Analysis of HR2 DOE II Results
(Data Collected at FAA Tech Center)

International Aircraft Materials Fire Test Working Group
Atlantic City, NJ
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Acknowledgements
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HR2 DOE II Results

- **Objective**
  - Evaluate effect of tolerance ranges of machine input parameters on output variation
  - Compare results of HR2 DOE I (2015) and DOE II (2017)
- **Background**
  - June 2015 FTWG HR2 Task Group: Boeing proposed preliminary screening DOE, without test coupons, to determine relative effect of the tolerance range of certain HR2 machine parameters on the thermopile output
  - August-September 2015: Preliminary screening DOE run at FAA Tech Center
    - Machine parameters: chamber airflow, center heat flux, upper pilot flame methane flow, upper pilot flame airflow
    - Data analyzed by Boeing (Yusuf Mansour) & data presented at March 2016 FTWG (Matt Anglin)
  - As a result of the screening DOE, the tolerance ranges for the following parameters were tightened considerably through HR2 hardware modifications
    - Chamber airflow: 20±1 -> 20.0±0.4 SCFM
    - Upper Pilot Flame Methane Flow: 1.50±0.20 -> 1.50±0.03 SLPM
    - Upper Pilot Flame Airflow: 1.00±0.20 -> 1.00±0.03 SLPM
  - September 2017: Screening DOE re-run at FAA Tech Center (“DOE II”) with Boeing assistance
    - Dates of DOE II experiment: 19-21 September 2017

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HR2 DOE II Results

- **DOE Description**
  - 4-factor, 3-level experiment
    - Response variable: Thermopile reading (deg C)
    - Symmetric high/low values around center point for each factor
  - Factors:
    - Center heat flux: 3.65±0.05 W/cm^2
    - Chamber airflow: 20±0.4 SCFM
    - Upper Pilot Flame Methane: 1.50±0.03 SLPM
    - Upper Pilot Flame Airflow: 1.00±0.05 SLPM
  - Experimental Procedure
    - Reference: M. Burns, “Heat Release Rate Updates,” June 2017 Materials Fire Test Working Group Meeting (Cologne, GER)
    - 3 types of experimental runs:
      - Calibration runs (once per “day”)
      - Stability runs
        - Center point controls: 2x per day
        - Stabilize new heat flux & chamber airflow: 1x per day (not shown)
      - Test runs (4x per day): factors @ DOE settings
    - No randomization of test conditions and no replicates for a given set of 4-factors
    - Note: “Day 2” & “Day 3” are actually the same day (20SEP2017)

Day	Data Point	Chamber Airflow (SCFM)	Center Heat Flux (W/cm2)	Upper Pilot Flame Methane (SLPM)	Upper Pilot Flame Airflow (SLPM)
1	Cal	20.0	-	-	-
1	Pre	20.0	3.65	1.50	1.00
1	2	19.6	3.60	1.47	0.95
1	3	19.6	3.60	1.47	1.05
1	4	19.6	3.60	1.53	1.05
1	5	19.6	3.60	1.53	0.95
1	Post	20.0	3.65	1.50	1.00
2	Cal	20.0	-	-	-
2	Pre	20.0	3.65	1.50	1.00
2	2	19.6	3.70	1.47	0.95
2	3	19.6	3.70	1.47	1.05
2	4	19.6	3.70	1.53	1.05
2	5	19.6	3.70	1.53	0.95
2	Post	20.0	3.65	1.50	1.00
3	Cal	20.0	-	-	-
3	Pre	20.0	3.65	1.50	1.00
3	2	20.4	3.60	1.47	0.95
3	3	20.4	3.60	1.47	1.05
3	4	20.4	3.60	1.53	1.05
3	5	20.4	3.60	1.53	0.95
3	Post	20.0	3.65	1.50	1.00
4	Cal	20.0	-	-	-
4	Pre	20.0	3.65	1.50	1.00
4	2	20.4	3.70	1.47	0.95
4	3	20.4	3.70	1.47	1.05
4	4	20.4	3.70	1.53	1.05
4	5	20.4	3.70	1.53	0.95
4	Post	20.0	3.65	1.50	1.00

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HR2 DOE II Results

- **DOE Description**
  - Several notable differences between conditions for DOE I and DOE II

Comparison of Experimental Conditions for DOE I and DOE II

Item	DOE I (Fall 2015)	DOE II (Fall 2017)
Hardware		
Chamber Air	Mass Flow Meter	Mass Flow Controller
Upper Pilot Air	Volumetric Flow Meter	Mass Flow Controller
Thermopile TCs	5 hot, 5 reference	5 hot, 1 reference
Calibration		
Methodology	Step Method	Ramp Method
Thermopile Output	Voltage (mV)	Temperature (deg C)
Parameters		
Center Heat Flux (W/cm2)	3.60 - 3.70	3.60 - 3.70
Chamber Airflow (SCFM)	19.0 - 21.0	19.6 - 20.4
Upper Pilot Flame Methane(SLPM)	1.30 - 1.70	1.47 - 1.53
Upper Pilot Flame Airflow (SLPM)	0.8 - 1.2	0.95 - 1.05
Experimental Duration	4 days	3 days
Stability Run Data Collection	> 10 minutes	1 minute after Std Dev < 2%

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HR2 DOE II Data

- **Calibration Runs**
- **Stability Runs**
- **Factor Effects**

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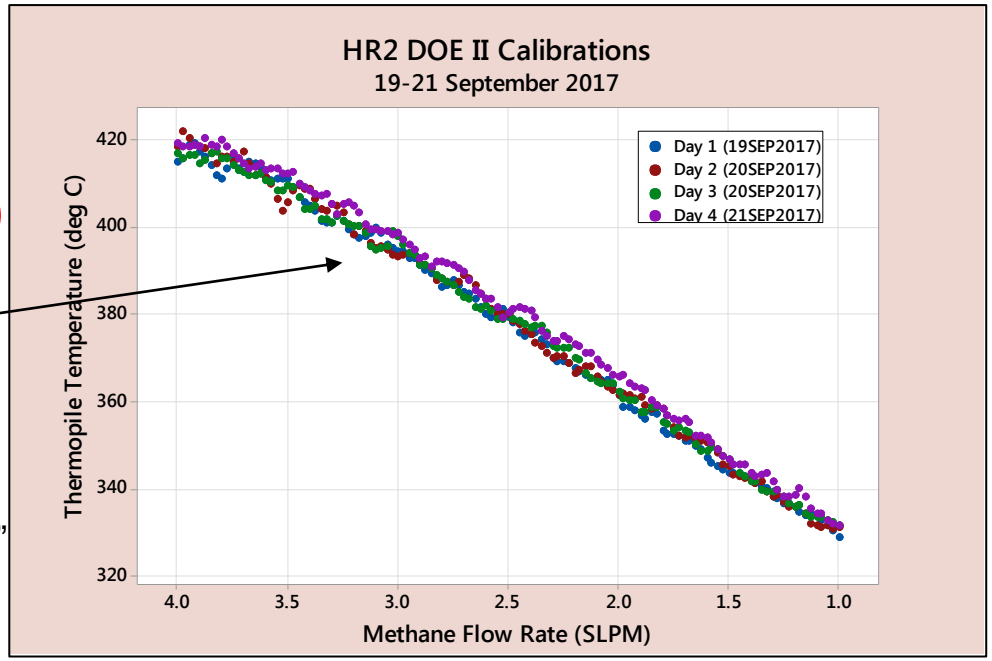
HR2 DOE II Results

