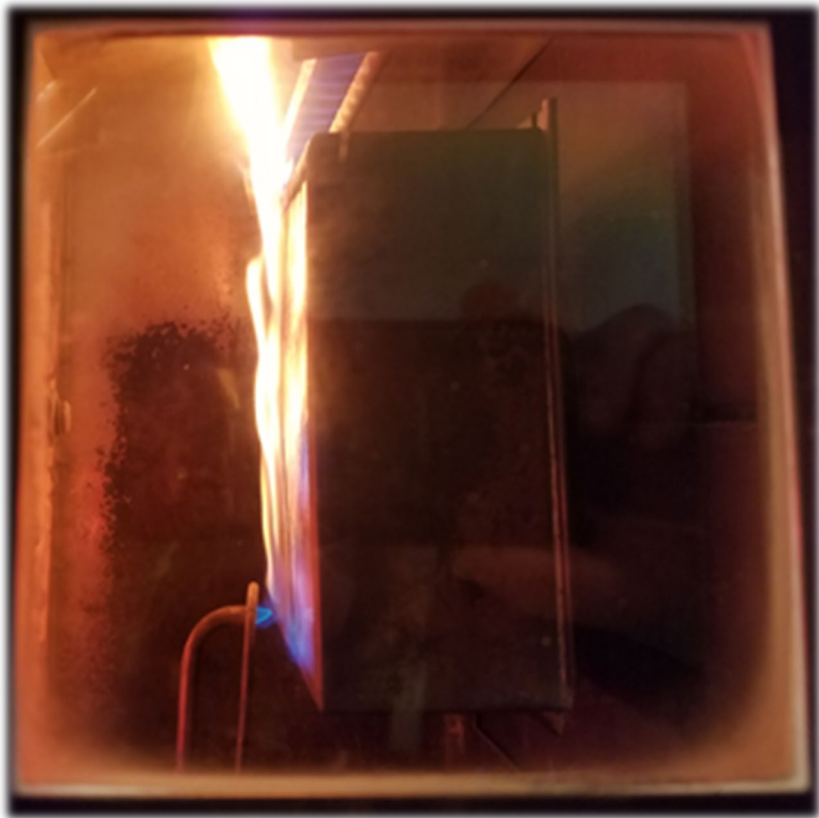




HR2 Development - TRL 5 Test Results



Presented by: Brian Johnson and Dr. Thomas Little,
both of The Boeing Company

Prepared by: Yaw Agyei, Yonas Behboud,
Dr. Thomas Little and Brian Johnson,
all of the Boeing Company

October 2018 MFTF

OSU Test Method

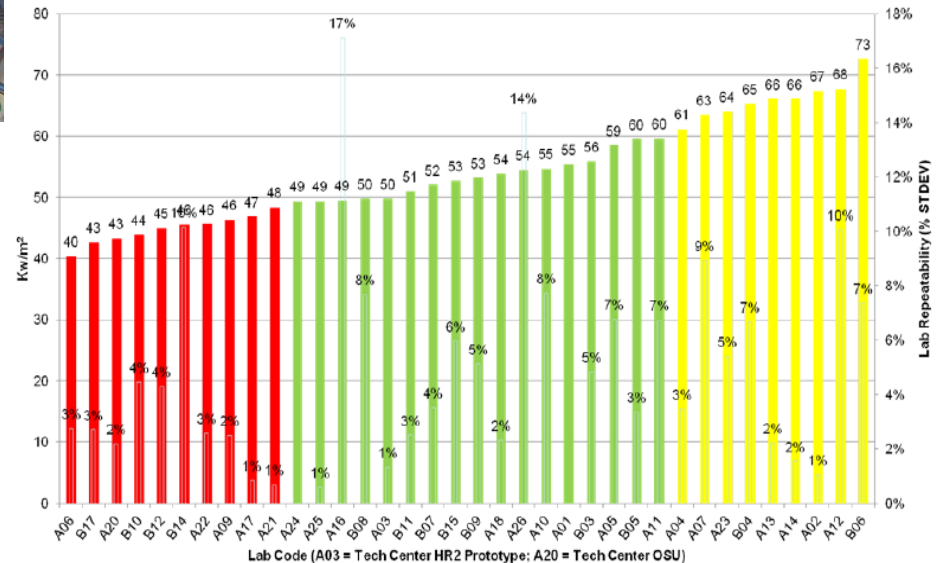


- Reproducibility challenges persist
- Specification does not tightly control some key parameters
- Decades of certification data in use

14CFR25.853(d)

- Added in 1986
- Current FAR - Appendix F Part IV
- Applicable to interior exposed surfaces greater than 144 square inches
- Measure heat release as a function of time
- Test code: HR

Light Brown Honeycomb Panel
Peak HRR vs. % STDEV
Avg = 54 kW/m²; 16% STDEV



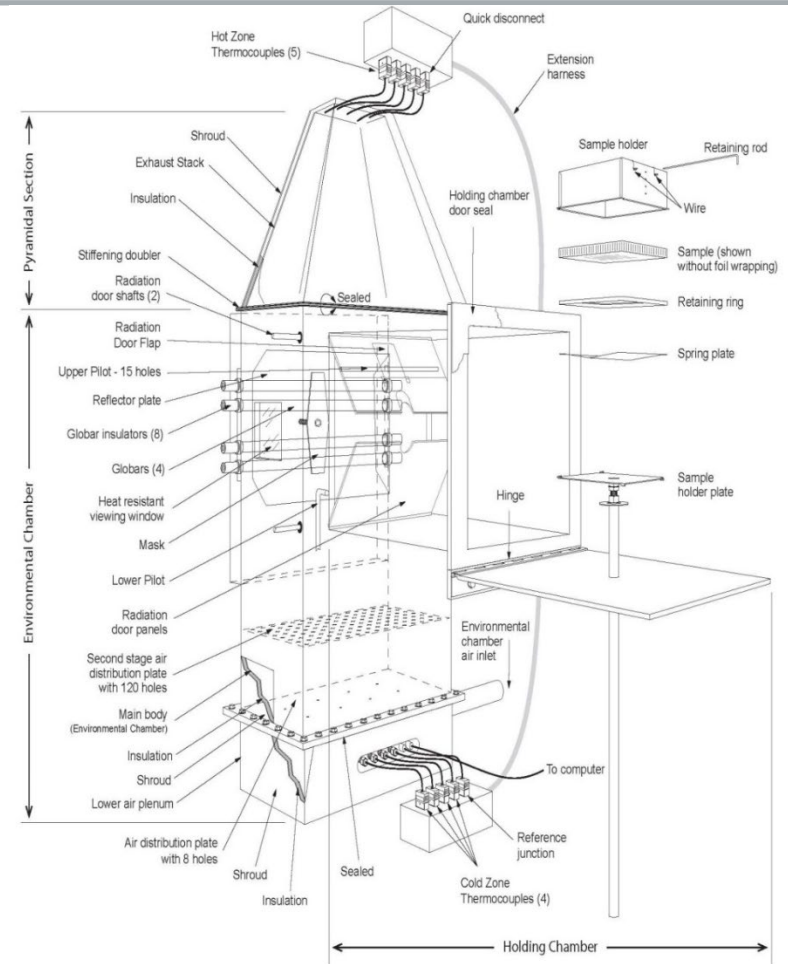
*Presented June 2012

HR2 - Next Generation OSU



Design and Other Changes

- Elimination of cooling flow / inner chimney
- Insulation / metal wall specification changes
- Coupon location in chamber specified
- Air and methane flows controlled via MFCs
- Single lower Tcouple - DAQ correction
- HFG calibration / limit changes (3.65 W/cm^2)
- Methane calibration and cal factor correction
- Multiple additional procedural changes



**Presented October 2016*

Anticipated Improvements

- Repeatability driven by design and cal changes
- Reproducibility increased via spec controls
- Cross industry variation greatly reduced

Introduction

- HR2 Goal: Define a robust method to determine peak and total heat release that improves[^] repeatability and reproducibility when compared with OSU.

Status

- Technical Readiness Level (TRL) model adopted
- TRL 4 - Robustness completed - DOE defined key parameters and variation
 - Identification of key parameter influence levels
 - Reduced variation in Calibration Factors
 - Improved uniformity of Stability Runs
- HR2 is in TRL phase 5 - Repeatability

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

**Presented November 2017*

[^] A specific improvement target not been agreed to in prior breakout sessions

Developmental Project Technical Readiness

Flammability Test Method/Equipment TRLs (Derived from NASA TRL)

<p>MATURITY LEVEL</p> <p>Discovery</p> <p>↓</p> <p>Feasibility</p> <p>↓</p> <p>Practicality</p> <p>↓</p> <p>Applicability</p> <p>↓</p> <p>Production Readiness</p>	TRL 1	Basic principles/concept of test equipment and procedure defined.
	TRL 2	Test method concept formulated and defined by draft standards.
	TRL 3	Analytical and experimental critical function and/or characteristic proof-of concept (e.g. by modifying old/existing equipment)
	TRL 4	New prototype equipment validation in laboratory environment (robustness)
	TRL 5	Updated prototype equipment validation in relevant production environment (repeatability). Documented test guidance framework.
	TRL 6	Multiple prototypes validation in relevant environment (reproducibility)
	TRL 7	Finalized prototype equipment demonstration on range of production configurations. Documented test guidance defined.
	TRL 8	Final test equipment drawings released, equipment built to the standards, and “qualified” through test and demonstration. Documented test guidance finalized.
	TRL 9	Multiple production units verified by successful round robin testing.

