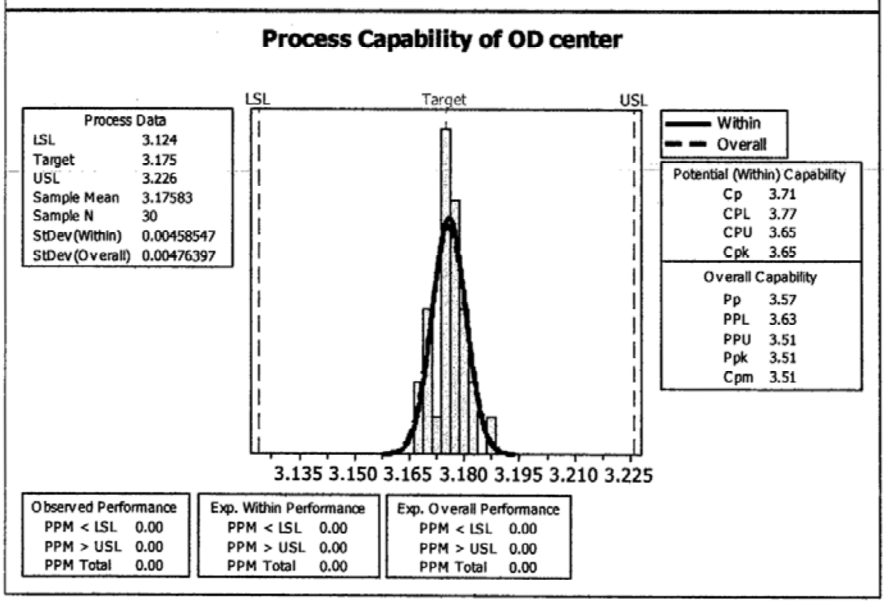
Outside Diameter – Center Section

Minitab Project Report

Outside Diameter – Center Section P/N 400-500-001 3.175 +/-.051

Variable	Mean	StDev	Minimum	Maximum	Range
OD center	3.1758	0.00476	3.1670	3.1880	0.0210