- **Calibration Runs**
  - Determination of cal factor (K_h) (unit = W/deg C)

$$K_h = \frac{(210.8-22)kCal}{mol} * \frac{mol\ (CH4)}{22.41L} * \frac{Watt*min}{0.01433\ kCal} * \frac{1000W}{1000W} * \frac{\Delta F}{\Delta °C}$$

  - Kh = constant*(ΔF/ΔT)
  - (ΔF/ΔT) = (1/slope)



  - "Cal factor must be in the range of 17±2 W/deg C"
  - Cal factor (K_h) variation: ~2.2%
    - Occurs within a single "day"
      - "Day 2" & "Day 3" actually the same day (20SEP2017)
    - 0.3% variation with outlier removed
  - Cal factor directly reflected in HRR
    - Assuming all other factors constant

Day	Date	[1/Slope] (L/min/C)	Cal Factor (W/deg C)
1	19-Sep	0.0319	18.75
2	20-Sep	0.0319	18.75
3	20-Sep	0.0326	19.17
4	21-Sep	0.0320	18.81

$$\text{Heat Release Rate} = (T'pile_{°C} - BL_{°C}) * \frac{K_h \div 1000}{0.02323}\ \ kW/m^2$$

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HR2 DOE II Data

- Calibration Runs
- **Stability Runs**
- Factor Effects

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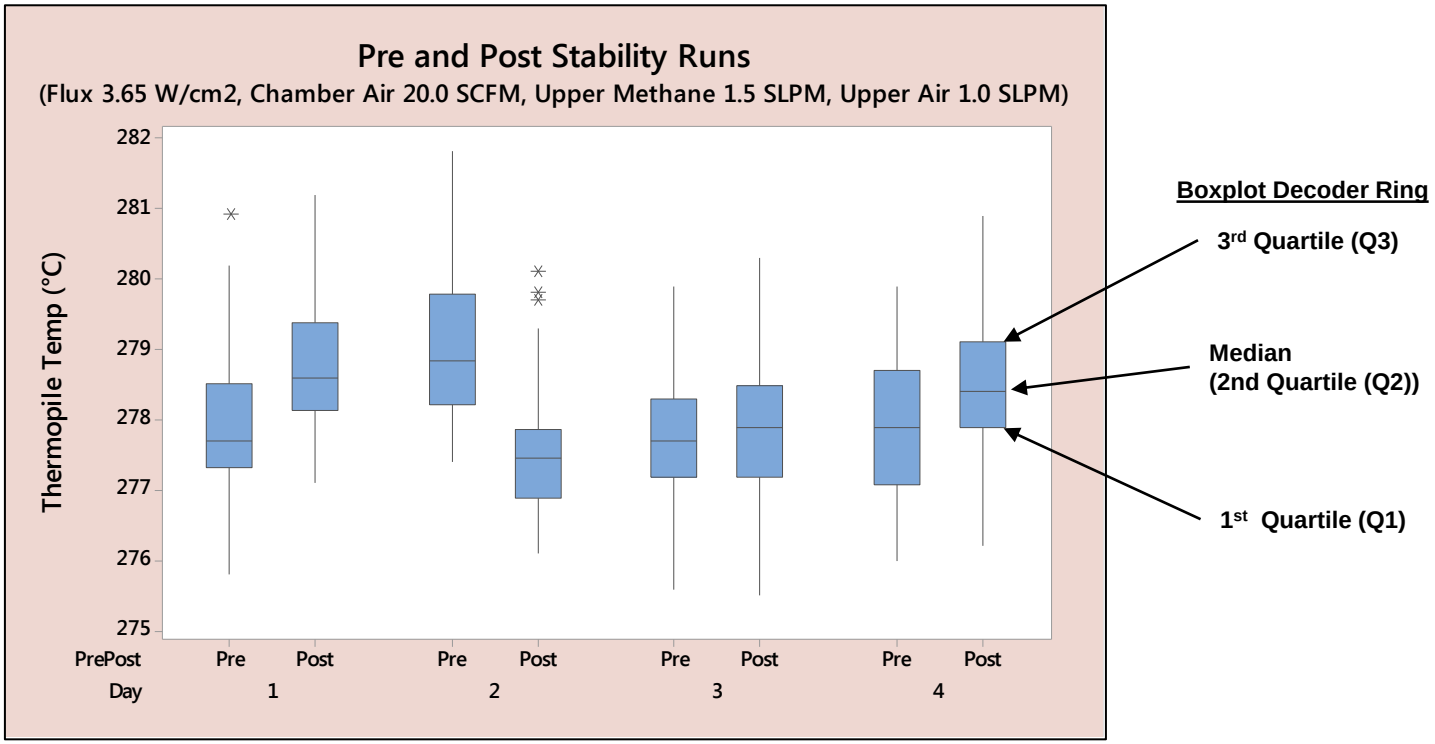
HR2 DOE II Results

- **Stability Runs (Center Point Controls)**
  - Collected twice per day
    - Pre and Post test data collection (beginning and end of each day's data collection)
  - Collected at factor center points
    - Flux 3.65 W/cm^2, Chamber Air 20.0 SCFM, Upper Methane 1.50 SLPM, Upper Air 1.00 SLPM
    - Each data set consists of 1 minute of data acquired at 1 sec intervals → 60 data points



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HR2 DOE II Results

- **Stability Runs**
  - Analysis of Variance (ANOVA)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Data Set	7	118.8	16.9669	18.52	0.000
Error	472	432.4	0.9162		
Total	479	551.2			

Data Set	N	Mean	StDev	95% CI
1	60	277.862	1.017	(277.619, 278.104)
2	60	278.770	0.916	(278.527, 279.013)
3	60	279.010	0.954	(278.767, 279.253)
4	60	277.545	0.892	(277.302, 277.788)
5	60	277.772	0.974	(277.529, 278.014)
6	60	277.938	1.025	(277.696, 278.181)
7	60	277.893	0.945	(277.651, 278.136)
8	60	278.543	0.926	(278.301, 278.786)