**Presented in October 2014*

HR2 Development TRLs & Gates

TRL 5 - *Repeatability* - variation in measurements taken on the same item under the same conditions. Homogenous coupon tested multiple times using one unit.

➔ Gate 5 / Enter **TRL 6**: Coefficient of Variation (CoV) improvement vs. OSU

TRL 6 - *Reproducibility* - variation in measurements taken on the same items under the same conditions using different machines.

➔ Gate 6 / Enter **TRL 7**: Individual coupon type CoV and ANOVA evaluation

TRL 7 - *Range* - Finalized prototype equipment demonstration on range of production configurations. HR2 pass/fail criteria (peak/total) established.

➔ Gate 7 / Enter **TRL 8**: Consistent results over a range of sample types

TRL 8 - *Guidance* - drawings release, equipment built to standards, 'qualified' through test and demonstration.

➔ Gate 8 / Enter **TRL9**: Qualification criteria and test guidance established

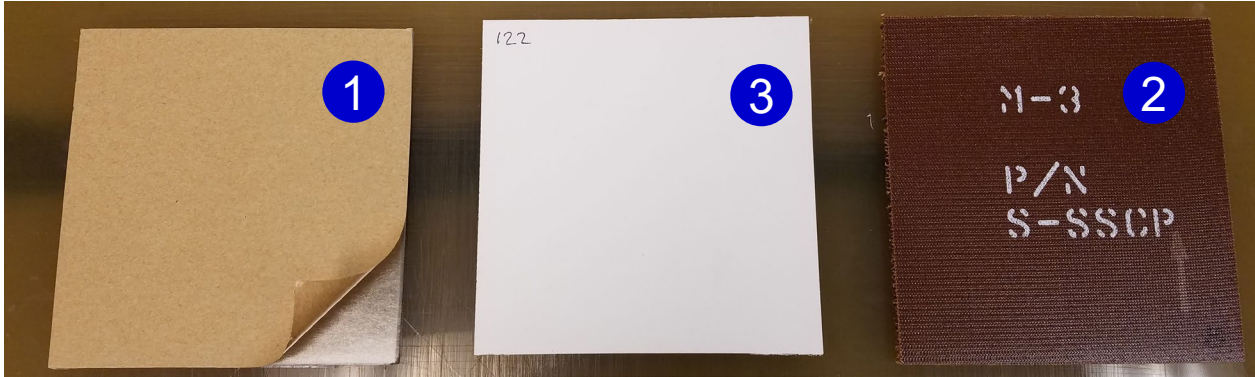
TRL 9 - *Round Robin* - Multiple production units verified by successful round robin testing.

➔ Gate 9 / **Production Readiness**: Significant R&R improvements vs. OSU

TRL 5 Test Plan

30 randomized samples of 3 homogenous coupon types

1. 0.060" Al panel with 3M 950 transfer tape - provided by Boeing
2. Standard laminate panel - provided by Schneller
3. Honeycomb panel with decorative (dec) - provided by Boeing



Two test locations - two instruments

- Marlin Engineering OSU baseline - tested August 15 - 18th at Boeing, Everett, WA
- Marlin Engineering HR2 - tested September 11 - 14th at FAA TC, Egg Harbor Twp, NJ

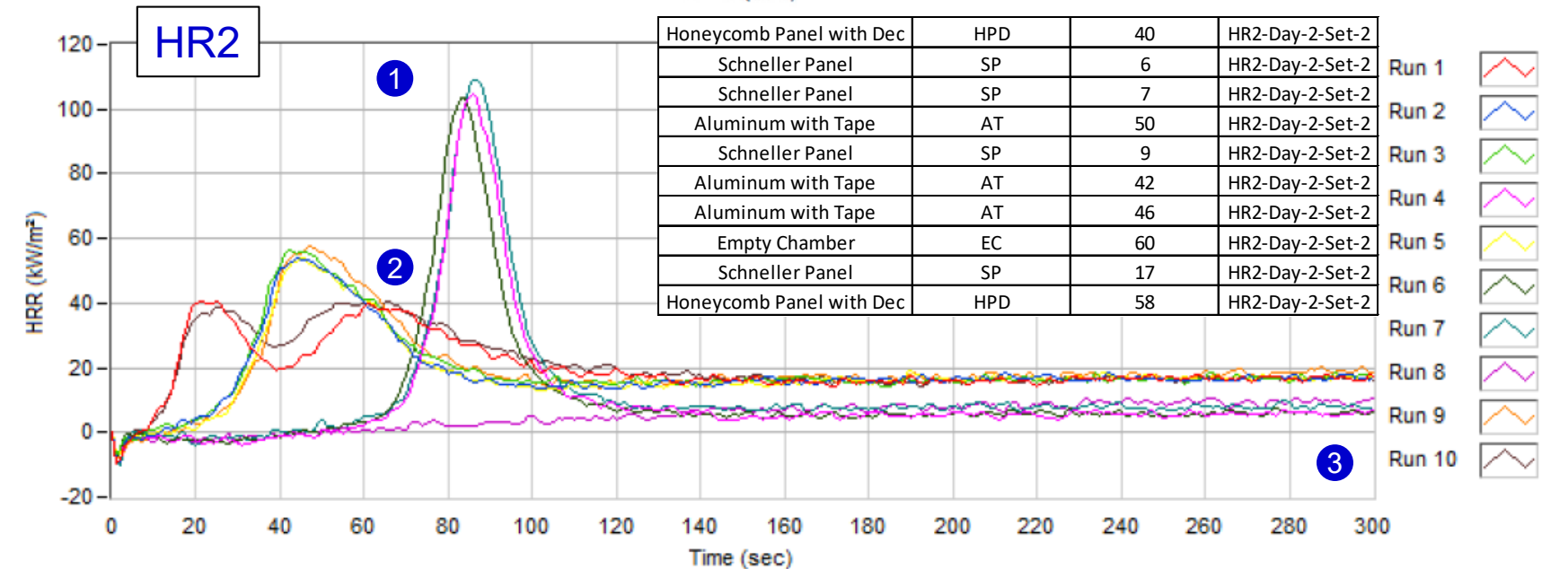
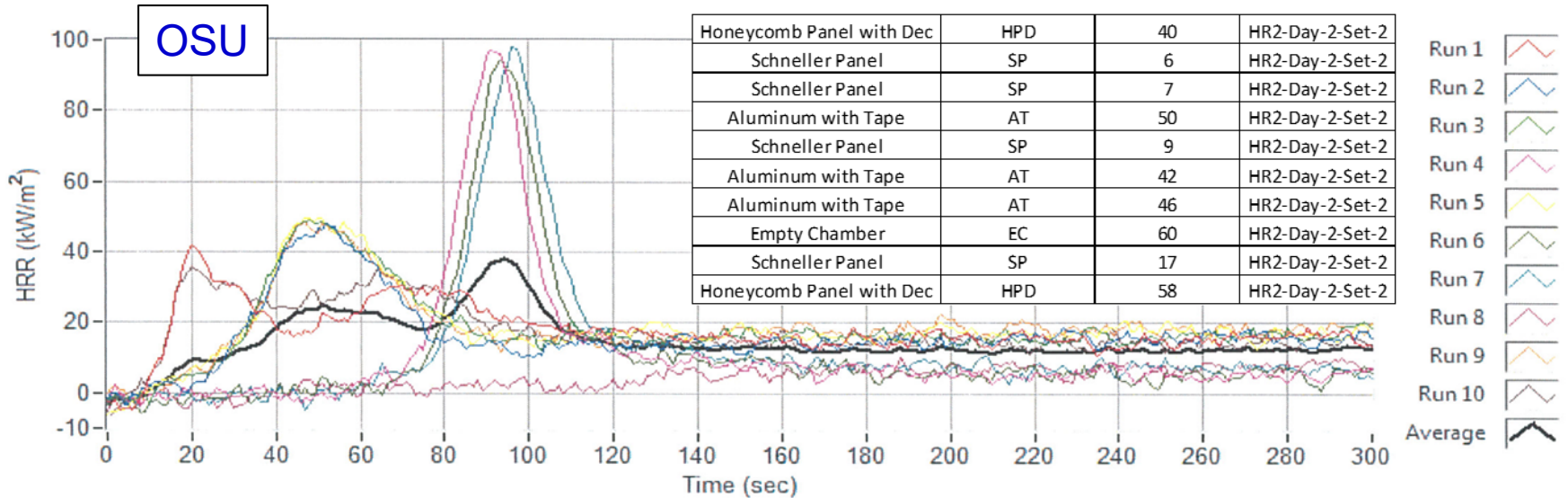
Repeatability evaluated using the coefficient of variation ($CoV = \sigma/\mu$)