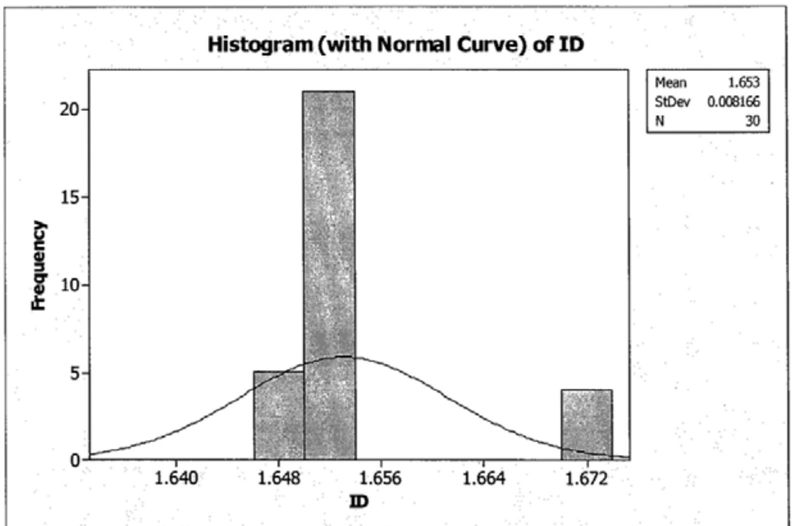
Inside Diameter

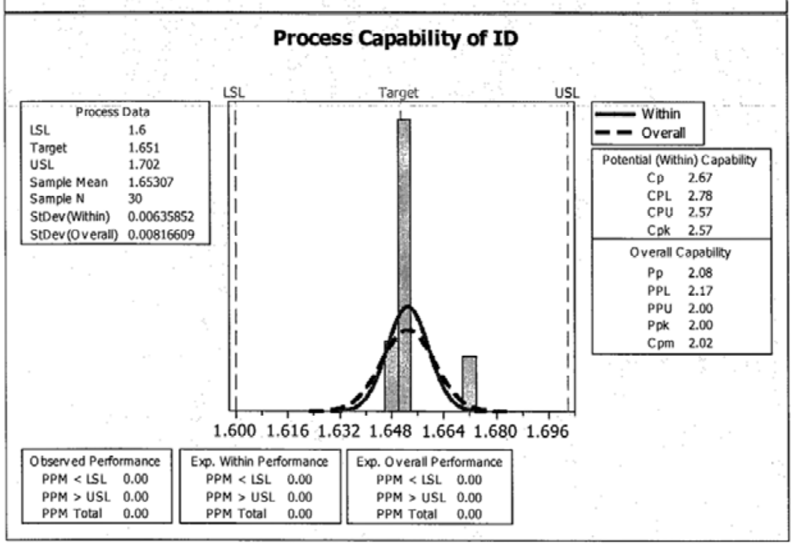
Minitab Project Report

Inside Diameter – P/N 400-500-001 1.651 +/- .051mm

Used 3 "GO" pin gages: 1.673, 1.651, 1.646mm

Variable	Mean	StDev	Minimum	Maximum	Range
ID	1.6531	0.00817	1.6460	1.6730	0.0270



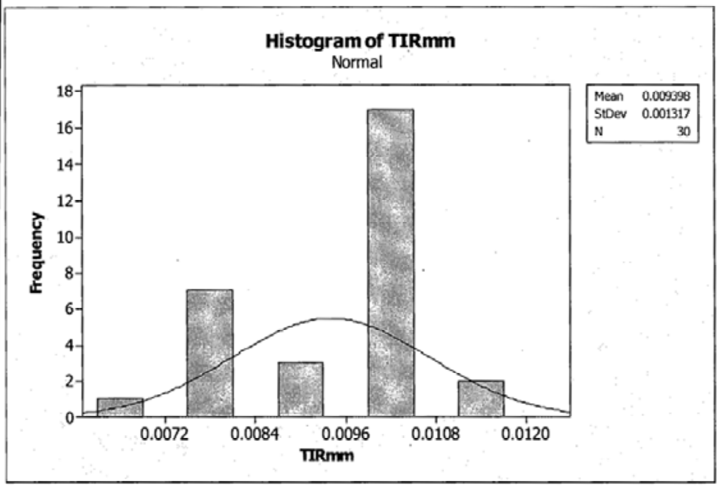


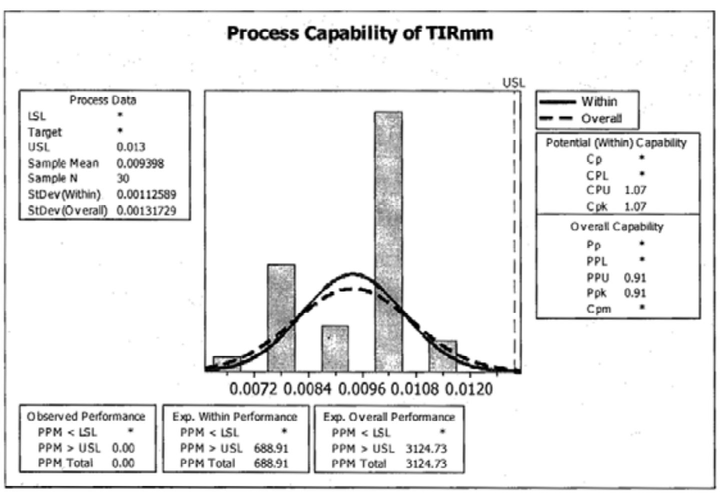
Total Indicator Runout

Minitab Project Report

TIR –P/N 400-500-001 .013mm Max

Variable	Mean	StdDev	Minimum	Maximum	Range
TIR mm	.009398	.001317	.006350	.011430	.005080



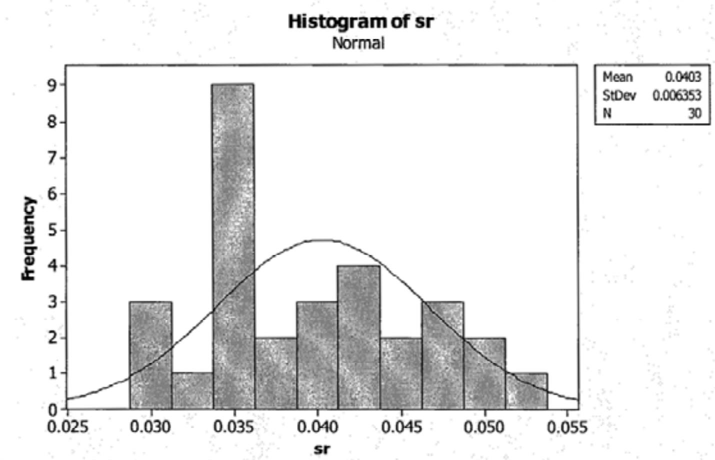


Surface Finish

Minitab Project Report

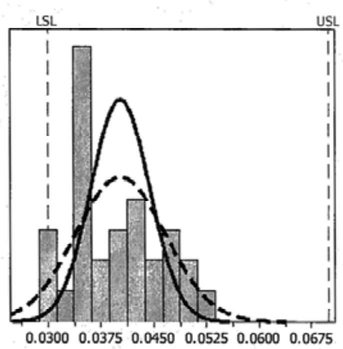
Surface Roughness - P/N 400-500-001 0.03 – 0.07 nanometers