Pooled StDev = 0.957175

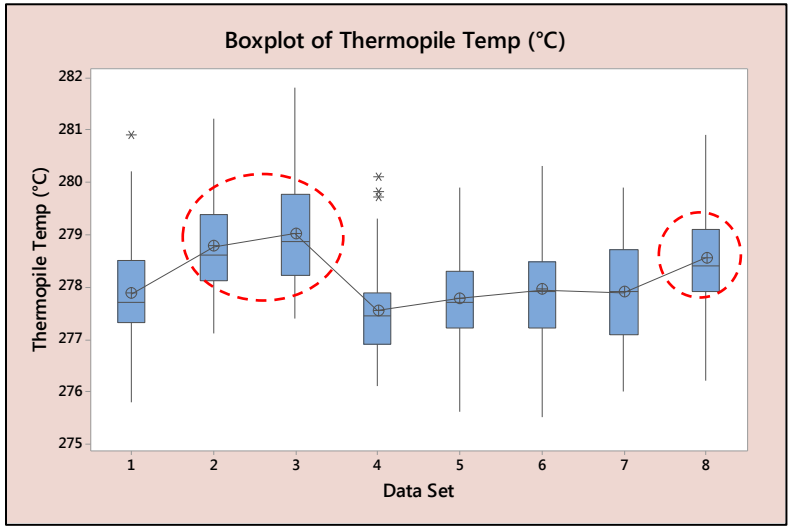
Grouping Information Using the Tukey Method and 95% Confidence

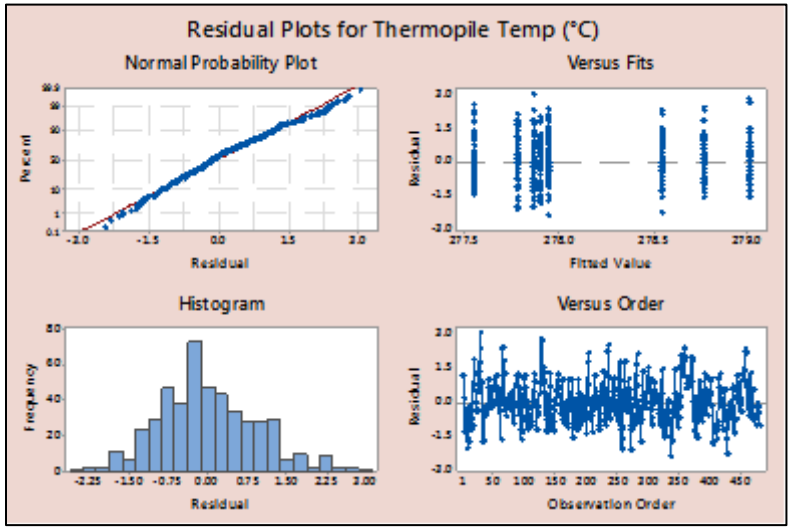
Data Set	N	Mean	Grouping
3	60	279.010	A
2	60	278.770	A
8	60	278.543	A
6	60	277.938	B
7	60	277.893	B
1	60	277.862	B
5	60	277.772	B
4	60	277.545	B

Means that do not share a letter are significantly different.

Effect Size Calculation (Example)
Max D = (279.01 – 277.55) / 0.96 = 1.52

-> Sizeable difference





- Statistical difference among stability run average temperatures.
- Reason unclear. May be discernible upon further investigation.

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HR2 DOE II Data

- **Calibration Runs**
- **Stability Runs**
- **Factor Effects**

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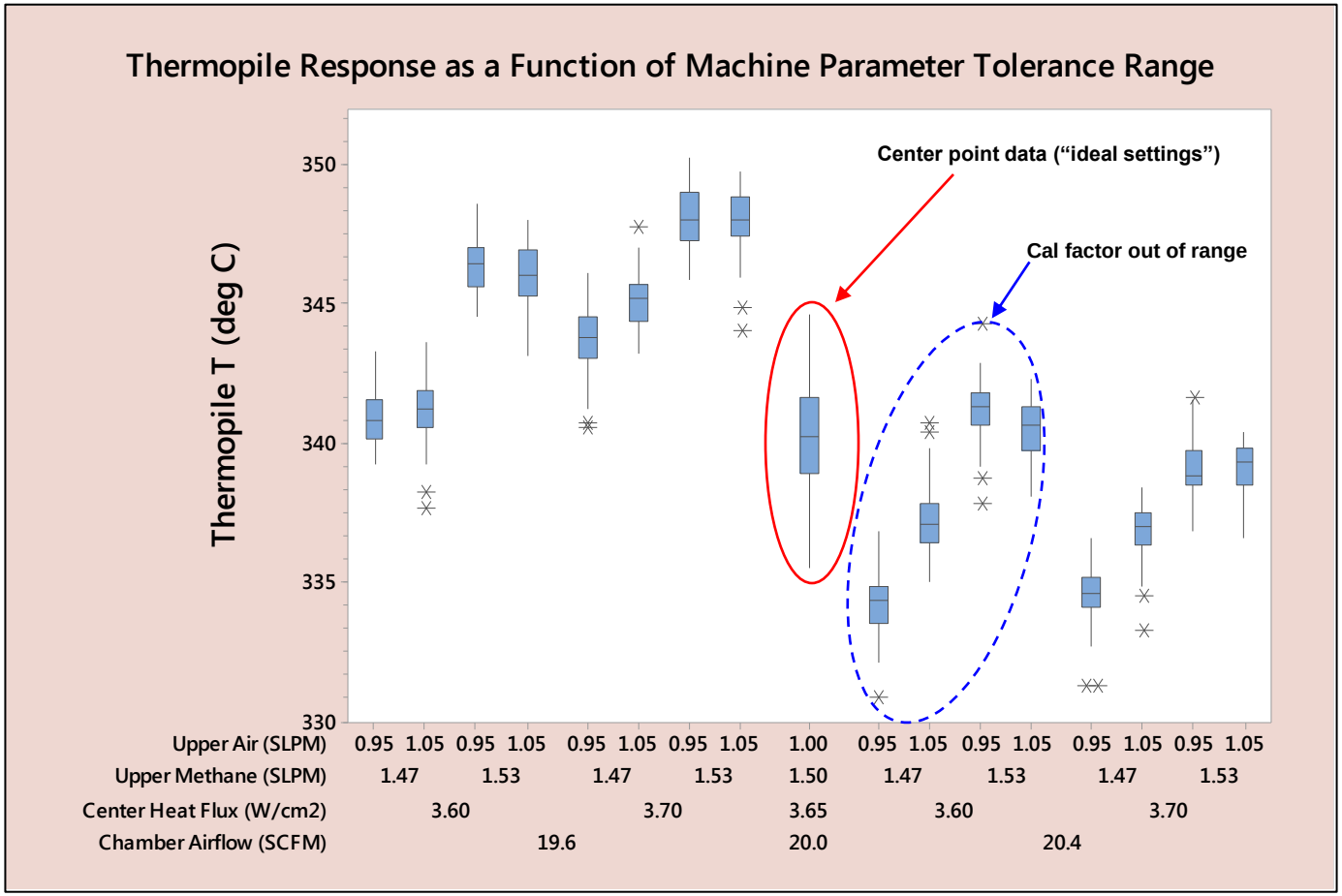
HR2 DOE II Results

- **Factor Effects**
  - Assessment of machine tolerance ranges: heat flux, chamber airflow, upper methane flow, upper air flow
  - Overview