- Anticipated CoV improvement versus OSU baseline - no exact target defined

TRL 5 Test Matrix - OSU and HR2

Day	Set #	Run Order	Specimen ID	Specimen	Specimen Code	Specimen Run	Filename	Time of Test	Peak (kW/m2)	Peak Time (seconds)	2-Min Total HR (kW-min/m2)	Baseline (mV)
1	1	1	HPD-41	Honeycomb Panel with Dec	HPD	41	OSU-Day-1-Set-1	12:14	39.15	20	42.81	26.48
1	1	2	SP-39	Schneller Panel	SP	39	OSU-Day-1-Set-1	12:21	54.84	48	43.01	26.17
1	1	3	AT-19	Aluminum with Tape	AT	19	OSU-Day-1-Set-1	12:27	95.08	92	33.89	26.32
1	1	4	SP-50	Schneller Panel	SP	50	OSU-Day-1-Set-1	12:34	46.41	46	36.80	26.09
1	1	5	SP-48	Schneller Panel	SP	48	OSU-Day-1-Set-1	12:41	47.41	51	39.57	26.10
1	1	6	HPD-37	Honeycomb Panel with Dec	HPD	37	OSU-Day-1-Set-1	12:50	37.46	20	41.34	26.30
1	1	7	EC-54	Empty Chamber	EC	54	OSU-Day-1-Set-1	12:57	12.11	280	3.64	26.04
1	1	8	SP-12	Schneller Panel	SP	12	OSU-Day-1-Set-1	1:04	52.03	46	42.63	25.78
1	1	9	SP-18	Schneller Panel	SP	18	OSU-Day-1-Set-1	1:11	44.01	49	40.02	26.16
1	1	10	EC-7	Empty Chamber	EC	7	OSU-Day-1-Set-1	1:17	11.23	210	5.26	26.18
1	2	11	EC-13	Empty Chamber	EC	13	OSU-Day-1-Set-2	1:28	9.11	262	1.75	26.40
1	2	12	EC-24	Empty Chamber	EC	24	OSU-Day-1-Set-2	1:35	14.14	273	6.06	26.00
1	2	13	SP-24	Schneller Panel	SP	24	OSU-Day-1-Set-2	1:41	49.57	43	45.08	25.96
1	2	14	EC-51	Empty Chamber	EC	51	OSU-Day-1-Set-2	1:47	12.51	267	2.46	26.41
1	2	15	EC-41	Empty Chamber	EC	41	OSU-Day-1-Set-2	1:54	13.61	247	5.24	26.06
1	2	16	SP-60	Schneller Panel	SP	60	OSU-Day-1-Set-2	2:01	50.22	49	41.82	26.11
1	2	17	HPD-59	Honeycomb Panel with Dec	HPD	59	OSU-Day-1-Set-2	2:11	35.94	18	45.48	26.50
1	2	18	HPD-47	Honeycomb Panel with Dec	HPD	47	OSU-Day-1-Set-2	2:18	38.25	20	41.67	26.35
1	2	19	EC-19	Empty Chamber	EC	19	OSU-Day-1-Set-2	2:25	10.16	251	3.11	26.20
1	2	20	SP-19	Schneller Panel	SP	19	OSU-Day-1-Set-2	2:31	47.83	46	40.49	26.05
1	3	21	EC-48	Empty Chamber	EC	48	OSU-Day-1-Set-3	2:43	10.26	288	1.54	26.53
1	3	22	EC-39	Empty Chamber	EC	39	OSU-Day-1-Set-3	2:50	12.46	295	4.12	26.24
1	3	23	HPD-29	Honeycomb Panel with Dec	HPD	29	OSU-Day-1-Set-3	2:57	37.28	19	48.73	26.12
1	3	24	AT-180	Aluminum with Tape	AT	180	OSU-Day-1-Set-3	3:03	95.79	94	35.68	26.23
1	3	25	EC-12	Empty Chamber	EC	12	OSU-Day-1-Set-3	3:10	12.57	218	7.49	25.88
1	3	26	HPD-19	Honeycomb Panel with Dec	HPD	19	OSU-Day-1-Set-3	3:17	39.61	19	47.70	26.09
1	3	27	AT-44	Aluminum with Tape	AT	44	OSU-Day-1-Set-3	3:24	96.56	93	34.64	26.20
1	3	28	EC-5	Empty Chamber	EC	5	OSU-Day-1-Set-3	3:30	11.57	264	4.52	26.02
1	3	29	SP-40	Schneller Panel	SP	40	OSU-Day-1-Set-3	3:37	48.63	51	42.56	25.92
1	3	30	HPD-20	Honeycomb Panel with Dec	HPD	20	OSU-Day-1-Set-3	3:44	39.31	18	42.89	26.28
2	1	31	HPD-60	Honeycomb Panel with Dec	HPD	60	OSU-Day-2-Set-1	12:32	41.12	19	41.03	26.55
2	1	32	HPD-53	Honeycomb Panel with Dec	HPD	53	OSU-Day-2-Set-1	12:39	36.59	20	43.54	26.36
2	1	33	SP-30	Schneller Panel	SP	30	OSU-Day-2-Set-1	12:45	47.35	49	38.52	26.24
2	1	34	SP-4	Schneller Panel	SP	4	OSU-Day-2-Set-1	12:52	50.41	49	41.12	26.19
2	1	35	HPD-8	Honeycomb Panel with Dec	HPD	8	OSU-Day-2-Set-1	12:58	37.74	21	44.27	26.19
2	1	36	EC-57	Empty Chamber	EC	57	OSU-Day-2-Set-1	1:06	9.92	278	1.21	26.50
2	1	37	HPD-9	Honeycomb Panel with Dec	HPD	9	OSU-Day-2-Set-1	1:12	40.80	21	47.67	26.04
2	1	38	HPD-11	Honeycomb Panel with Dec	HPD	11	OSU-Day-2-Set-1	1:20	42.17	20	45.18	26.03
2	1	39	EC-30	Empty Chamber	EC	30	OSU-Day-2-Set-1	1:29	10.00	288	2.83	26.01

TRL 5 Test Results



TRL 5 Test Results

General Observations

Coupon Complexity

- CoV's confirmed anticipated coupon material variability

OSU vs HR2 Peak Time and Shape

- HR2 peaks appeared earlier and were larger than in OSU testing*
- Honeycomb w/ dec: panel peak exceeded dec peak - affected recorded time



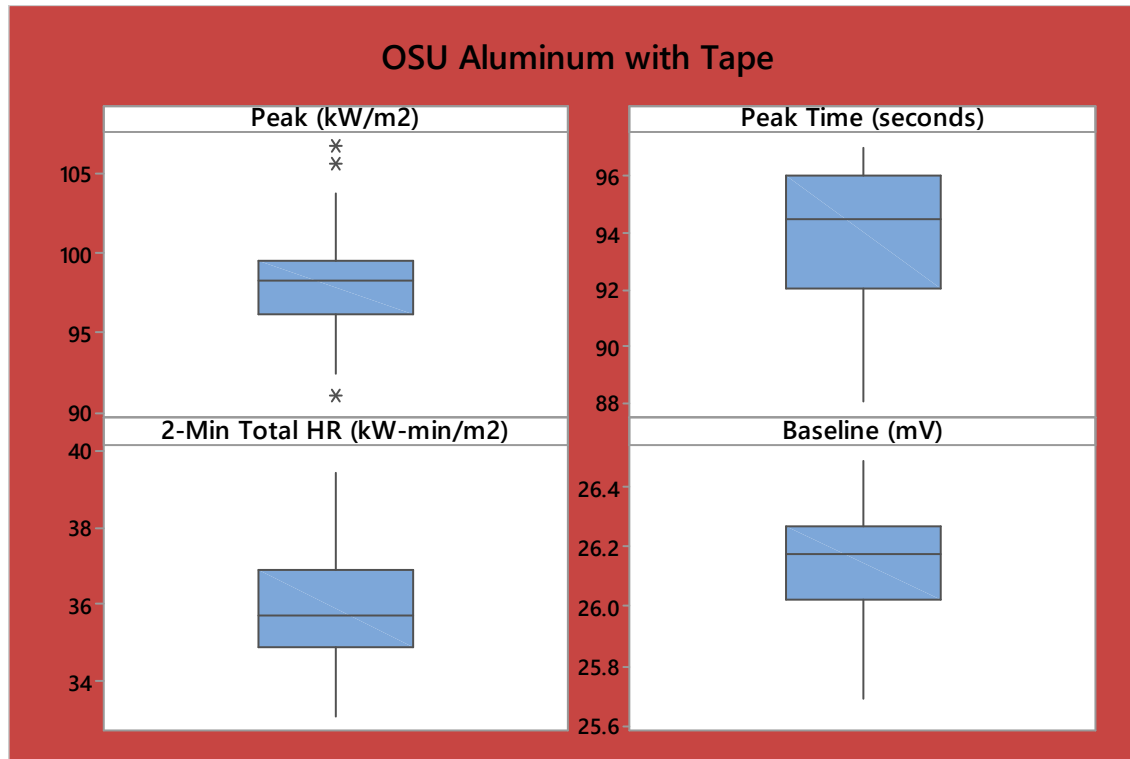
Baseline Equilibration is Coupon Type Dependent