Variable	Mean	StDev	Minimum	Maximum	Range
sr	0.04030	0.00635	0.03100	0.05300	0.02200



Process Capability of sr

Process Data	
LSL	0.03
Target	*
USL	0.07
Sample Mean	0.0403
Sample N	30
StDev(Within)	0.00412693
StDev(Overall)	0.00635257



Potential (Within) Capability	
Cp	1.62
CPL	0.83
CPU	2.40
Cpk	0.83

Overall Capability	
Pp	1.05
PPL	0.54
PPU	1.56
Ppk	0.54
Cpm	*

Observed Performance	
PPM < LSL	0.00
PPM > USL	0.00
PPM Total	0.00

Exp. Within Performance	
PPM < LSL	6283.59
PPM > USL	0.00
PPM Total	6283.59

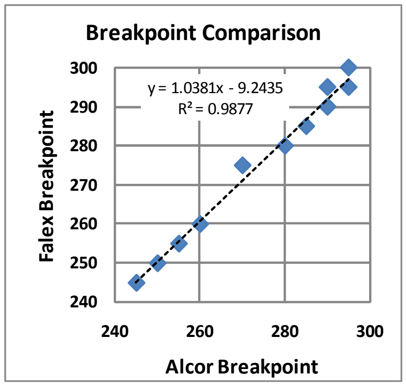
Exp. Overall Performance	
PPM < LSL	52466.96
PPM > USL	1.47
PPM Total	52468.43

Annex A2

Breakpoint Test Data

Heater Tube Equivalence Breakpoint Data

	Tube Source		
Breakpoint	Alcor	Falex	Fuel
Fuel #1	255	255	SwRI - 1
Fuel #2	290	290	ITC - Jet 'A'
Fuel #3	295	295	ITC - Jet 'B'
Fuel #4	245	245	SwRI - 2
Fuel #5	250	250	SwRI - 3
Fuel #6	280	280	SwRI - 4
Fuel #7	290	295	Chevron #1
Fuel #8	290	290	SwRI - 5
Fuel #9	260	260	Chevron #2
Fuel #10	285	285	SGS Houston
Fuel #11	295	300	Flint Hills
Fuel #12	270	275	ExxonMobil



Fuel #1		
	A-1	F-1
250	1	
255	**1**	**0.5**
260	<4P	4P
265		>4AP

Fuel #2		
Temp	A-2	F-2
280	1	
290	**1**	**1**
295	<3A	>4
300	>4	

Fuel #3		
Temp	A-3	F-3
290	2	1
295	**1**	**2**
300	3	>4A

Fuel #4	Differential Pressure	
	A-4 DP	F-4 DP
240	3.7	3.7
245	**7.3**	**8**
250	>25	>25

Fuel #5		
	A-5	F-5
240	<1	
250	**1**	**2**
255	4	3
260	4	>4

Fuel #6		
	A-6	F-6
280	**2**	**<2**
285	4	3
290	>4P	<4

Fuel #7		
	A-7	F-7
290	**<1**	<1
295	<4A	**<1**
300		1A

Fuel #8		
	A-8	F-8
285	2	1
290	**<3**	**<3**
295	>4AP	<4AP

Fuel #9		
	A-9	F-9
260	**2**	**<1**
265	2A	2A
270	4A	<3A

Fuel #10		
	A-10	F-10
275		1
285	**<3**	**<3**
290	3P	4
295	4	4

Fuel #11		
	A-11	F-11
295	**1**	1
300	2A	**1**
305	4A	2P

Fuel #12		
	A-12	F-12
270	**2**	2
275	2A	**2**
280		2A

Annex A3

Student *t* Analysis

Student *t* Analysis

Student *t* test of Falex-Alcor Heater Tubes for the Breakpoint Data:

$$t = \frac{\bar{X}_F - \bar{X}_A}{\sigma\sqrt{\frac{1}{N_F} + \frac{1}{N_F}}}$$

Where F = Falex
A = Alcor
σ = Standard deviation of Breakpoint test assumed to be 5°C

$$t = \frac{276.7 - 275.4}{5\sqrt{\frac{1}{12} + \frac{1}{12}}} = 0.64$$

Minimum *t* required for 95% two tailed test with 22 degrees of freedom is 2.07[1]

Conclusion: *t* - test indicates no statistical difference between Falex and Alcor Breakpoint means.

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[1] Source O.L. Davies "Statistical Methods in Research & Production" 3rd Ed., Hafner Publications, NY, pgs 65, 366