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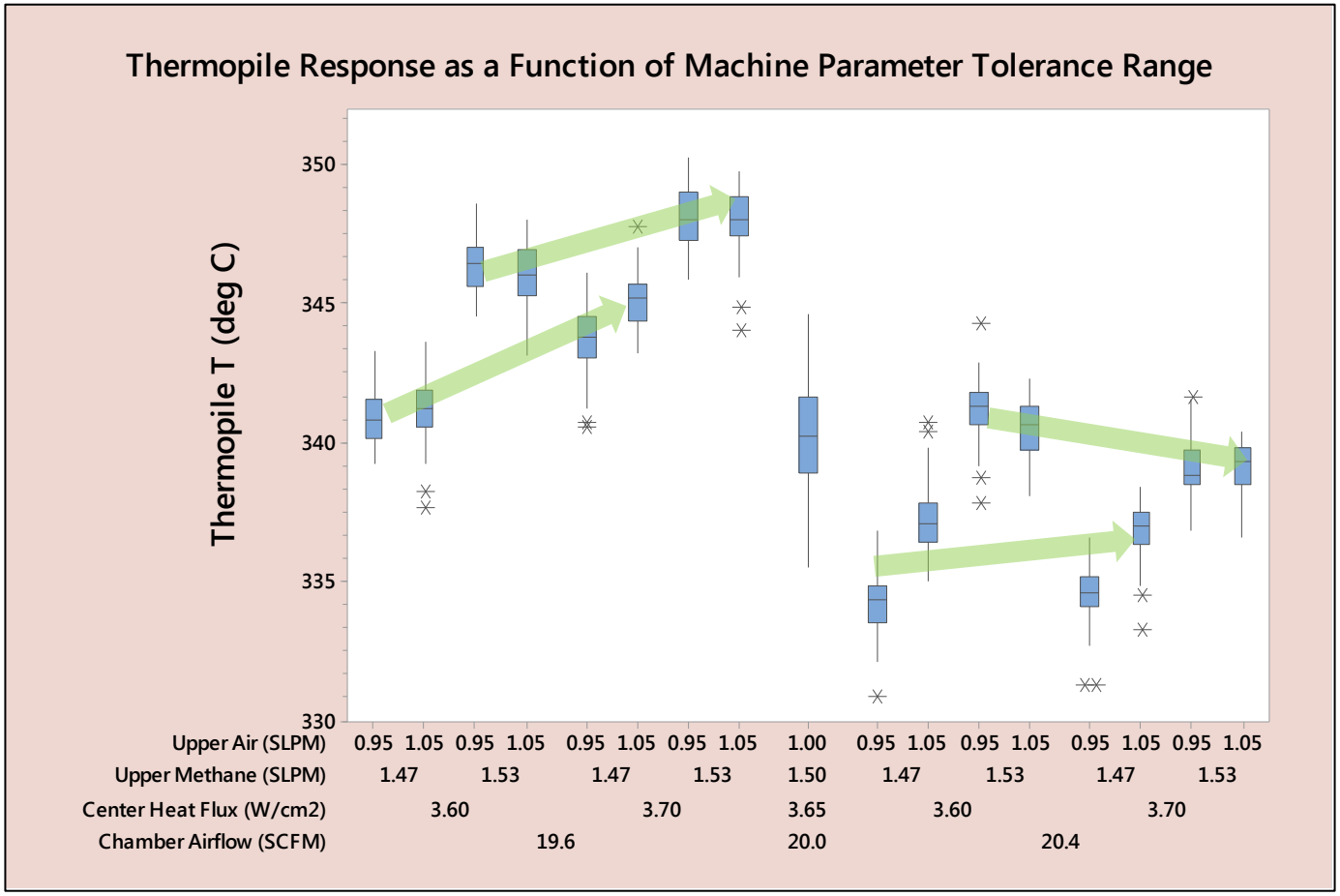
HR2 DOE II Results

- **Factor Effects**
  - **Heat Flux**: 3.65±0.05 W/cm^2
  - "Moderate" impact: ΔT approximately -2 to +3 deg C for full-scale swing of 3.60 -> 3.70 W/cm^2



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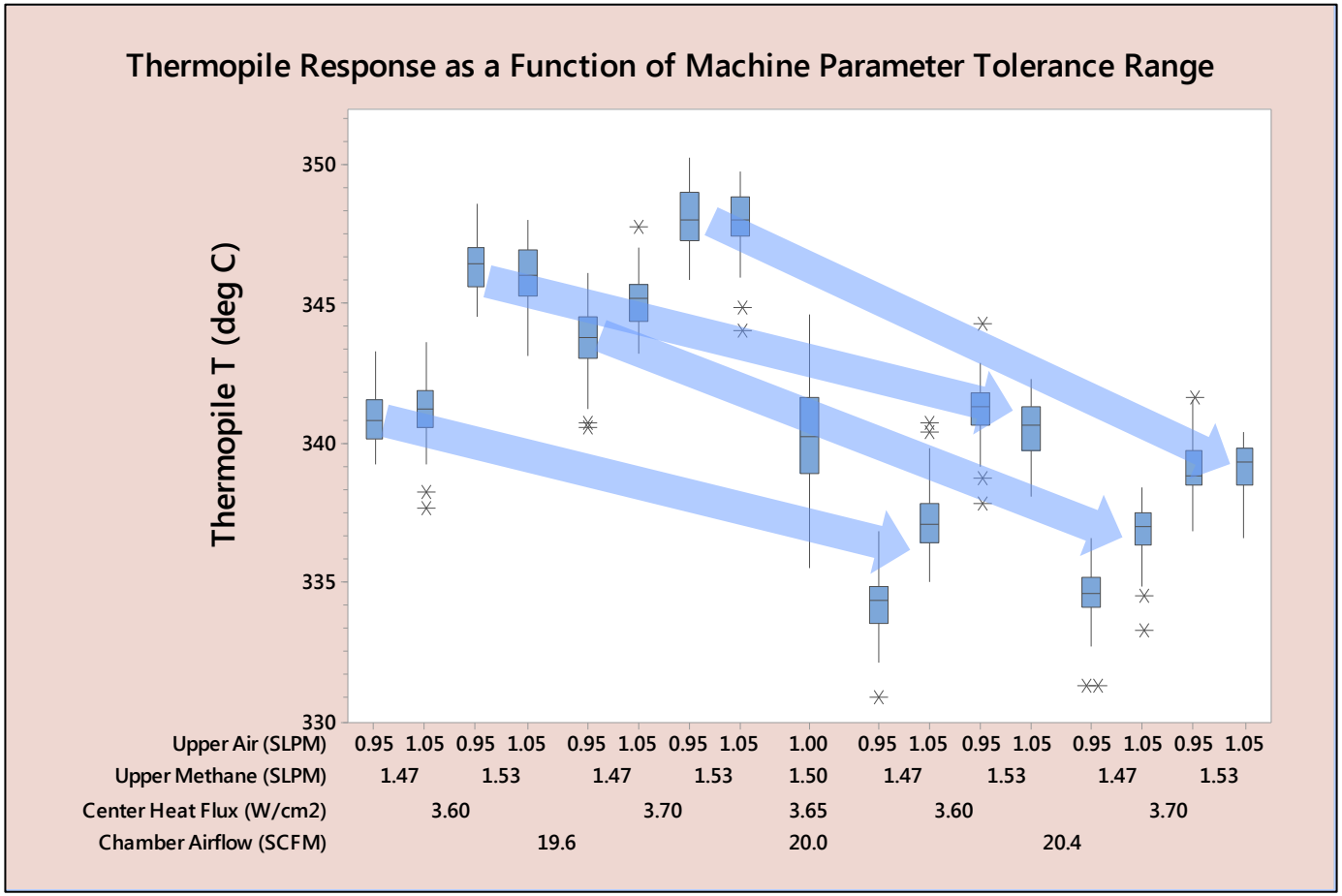
HR2 DOE II Results