- Final baseline higher for honeycomb coupons, lower for sample holder & aluminum

Empty Sample Holder Results

- Both OSU and HR2 testing indicated non-zero results due to empty sample holder presence

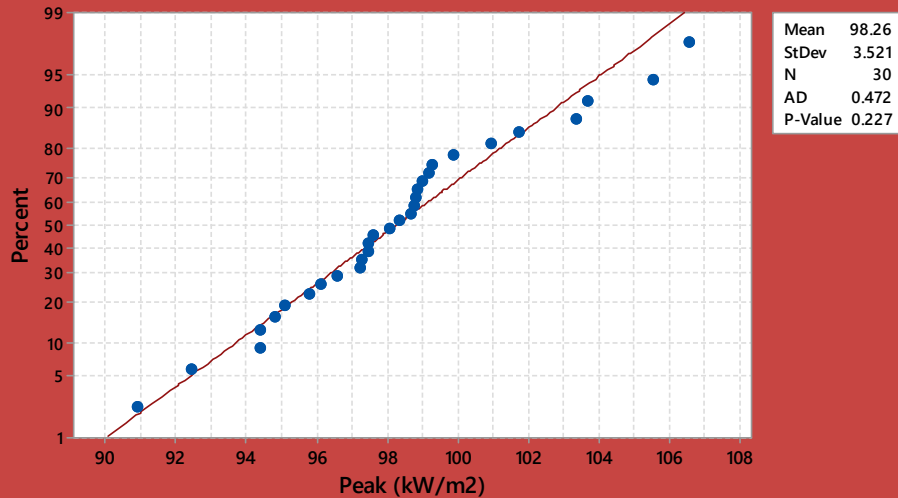
Analysis - OSU Aluminum with Tape



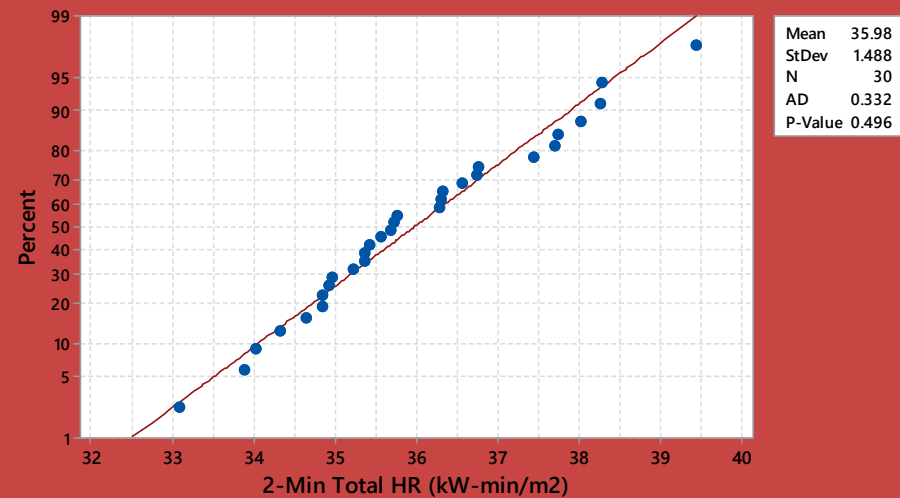
Variable	Total Count	Mean	SE Mean	StDev	CoefVar (%)
Peak (kW/m2)	30	98.26	0.64	3.52	3.58
Peak Time (seconds)	30	93.93	0.39	2.15	2.29
2-Min Total HR (kW-min/m2)	30	35.98	0.27	1.49	4.14
Baseline (mV)	30	26.14	0.04	0.20	0.78

Analysis - OSU Aluminum with Tape

OSU AI with Tape Peak Normality
Normal

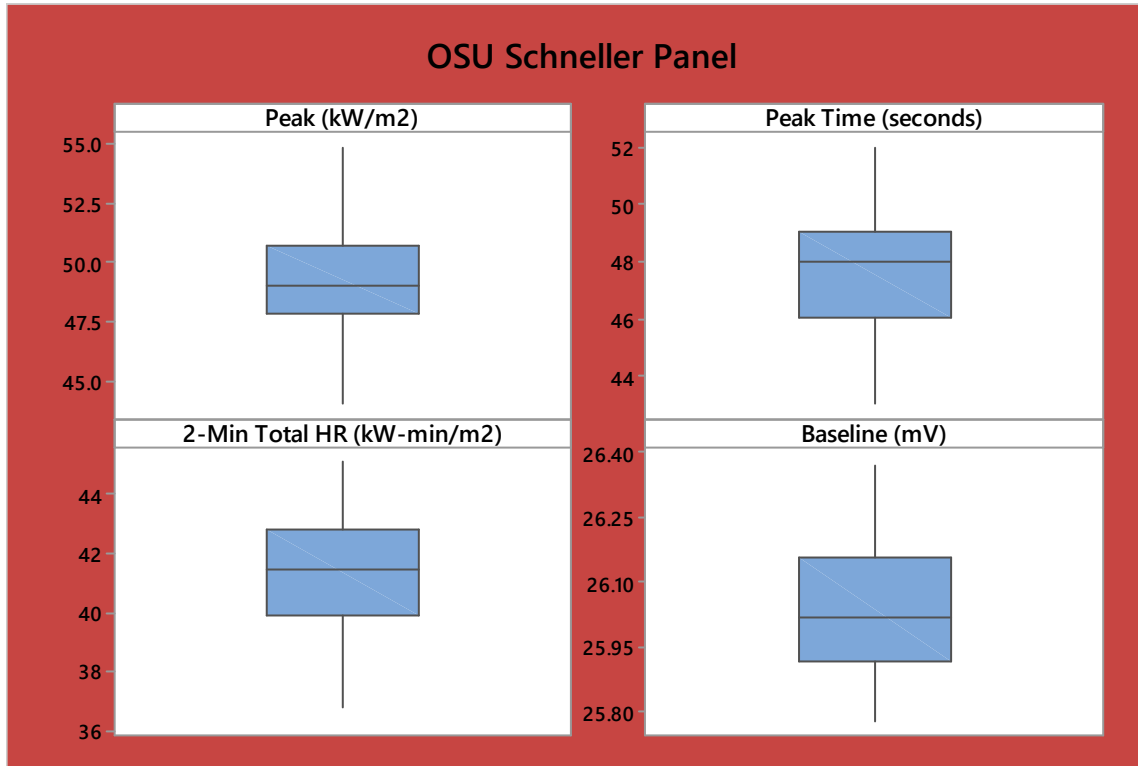


OSU AI with Tape 2-min Total Normality
Normal



Variable	Total Count	Mean	SE Mean	StDev	CoefVar (%)
Peak (kW/m2)	30	98.26	0.64	3.52	3.58
Peak Time (seconds)	30	93.93	0.39	2.15	2.29
2-Min Total HR (kW-min/m2)	30	35.98	0.27	1.49	4.14
Baseline (mV)	30	26.14	0.04	0.20	0.78

