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Comparative Angle of Incidence Characterization of Utility Grade Photovoltaic Modules

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ABSTRACT

Angle of incidence response of a photovoltaic module describes its light gathering capability when incident sunlight is at an orientation other than normal to the module's surface. At low incident angles (i.e. close to normal), most modules have similar responses. However, at increasing incident angles, reflective losses dominate response and relative module performance becomes differentiated. Relative performance in this range is important for understanding the potential power output of utility-scale photovoltaic systems. In this report, we document the relative angle of incidence response of four utility-grade panels to each other and to four First Solar modules. We found that response was nearly identical between all modules up to an incident angle of ~55°. At higher angles, differences of up to 5% were observed. A module from Yingli was the best performing commercial module while a First Solar test module with a non-production anti-reflective coating was the best overall performer.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AOI	Angle of Incidence
ARC	Anti-Reflective Coating
DNI	Direct Normal Irradiance
GNI	Global Normal Irradiance
I_{sc}	Short Circuit Current
IV	Current-Voltage
SPP	Strategic Partnerships Project
V_{oc}	Open Circuit Voltage

1. INTRODUCTION

This report documents angle of incidence (AOI) characterization of eight modules performed by Sandia National Labs for First Solar under Strategic Partnership Project (SPP) 088170919-0. This report serves as the final deliverable for the project. Each of the modules under test were supplied by First Solar. Characterization utilized unique outdoor solar tracking capabilities developed by Sandia specifically to support AOI characterization. All characterization was performed simultaneously, with all modules mounted in the same test plane. Processed results were provided to First Solar and were presented at the 7th World Conference on Photovoltaic Energy Conversion (WCPEC-7) [1]. Processed results are tabulated in Appendix A. Raw measurements are available to First Solar upon request.

2. MODULES AND MOUNTING CONFIGURATION

Eight modules were provided by First Solar to Sandia in February 2018. Four of these were commercial, utility scale modules procured by First Solar. The remaining four were First Solar Series 4 modules with different anti-reflective coatings (ARC). The test devices are listed below in Table 2-1. All eight modules were mounted coplanar on a two-axis solar tracker in landscape orientation, shown below in Figure 2-1. The four commercial modules were mounted as one group on the right arm of the tracker while the four First Solar modules were mounted as a second group on the left arm of the tracker.

Table 2-1. Test Devices

Manufacturer	Model	PVID	Serial Number	other
Canadian Solar	CS6U-330P	3265	11706211720526	
JA Solar	JAM6(k)-72-4BB 345W	3268	176M6K72Y1022680	
Hanwha Q-Cells	Q.PLUS L-G4.2 325W	3266	824616464231602205	
Yingli	YL330P-35b	3267	162507000204260	
First Solar	FS4 (No ARC)	3262	170614391453	FS-4105-2
First Solar	FS4 (Production ARC)	3263	170614391469	FS-4107-2
First Solar	FS4 (non-prod ARC 1)	3261	170725401549	FS-4112-2
First Solar	FS4 (non-prod ARC 2)	3264	170614391732	FS-4107-2

Figure 2-1. Test Devices mounted on two-axis solar tracker

3. INSTRUMENTATION AND TEST DETAILS

3.1. Instrumentation and Preconditioning

A minimum of two Type-T thermocouples were attached to the rear side of each module in one corner and the center. Select modules had an additional thermocouple attached to the opposite corner. Ordinarily, all modules would have at least three thermocouples. Due to a limited number of thermocouple channels, an exception to standard practice had to be made to accommodate simultaneous characterization of all eight modules. Each module was connected to a custom current-voltage (IV) sweep system using the supplied leads. Once the modules were mounted to the test plane, the tracker was put into automatic Sun tracking mode, positioning each module normal to the Sun. Each module was held at maximum power by the IV system. IV sweeps (I_{sc} to V_{oc}) were performed every 2 minutes during daylight periods. During night time, the tracker was stowed at an azimuth of 180° and elevation of 45°. The modules were held normal to the Sun for approximately four weeks prior to performing AOI characterization. Collected IV data from this period was used to derive in-situ temperature coefficients, which were subsequently used to temperature correct measured data.