- **Factor Effects**
  - **Chamber Airflow**: 20±0.4 SCFM
  - "Large" impact: ΔT approximately -5 to -9 deg C for full-scale swing of 19.6 -> 20.4 SCFM



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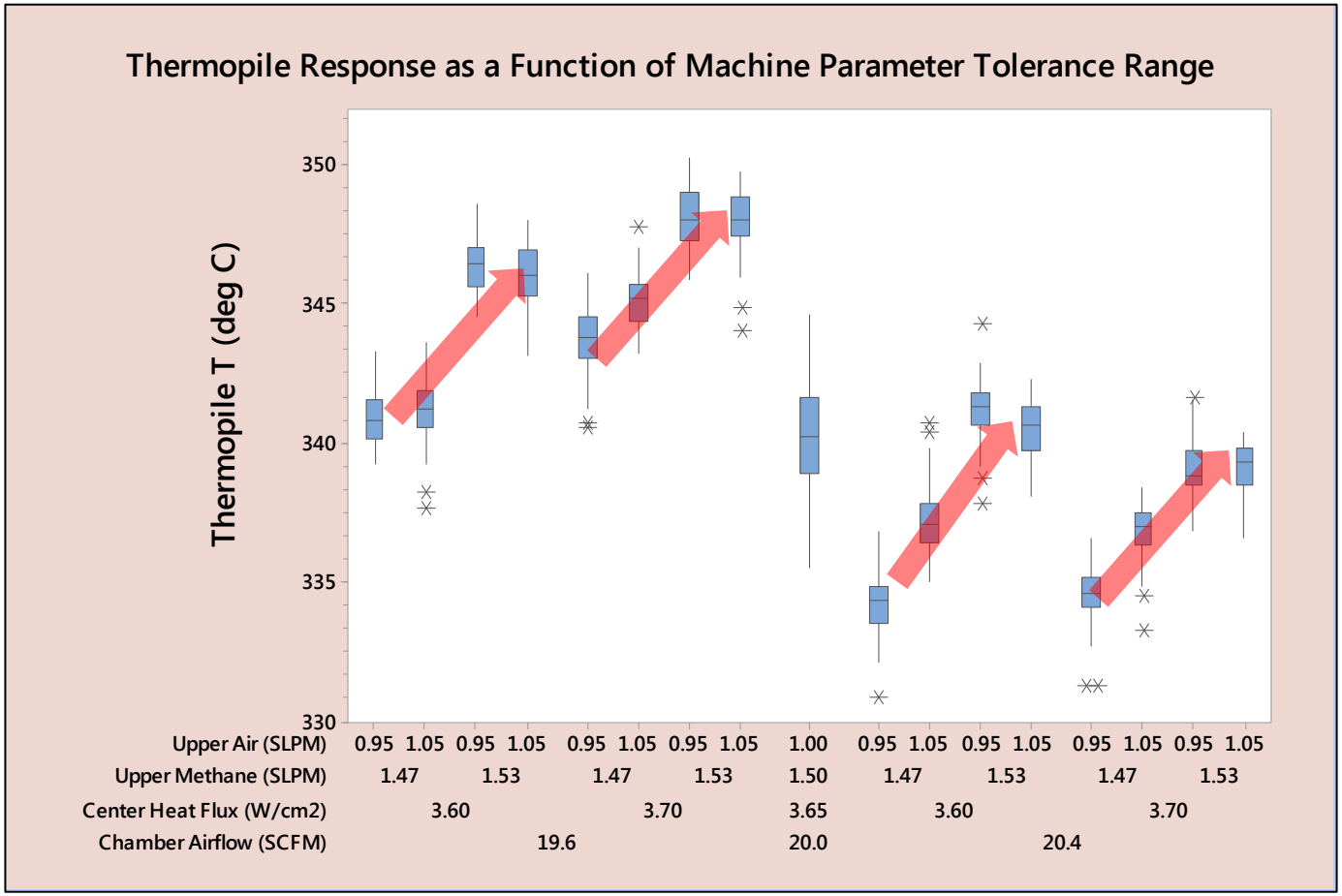
HR2 DOE II Results

- **Factor Effects**
  - **Upper Pilot Methane Flow**: 1.50±0.03 SLPM
  - "Large" impact: ΔT approximately +5 deg C for full-scale swing of 1.47 -> 1.53 SLPM



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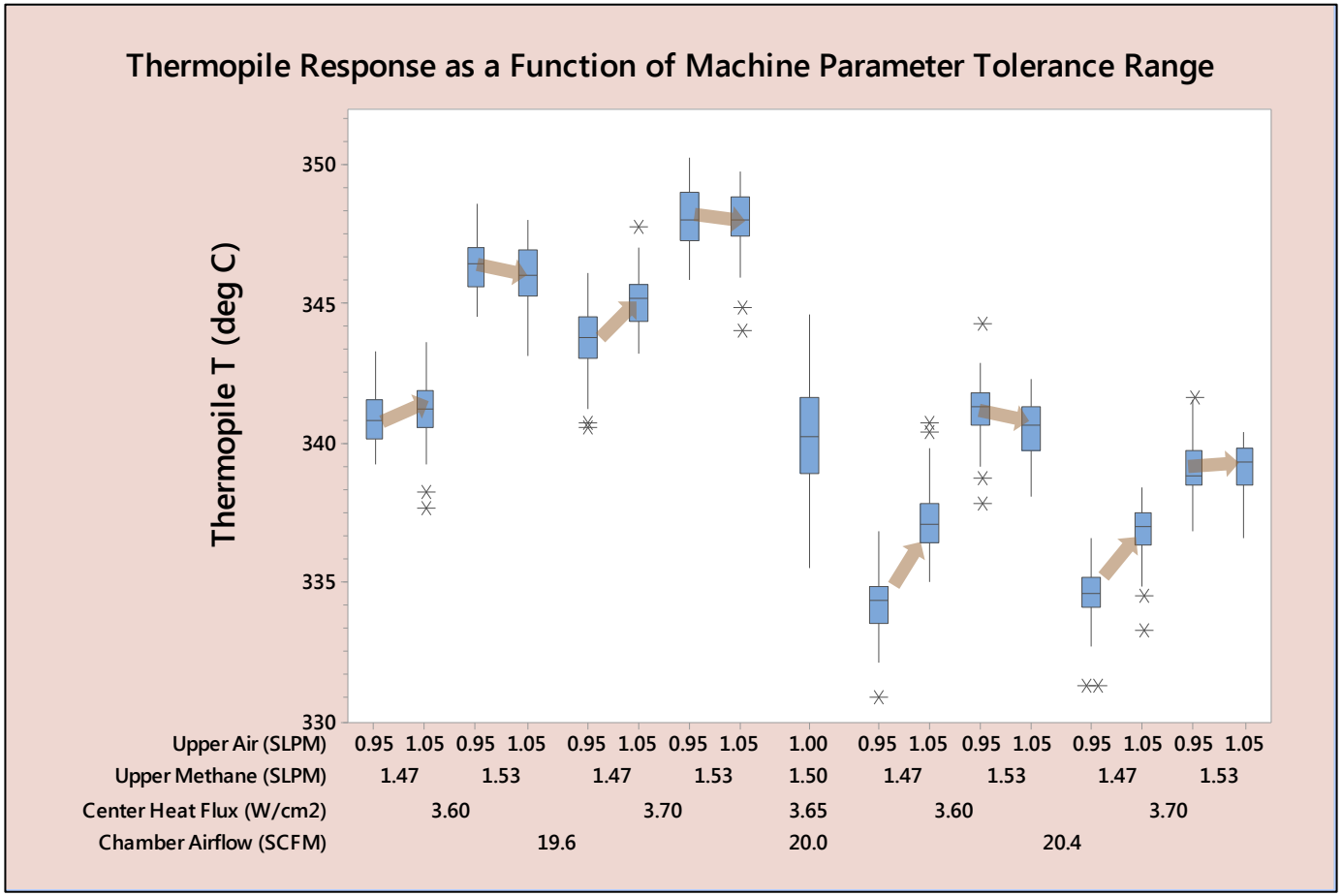
HR2 DOE II Results