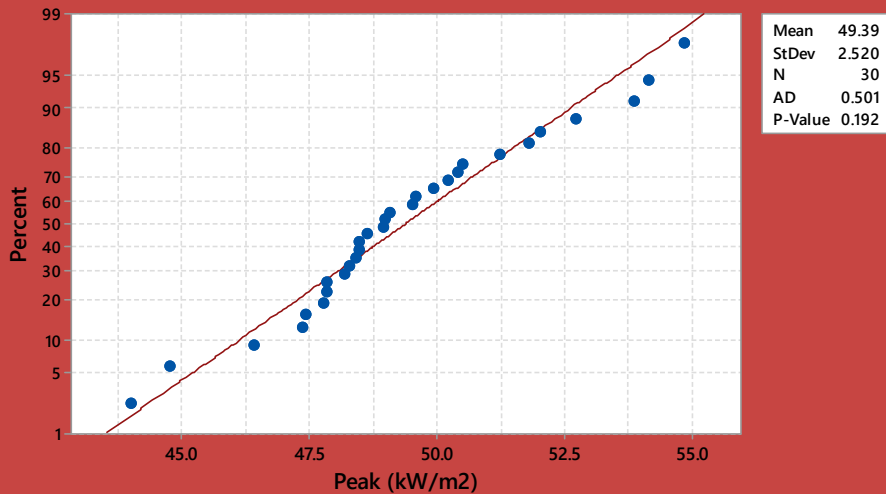
Analysis - OSU Schneller Panel



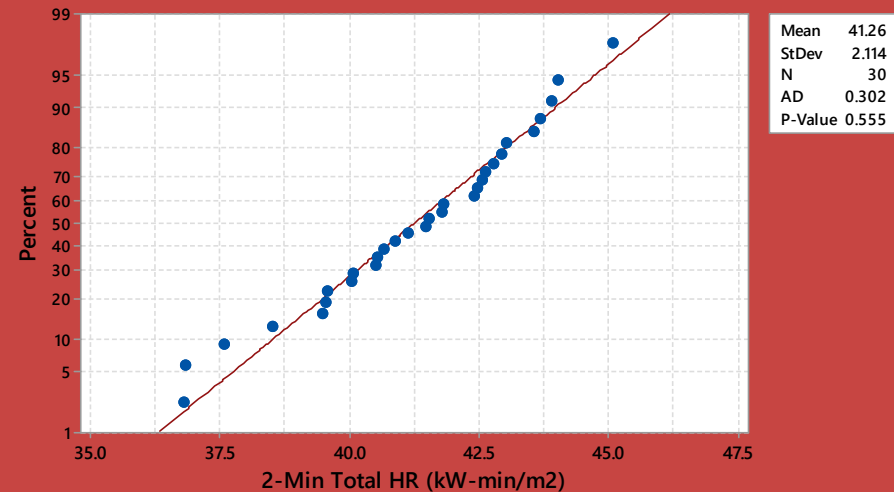
Variable	Total Count	Mean	SE Mean	StDev	CoefVar (%)
Peak (kW/m2)	30	49.39	0.46	2.52	5.10
Peak Time (seconds)	30	47.63	0.41	2.24	4.69
2-Min Total HR (kW-min/m2)	30	41.26	0.39	2.11	5.12
Baseline (mV)	30	26.04	0.03	0.15	0.56

Analysis - OSU Schneller Panel

OSU Schneller Peak Normality
Normal

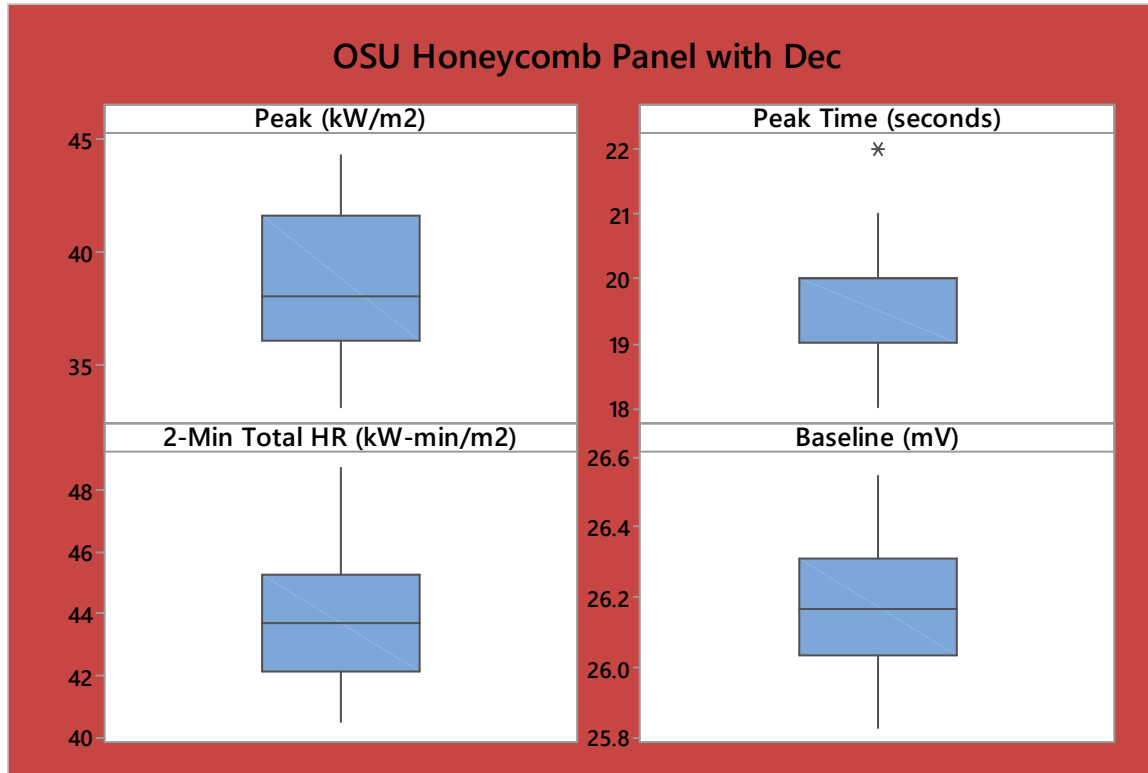


OSU Schneller 2-min Total Normality
Normal



Variable	Total Count	Mean	SE Mean	StDev	CoefVar (%)
Peak (kW/m2)	30	49.39	0.46	2.52	5.10
Peak Time (seconds)	30	47.63	0.41	2.24	4.69
2-Min Total HR (kW-min/m2)	30	41.26	0.39	2.11	5.12
Baseline (mV)	30	26.04	0.03	0.15	0.56

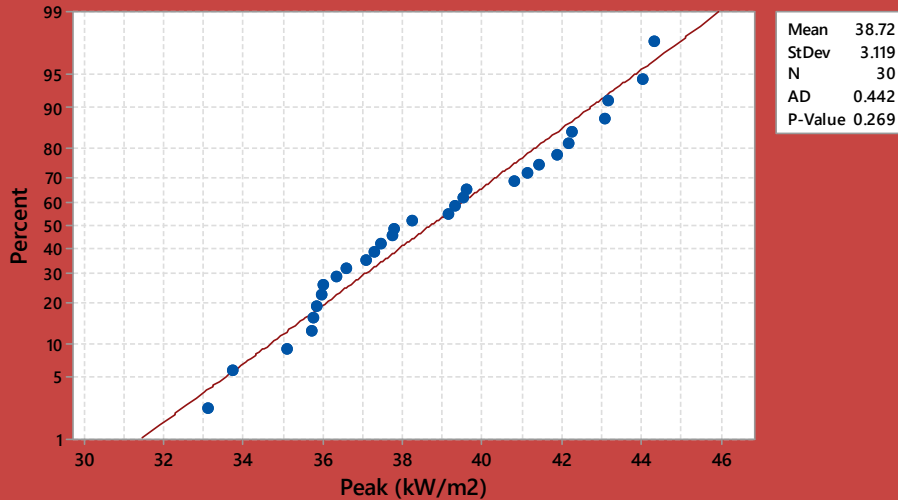
Analysis - OSU Honeycomb Panel with Dec



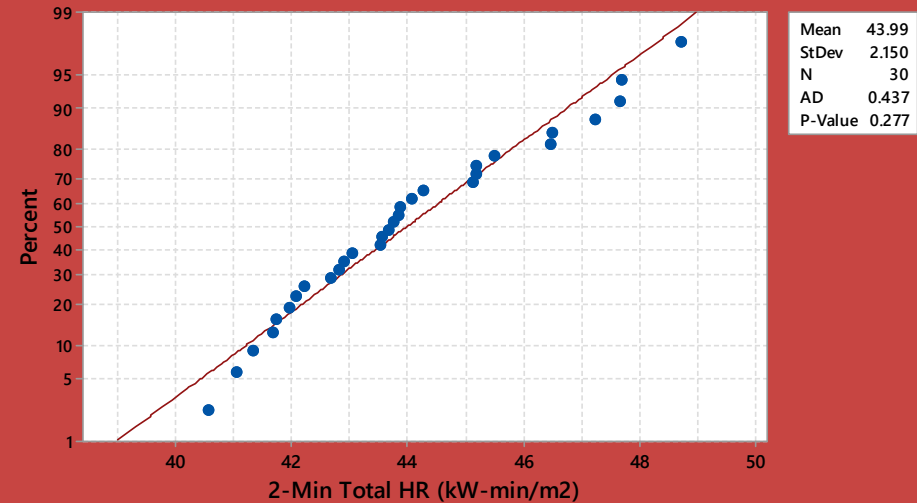
Variable	Total Count	Mean	SE Mean	StDev	CoefVar (%)
Peak (kW/m2)	30	38.72	0.57	3.12	8.05
Peak Time (seconds)	30	19.80	0.17	0.93	4.67
2-Min Total HR (kW-min/m2)	30	43.99	0.39	2.15	4.89
Baseline (mV)	30	26.19	0.04	0.19	0.74