3.2. Environmental Conditions

AOI characterization was performed simultaneously on all eight modules. Characterization was performed near solar noon under clear sky conditions on nine different days. However, due to dynamic weather conditions, results are reported for three days (4/15, 4/18 and 4/26). Environmental conditions during each test are listed in Table 3-1. Peak-to-peak variation in global normal irradiance (GNI) during the reported test periods was 16 W/m^2 or less (~1.4%).

Table 3-1. Environmental conditions during characterization

Condition	4/15/18	4/18/18	4/26/18
Ambient Temp, °C	16.9	15.5	23.9
Wind Speed, m/s	2.5	2.2	6.2
Relative Humidity, %	9.6	5.4	6.6
DNI, W/m2	1044	1053	1012
GNI, W/m2	1106	1132	1101
DNI/GNI	0.94	0.93	0.91
Air Mass	0.92	0.92	0.89

3.3. Angle of Incidence Testing

AOI test and analysis procedures followed the Preferred Method described in [2]. The tracker was indexed in elevation only during the test and continued to track the Sun in azimuth. Indexing was from 0° to 85° in decreasing angular steps. The tracker was held at each angular offset while a minimum of five IV sweeps were measured. I_{sc} values used in the analysis were temperature corrected using the in-situ derived temperature coefficients and averaged for each angular offset. Diffuse irradiance was measured in the plane of array using a pyranometer equipped with a vertical shadow band. It should be noted that use of this measurement differs from similar procedures described in IEC 61853-2 [3], where diffuse irradiance is calculated from direct normal (DNI) and GNI.

4. TEST RESULTS

Test results for all modules are shown below. Results are grouped by Commercial Modules, First Solar Modules and a comparison of the best performer from each group. Results are presented by Test Date for each group.

4.1. Commercial Modules

AOI responses for all commercial Test Devices are shown below in Figure 3-1. All modules behaved essentially the same, with only minor differences. All modules showed a pure cosine response (i.e. flat) from 0° to approximately 55°. Yingli consistently outperformed all commercial modules, while FS4 (Production ARC) performed second best.

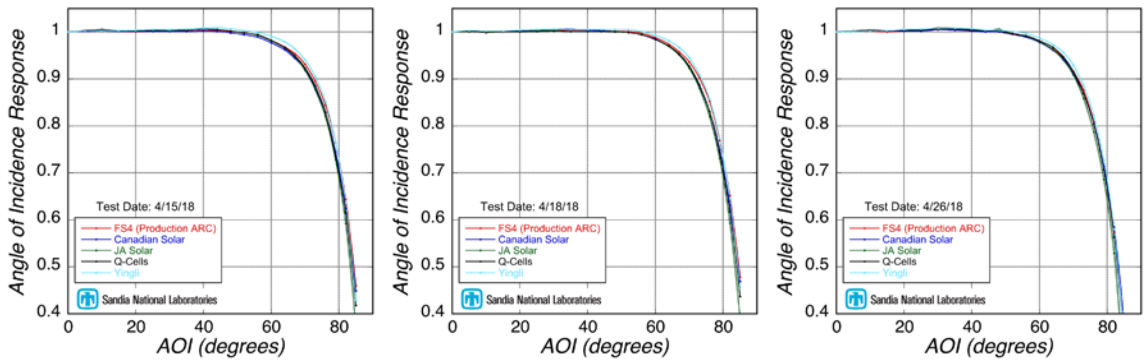

Figure 4-1. Angle of Incidence Response of Commercial modules

4.2. First Solar Modules

AOI responses for all First Solar Test Devices are shown below in Figure 3-2. There was more variation in performance of this group than observed in the commercial modules. All modules showed a pure cosine response (i.e. flat) from 0° to approximately 55°. FS4 (Production ARC) consistently outperformed FS4 (No ARC). FS4 (Non-Production ARC 1) was consistently the best performer of the group. FS4 (Non-Production ARC 2) appeared to provide no benefit over FS4 (No ARC).