- **Factor Effects**
  - **Upper Pilot Airflow**: 1.00±0.0.05 SLPM
  - "Slight" impact: ΔT approximately -0.4 to +2 deg C for full-scale swing of 0.95 -> 1.05 SLPM



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HR2 DOE II Results

- **Factor Effects Summary**
  - Assessment of machine tolerance ranges
    - Heat flux: Moderate effect
    - Chamber airflow: Large effect
    - Upper methane flow: Large effect
    - Upper air flow: Slight effect
  - Overall impact
    - Evaluate maximum temperature swing over combined tolerance ranges
      - Condition for Maximum Temperature
        - Chamber airflow 19.6 SCFM, Heat flux 3.70 W/cm^2, Upper methane 1.53 SLPM, Upper airflow 0.95 SLPM
        - Average temperature: 348 deg C
      - Condition for Minimum Temperature
        - Chamber airflow 20.4 SCFM, Heat flux 3.60 W/cm^2, Upper methane 1.47 SLPM, Upper airflow 0.95 SLPM
        - Average temperature: 334 deg C
    - Swing of average temperature over combined tolerance ranges: ~14 deg C or ~4.1%

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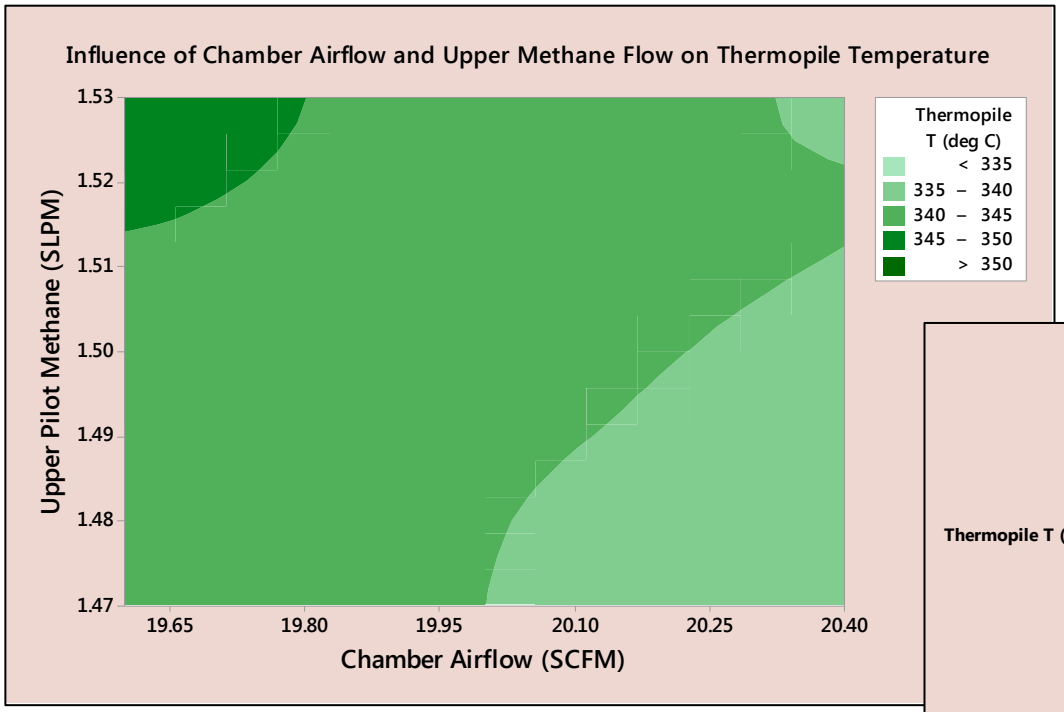
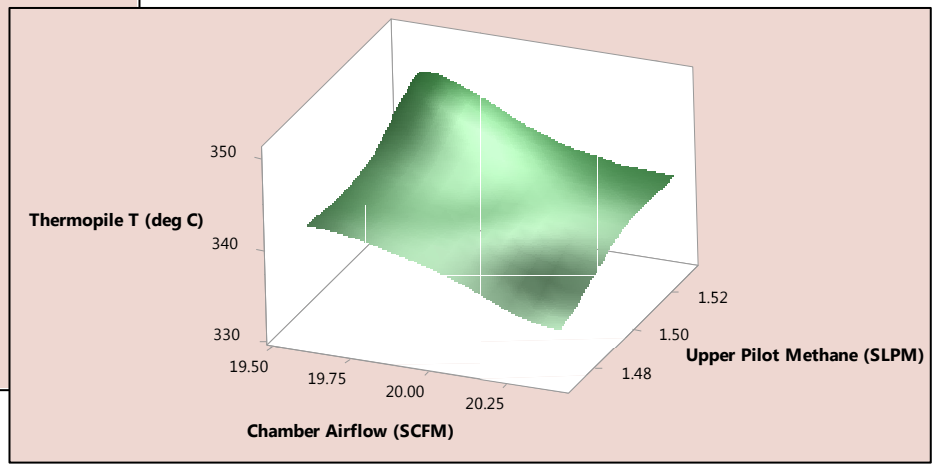
HR2 DOE II Results

- **Factor Effects Summary: Contour Plots**
  - Assessment of machine tolerance ranges
    - Chamber Airflow & Upper Methane Flow: Large effects
  - Overall impact
    - Swing of average temperature over combined tolerance ranges: ~14 deg C or ~4.1%





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HR2 DOE II Results

- **DOE I vs DOE II Comparison**
  - As noted earlier, there have been several significant changes in hardware and methodology in going from DOE I (Fall 2015) to DOE II (Fall 2017).
  - As a result, direct numerical comparisons between the results of DOE I and DOE II are not straightforward.
  - Additionally, both DOEs were limited in scope and represent a brief snap-shot in time.
  - Disclaimers aside, however, the results of DOE II seem quite promising as shown in the table below.
  - The various changes appear to have resulted in significant improvements in calibration factor variation, uniformity of stability runs, and maximum variation over the range of allowed tolerance ranges.