Analysis - OSU Honeycomb Panel with Dec

OSU Honeycomb Panel Peak Normality
Normal

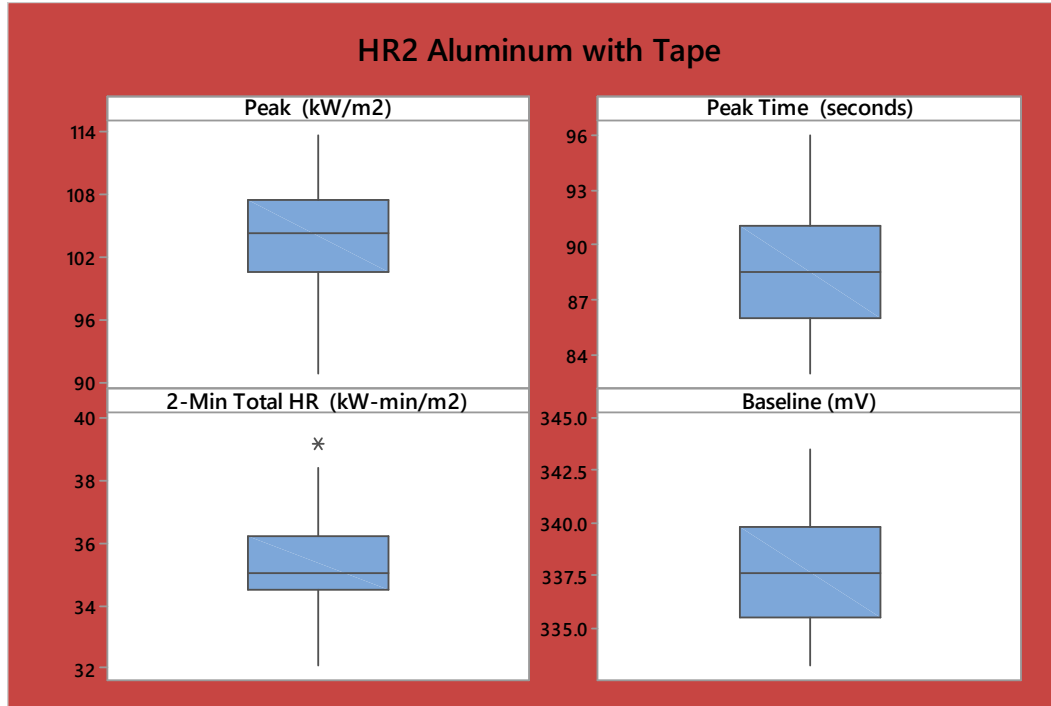


OSU Honeycomb Panel 2-min Total Normality
Normal



Variable	Total Count	Mean	SE Mean	StDev	CoefVar (%)
Peak (kW/m2)	30	38.72	0.57	3.12	8.05
Peak Time (seconds)	30	19.80	0.17	0.93	4.67
2-Min Total HR (kW-min/m2)	30	43.99	0.39	2.15	4.89
Baseline (mV)	30	26.19	0.04	0.19	0.74

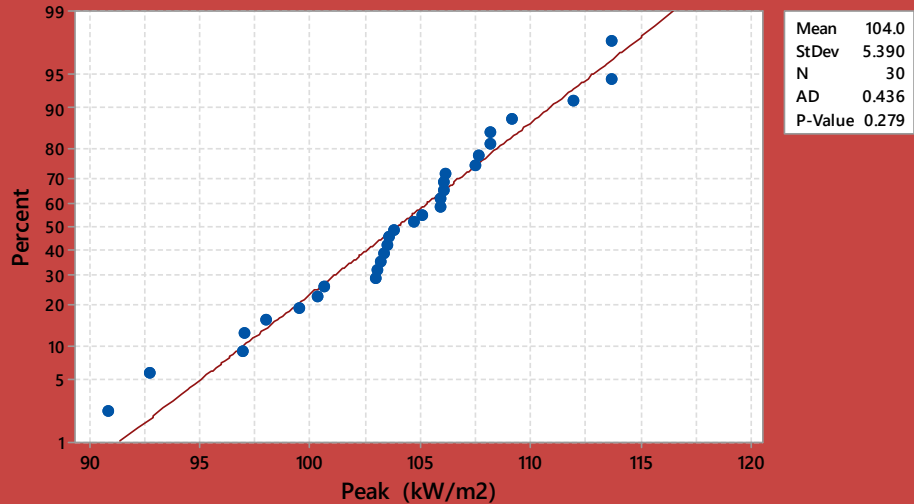
Analysis - HR2 Aluminum with Tape



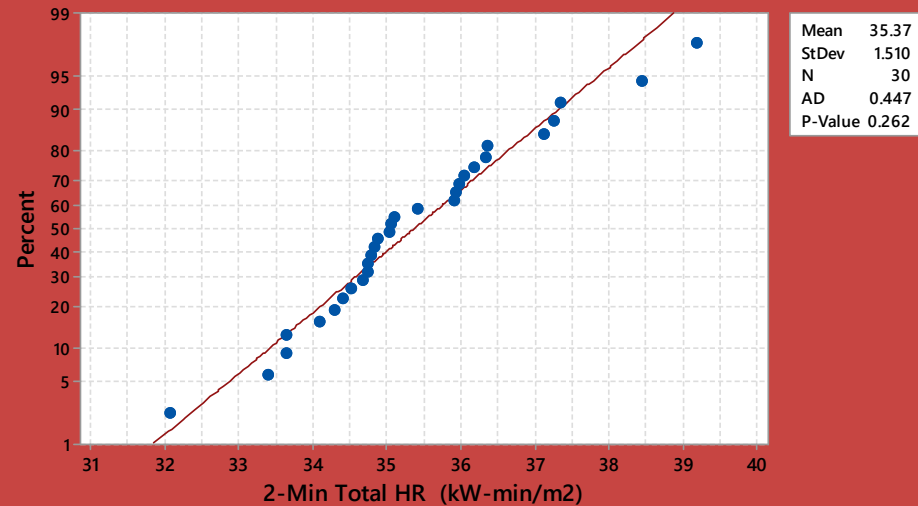
Variable	Total Count	Mean	SE Mean	StDev	CoefVar
Peak (kW/m2)	30	103.96	0.98	5.39	5.18
Peak Time (seconds)	30	88.50	0.59	3.22	3.64
2-Min Total HR (kW-min/m2)	30	35.37	0.28	1.51	4.27
Baseline (mV)	30	337.90	0.50	2.76	0.82

Analysis - HR2 Aluminum with Tape

HR2 Aluminum with Tape Peak Normality
Normal

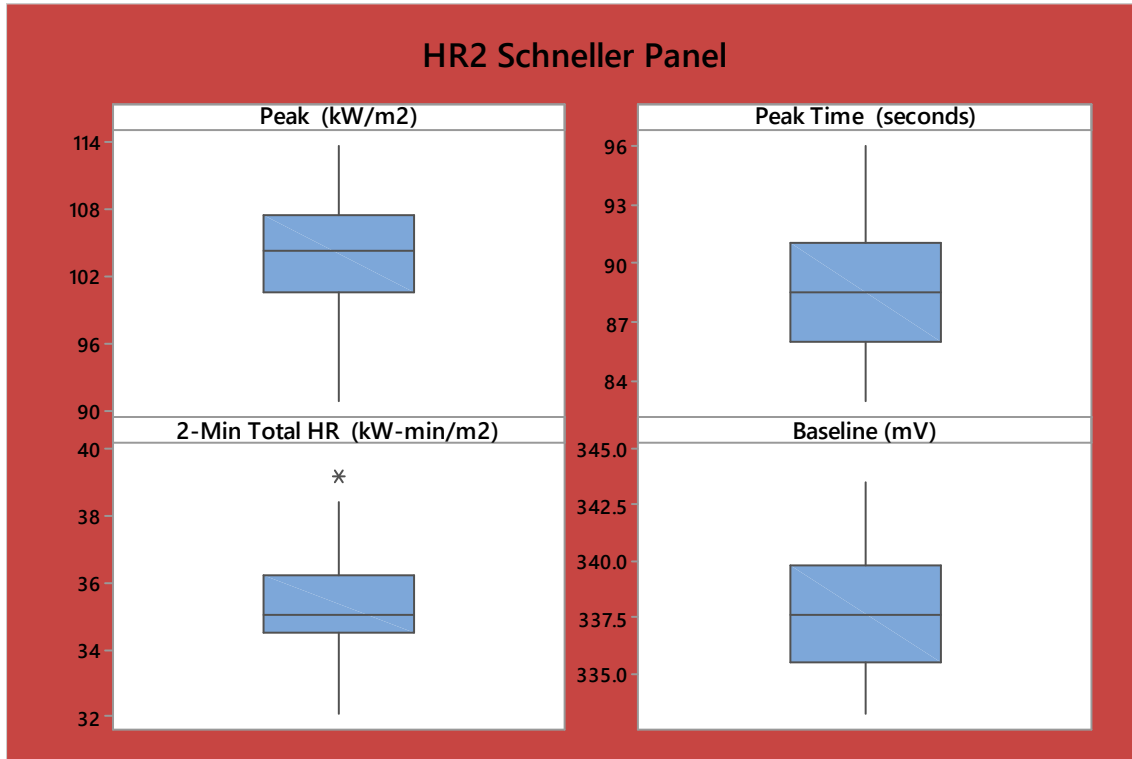


HR2 Aluminum with Tape 2-min Total Normality
Normal



Variable	Total Count	Mean	SE Mean	StDev	CoefVar
Peak (kW/m ²)	30	103.96	0.98	5.39	5.18
Peak Time (seconds)	30	88.50	0.59	3.22	3.64
2-Min Total HR (kW-min/m ²)	30	35.37	0.28	1.51	4.27
Baseline (mV)	30	337.90	0.50	2.76	0.82