Item	DOE I (Fall 2015)	DOE II (Fall 2017)	Improvement? (Y/N)
Variation in Calibration Factors (%)	5.8	2.2 (0.3)	Y
Uniformity of Stability Runs (Max D)	3.5	1.5	Y
Factor Effect Impacts			
Heat Flux	Moderate	Moderate	--
Chamber Airflow	Large	Large	--
Upper Pilot Methane Flow	Large	Large	--
Upper Pilot Airflow	Slight	Slight	--
Maximum Response Variation (%)	13.1	4.1	Y

- **Screening DOE Summary**
  - DOEs I & II have successfully identified significant “knobs” for reduction in heat release variation and implementation of actions resulting from the screening DOEs seem to have yield significant improvements toward the end-goal of reducing variation in heat release measurements.

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Backup

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HR2 DOE II Results

- **Factor Effects**
  - Assessment of machine tolerance ranges: heat flux, chamber airflow, upper methane flow, upper air flow
  - Summary statistics

Chamber Airflow (SCFM) = 19.6, Center Heat Flux (W/cm2) = 3.60, Upper Pilot Methane (SLPM) = 1.47

Variable	Upper Pilot Airflow (SLPM)	Total Count	Mean	SE Mean	StDev	CoefVar	Minimum	Median	Maximum
Thermopile T (deg C)	0.95	60	340.90	0.122	0.944	0.28	339.20	340.80	343.30
	1.05	60	341.11	0.147	1.14	0.33	337.60	341.20	343.60

Chamber Airflow (SCFM) = 19.6, Center Heat Flux (W/cm2) = 3.60, Upper Pilot Methane (SLPM) = 1.53

Variable	Upper Pilot Airflow (SLPM)	Total Count	Mean	SE Mean	StDev	CoefVar	Minimum	Median	Maximum
Thermopile T (deg C)	0.95	60	346.36	0.124	0.958	0.28	344.50	346.40	348.60
	1.05	60	346.01	0.137	1.06	0.31	343.10	346.00	348.00

Chamber Airflow (SCFM) = 19.6, Center Heat Flux (W/cm2) = 3.70, Upper Pilot Methane (SLPM) = 1.47

Variable	Upper Pilot Airflow (SLPM)	Total Count	Mean	SE Mean	StDev	CoefVar	Minimum	Median	Maximum
Thermopile T (deg C)	0.95	60	343.66	0.148	1.15	0.33	340.50	343.75	346.10
	1.05	60	345.13	0.125	0.972	0.28	343.20	345.20	347.70

Chamber Airflow (SCFM) = 19.6, Center Heat Flux (W/cm2) = 3.70, Upper Pilot Methane (SLPM) = 1.53

Variable	Upper Pilot Airflow (SLPM)	Total Count	Mean	SE Mean	StDev	CoefVar	Minimum	Median	Maximum
Thermopile T (deg C)	0.95	60	348.08	0.136	1.05	0.30	345.80	348.00	350.20
	1.05	60	348.03	0.146	1.13	0.33	344.00	348.00	349.70

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HR2 DOE II Results

- **Factor Effects**
  - Summary statistics

CENTER POINTS Chamber Airflow (SCFM) = 20.0, Center Heat Flux (W/cm2) = 3.65, Upper Pilot Methane (SLPM) = 1.50

Variable	Upper Pilot Airflow (SLPM)	Total Count	Mean	SE Mean	StDev	CoefVar	Minimum	Median	Maximum
Thermopile T (deg C)	1.00	480	340.26	0.0835	1.83	0.54	335.50	340.20	344.60

Chamber Airflow (SCFM) = 20.4, Center Heat Flux (W/cm2) = 3.60, Upper Pilot Methane (SLPM) = 1.47

Variable	Upper Pilot Airflow (SLPM)	Total Count	Mean	SE Mean	StDev	CoefVar	Minimum	Median	Maximum
Thermopile T (deg C)	0.95	60	334.27	0.139	1.08	0.32	330.80	334.35	336.80
	1.05	60	337.28	0.167	1.29	0.38	335.00	337.05	340.70

Chamber Airflow (SCFM) = 20.4, Center Heat Flux (W/cm2) = 3.60, Upper Pilot Methane (SLPM) = 1.53

Variable	Upper Pilot Airflow (SLPM)	Total Count	Mean	SE Mean	StDev	CoefVar	Minimum	Median	Maximum
Thermopile T (deg C)	0.95	60	341.18	0.138	1.07	0.31	337.80	341.25	344.20
	1.05	60	340.48	0.129	0.999	0.29	338.10	340.65	342.30

Chamber Airflow (SCFM) = 20.4, Center Heat Flux (W/cm2) = 3.70, Upper Pilot Methane (SLPM) = 1.47

Variable	Upper Pilot Airflow (SLPM)	Total Count	Mean	SE Mean	StDev	CoefVar	Minimum	Median	Maximum
Thermopile T (deg C)	0.95	60	334.57	0.130	1.01	0.30	331.20	334.55	336.60
	1.05	60	336.75	0.136	1.05	0.31	333.20	337.00	338.40

Chamber Airflow (SCFM) = 20.4, Center Heat Flux (W/cm2) = 3.70, Upper Pilot Methane (SLPM) = 1.53

Variable	Upper Pilot Airflow (SLPM)	Total Count	Mean	SE Mean	StDev	CoefVar	Minimum	Median	Maximum
Thermopile T (deg C)	0.95	60	338.98	0.122	0.943	0.28	336.80	338.80	341.60
	1.05	60	339.11	0.115	0.888	0.26	336.60	339.30	340.40

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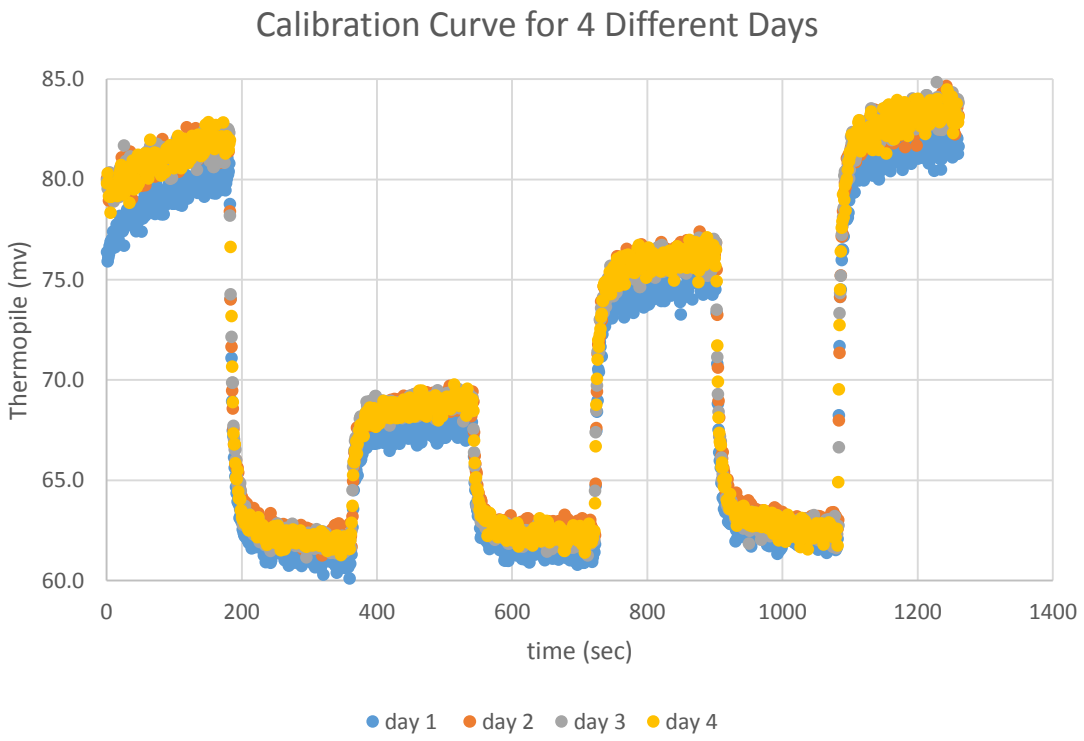
HR2 DOE II Results

Calibration (DOE I, Fall 2015)



day	Cal factor	% difference from mean	Pressure (milibar)	Room temp (F)	Room RH (%)	Inlet air RH(%)
1	0.091	3.88%	1020	79.2	50	11.82
2	0.088	0.34%	1018	81	54	14.02
3	0.086	-2.17%	1014	81.1	53	13.4
4	0.086	-2.05%	1020	80.2	55	12.69

There is ~6% spread in in cal factor (same machine, same lab, same operator… etc.), which will directly result in a 6% spread in the heat release rate assuming all other factors are constant

$$Heat\ Release\ Rate = (Test_{mV} - Baseline_{mV}) * (\frac{K_h}{0.02323})$$

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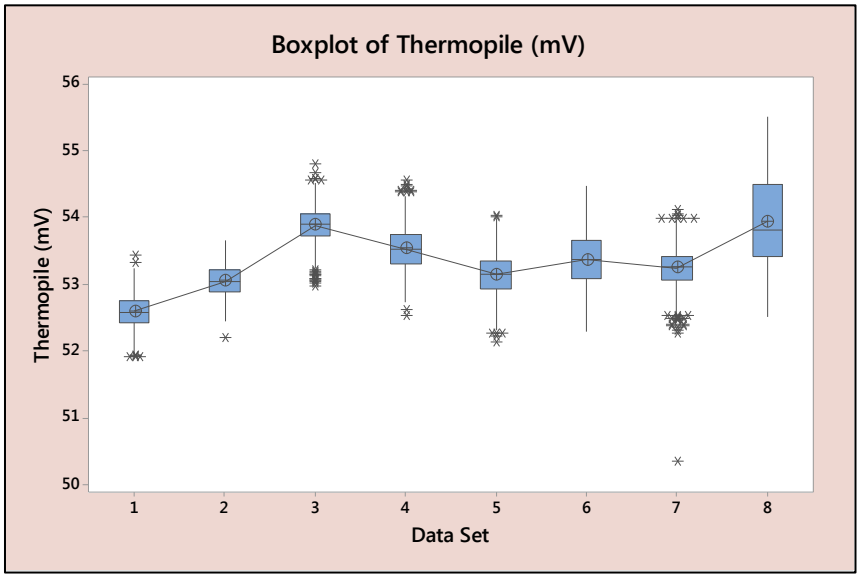
HR2 DOE II Results

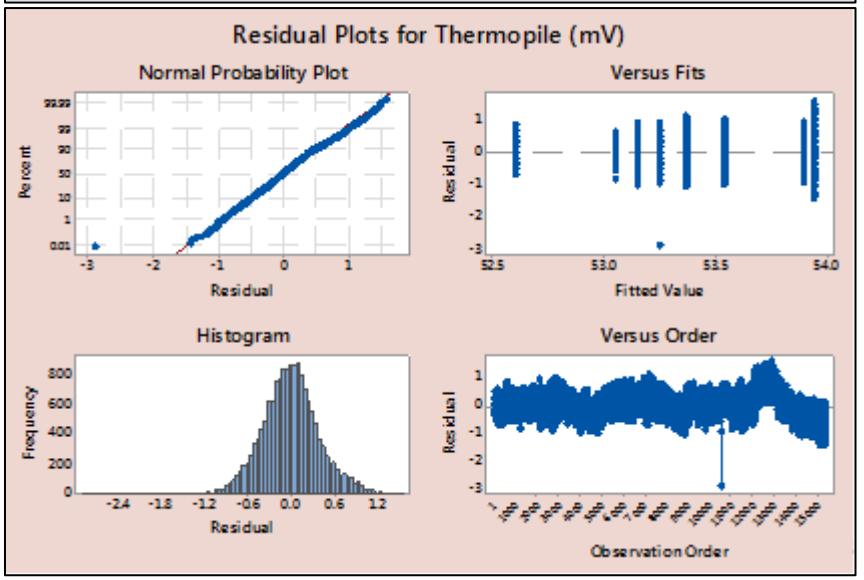
- **Stability Runs (DOE I, Fall 2015)**
  - Analysis of Variance (ANOVA)

```
Source        DF  Adj SS   Adj MS  F-Value  P-Value
Data Set       7    2044  292.004  1927.24    0.000
Error      15438    2339    0.152
Total      15445    4383

Data
Set       N     Mean   StDev         95% CI
1       645  52.5992  0.2454  (52.5691, 52.6292)
2      1158  53.0500  0.2320  (53.0276, 53.0724)
3       983  53.8916  0.2679  (53.8673, 53.9160)
4      1235  53.5386  0.3114  (53.5169, 53.5603)
5      2829  53.1484  0.3041  (53.1340, 53.1627)
6      2047  53.3645  0.3805  (53.3477, 53.3814)
7      3243  53.2487  0.2731  (53.2353, 53.2621)
8      3306  53.9432  0.6146  (53.9299, 53.9564)

Pooled StDev = 0.389248

Grouping Information Using the Tukey Method and 95% Confidence

Data
Set       N     Mean  Grouping
8      3306  53.9432  A
3       983  53.8916     B
4      1235  53.5386        C
6      2047  53.3645           D
7      3243  53.2487              E
5      2829  53.1484                 F
2      1158  53.0500                    G
1       645  52.5992                       H

Means that do not share a letter are significantly different.
```

Effect Size Calculation (Example)
Max D = (53.9432 – 52.5992) / 0.39 = 3.45

- Statistical difference among stability run average temperatures.
- All stability run data included, not just last 1 minute after stabilization





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