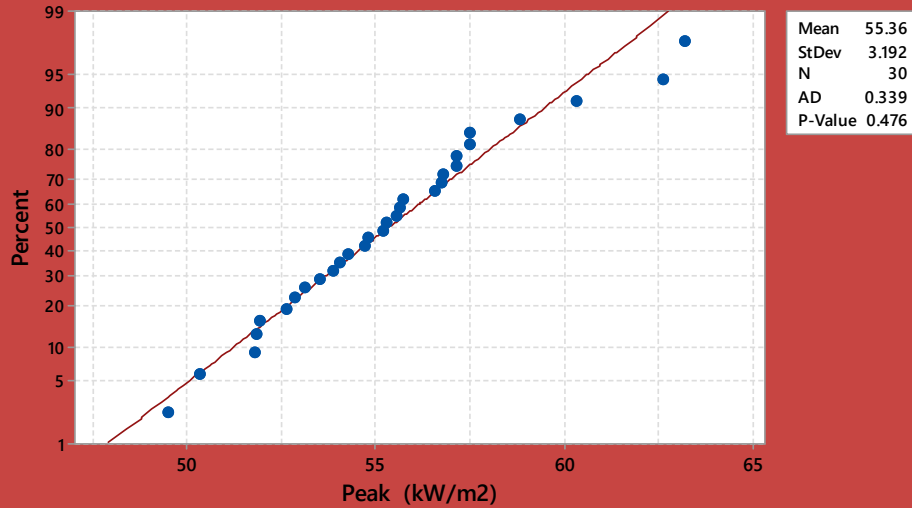
Analysis - HR2 Schneller Panel



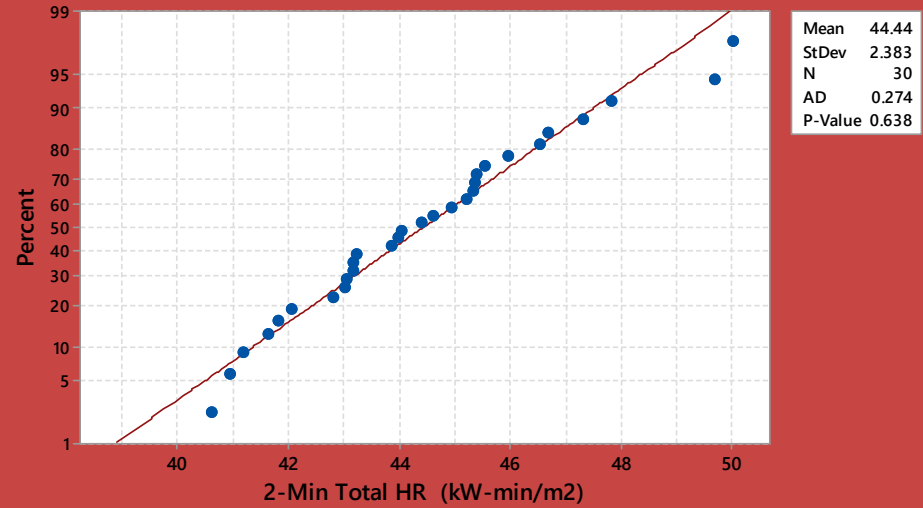
Variable	Total Count	Mean	SE Mean	StDev	CoefVar
Peak (kW/m2)	30	55.36	0.58	3.19	5.77
Peak Time (seconds)	30	46.00	0.35	1.89	4.12
2-Min Total HR (kW-min/m2)	30	44.44	0.44	2.38	5.36
Baseline (mV)	30	336.46	0.42	2.31	0.69

Analysis - HR2 Schneller Panel

HR2 Schneller Panel Peak Normality
Normal

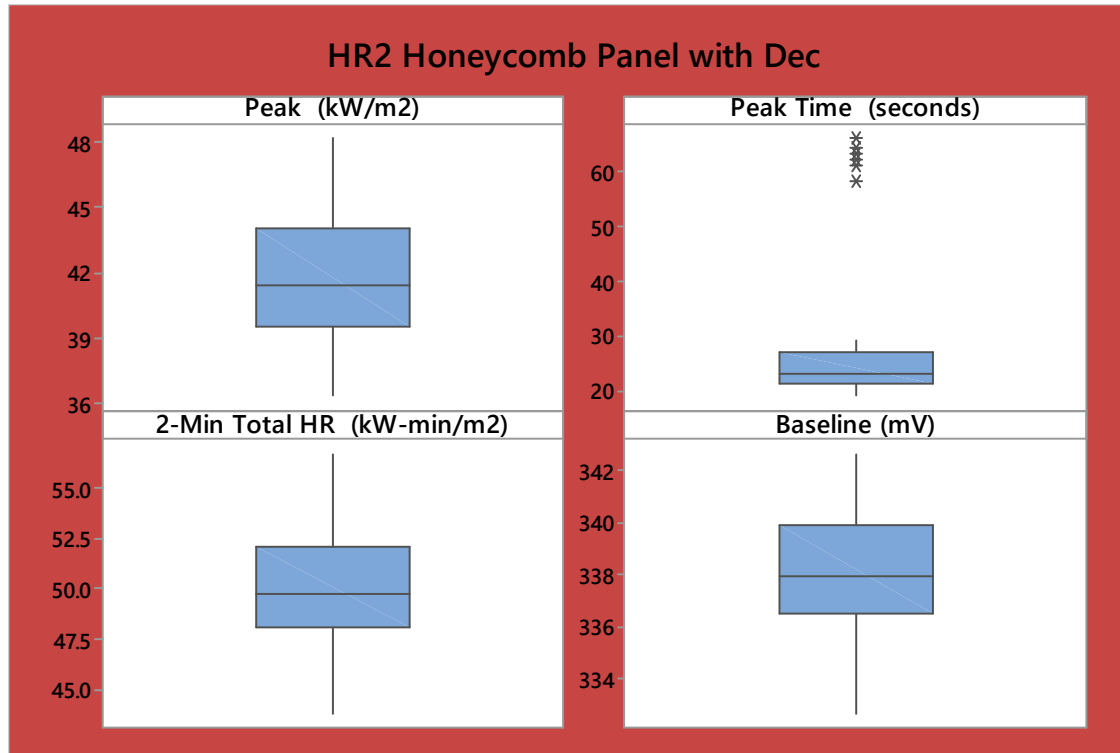


HR2 Schneller Panel 2-min Total Normality
Normal



Variable	Total Count	Mean	SE Mean	StDev	CoefVar
Peak (kW/m2)	30	55.36	0.58	3.19	5.77
Peak Time (seconds)	30	46.00	0.35	1.89	4.12
2-Min Total HR (kW-min/m2)	30	44.44	0.44	2.38	5.36
Baseline (mV)	30	336.46	0.42	2.31	0.69

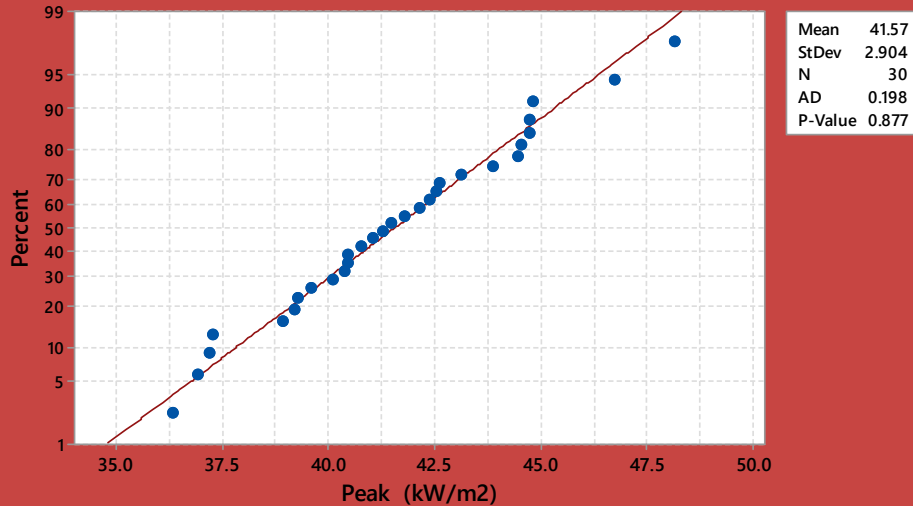
Analysis - HR2 Honeycomb Panel with Dec



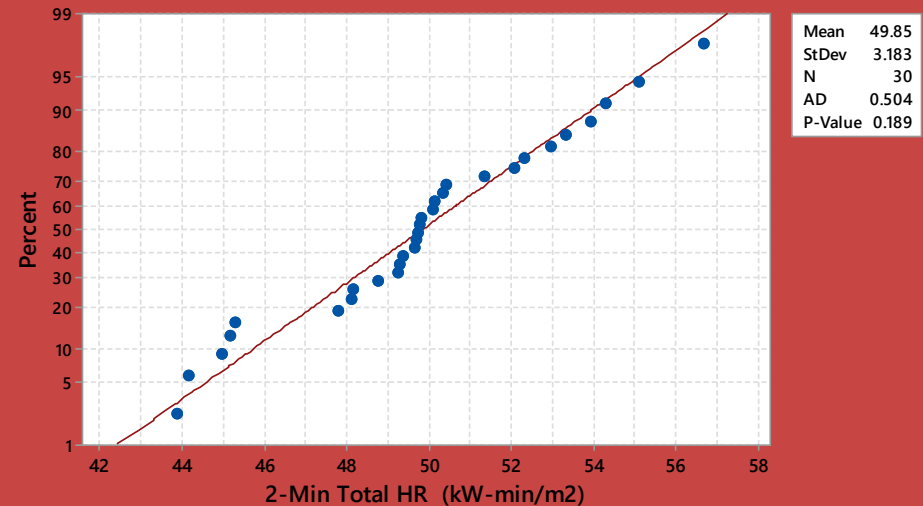
Variable	Total Count	Mean	SE Mean	StDev	CoefVar
Peak (kW/m2)	30	41.57	0.53	2.90	6.99
Peak Time (seconds)	30	30.40	3.00	16.42	54.00
2-Min Total HR (kW-min/m2)	30	49.85	0.58	3.18	6.38
Baseline (mV)	30	338.04	0.41	2.26	0.67

Analysis - HR2 Honeycomb Panel with Dec

HR2 Honeycomb Panel Peak Normality
Normal



HR2 Honeycomb Panel 2-min Total Normality
Normal



Variable	Total Count	Mean	SE Mean	StDev	CoefVar
Peak (kW/m2)	30	41.57	0.53	2.90	6.99
Peak Time (seconds)	30	30.40	3.00	16.42	54.00
2-Min Total HR (kW-min/m2)	30	49.85	0.58	3.18	6.38
Baseline (mV)	30	338.04	0.41	2.26	0.67

HR2 vs. OSU - Mean Comparison

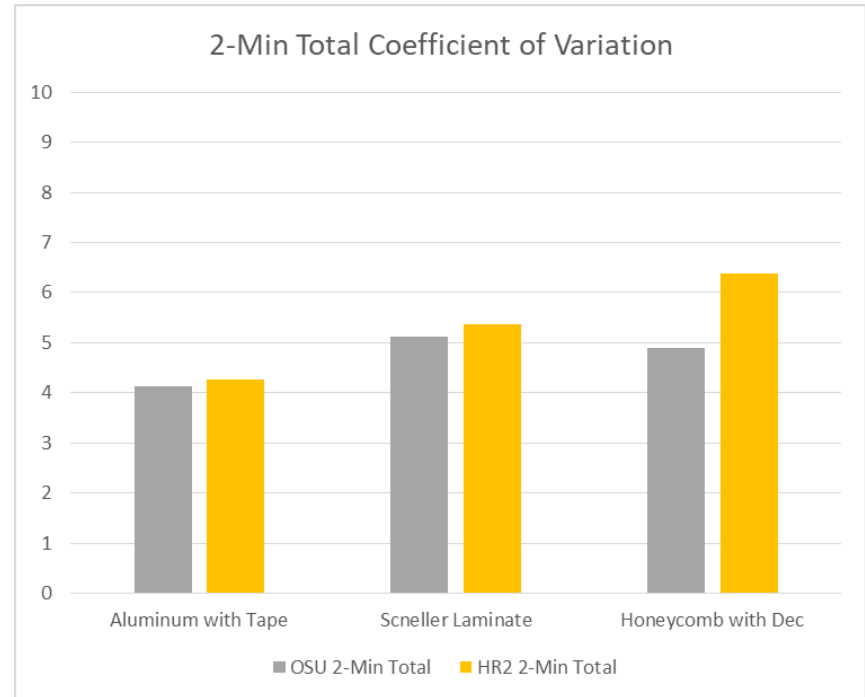
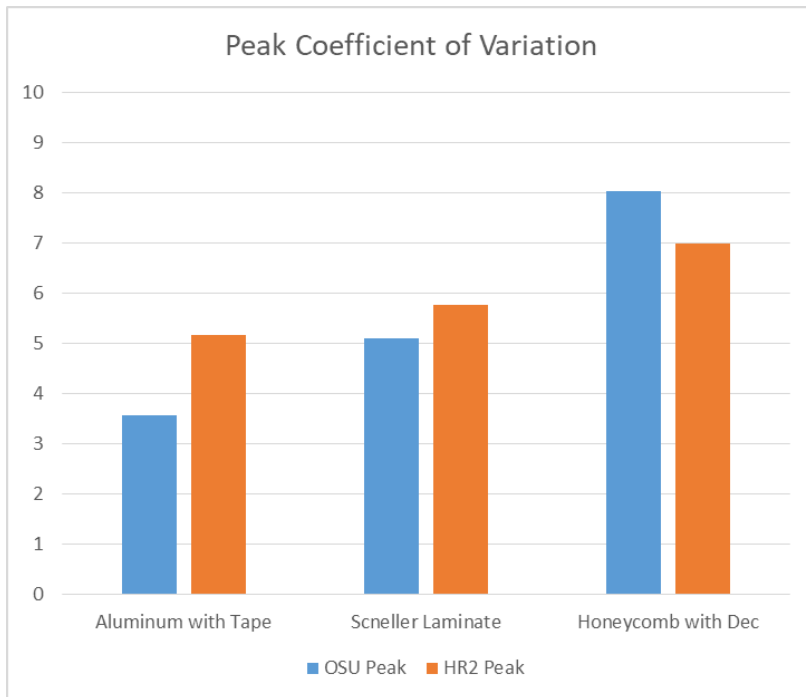
Construction	Coupon Count	Apparatus	Peak (kW/m2)			2-min Total (kW-min/m2)		
			Mean	StDev	HR2 vs OSU Means (%)	Mean	StDev	HR2 vs OSU Means (%)
Empty Chamber	30	OSU	11.82	1.44	-9.6	4.03	1.55	-5.2
	30	HR2	10.69	1.05		3.82	1.00	
Al/Tape	30	OSU	98.26	3.52	+5.8	35.98	1.49	-1.7
	30	HR2	103.96	5.39		35.37	1.51	
Schneller Panel	30	OSU	49.39	2.52	+12.1	41.26	2.11	+7.7
	30	HR2	55.36	3.19		44.44	2.38	
Honeycomb Panel/Dec	30	OSU	38.72	3.12	+7.4	43.99	2.15	+13.3
	30	HR2	41.57	2.90		49.85	3.18	

T-Test of OSU & HR2 Mean Equivalency (2-sided, 5% significance level)

Construction	Peak (kW/m2)					2-min Total (kW-min/m2)				
	Difference	Pooled StDev	95% CI	"Equivalent?" (Y/N)	p-value	Difference	Pooled StDev	95% CI	"Equivalent?" (Y/N)	p-value
Empty Chamber	1.130	1.260	(0.479, 1.781)	N	0.001	0.210	1.304	(-0.464, 0.884)	Y	0.535
Al/Tape	-5.70	4.55	(-8.05, -3.35)	N	0.000	0.610	1.500	(-0.165, 1.385)	Y	0.121
Schneller Panel	-5.970	2.875	(-7.456, -4.484)	N	0.000	-3.180	2.249	(-4.342, -2.018)	N	0.000
Honeycomb Panel/Dec	-2.850	3.012	(-4.407, -1.293)	N	0.001	-5.860	2.714	(-7.263, -4.457)	N	0.000

TRL 5 Test Data - Summary

Coupon Type	Coefficient of Variation (CoV) (%)			
	Peak		2-Min Total	
	OSU	HR2	OSU	HR2
Aluminum with Tape	3.58	5.18	4.14	4.27
Scneller Laminate	5.10	5.77	5.12	5.36
Honeycomb with Dec	8.05	6.99	4.89	6.38
Empty Sample Holder	12.2	9.86	38.4	26.2



- No significant repeatability improvement versus OSU CoV baseline
- Statistical analysis indicates that HR2 variation is equivalent to that of OSU

Next Steps

Gate 5 / Enter TRL 6 (Exit Criteria)

Coefficient of Variation (CV) improvement vs. OSU

Criteria to be defined and evaluated relative to OSU coupon CoV and be consistent with our stated goal of **improving repeatability when compared to the OSU results.**

- Criteria were not met

Three Potential Paths

1. **Stop HR2 development**
2. **Stay in TRL 5** make incremental changes to improve repeatability - repeat HR2 testing once sufficient improvements are complete
3. **Proceed to TRL 6** accept similar repeatability performance and focus efforts on improving reproducibility

Questions?

IF AT FIRST YOU DON'T SUCCEED



PERHAPS SKYDIVING ISN'T FOR YOU