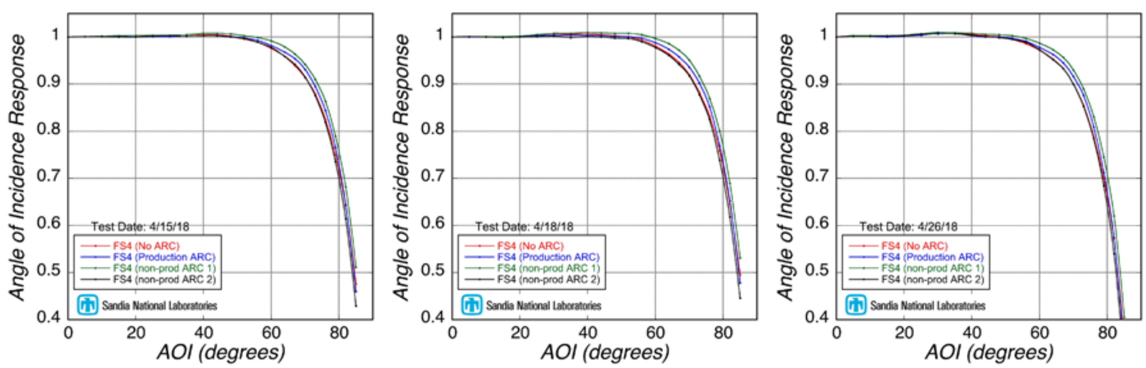

Figure 4-2. Angle of Incidence Response of First Solar modules

4.3. Best Commercial and Non-Production Modules Compared

As noted above, Yingli was the best performing commercial module, while FS4 (Non-Production ARC 1) was the best performing First Solar Module. AOI responses for these two modules are compared below in Figure 3-3. The two modules were comparable to each other out to very shallow incident angles, greater than approximately 70°. Here, FS4 (Non-Production ARC 1) may have had a slight advantage over Yingli.

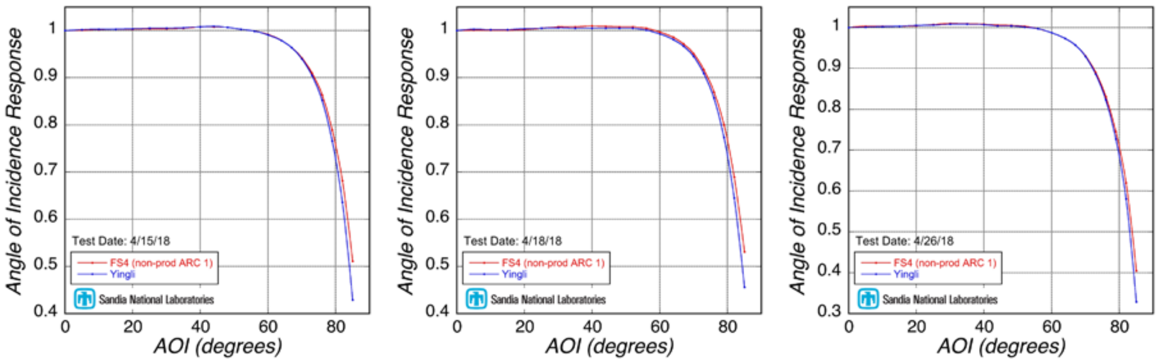

Figure 4-3. Angle of Incidence Response of best performing Commercial and Non-Production modules

4.4. Inter-Day Variability

As noted, characterization was performed on nine different days. However, due to dynamic weather conditions, results are reported for three days (4/15, 4/18 and 4/26). These days were chosen based on a combination of low environmental variability during the test as well as an absence of high, thin clouds as determined by visual observation. Even among these, inter-day variability was observed. An example is shown below in Figure 3-4 for two different commercial modules, FS4 (Production ARC) and Yingli. Results from two days, 4/15 and 4/18 were comparable, while results from 4/26 were slightly different. Divergence is at high incidence angles, greater than 55°. Modules from other vendors displayed the same sensitivity and are not shown here. Root cause for this variability has not been determined, however it was noted that GNI had the greatest variability on 4/26. This highlights the need for a common reference when comparing results from multiple days, particularly in cases where small variations at high incidence angle are of interest. As relative ranking between modules did not change from day to day, it also highlights the value of simultaneous testing when a comparison between products or coatings is desired.

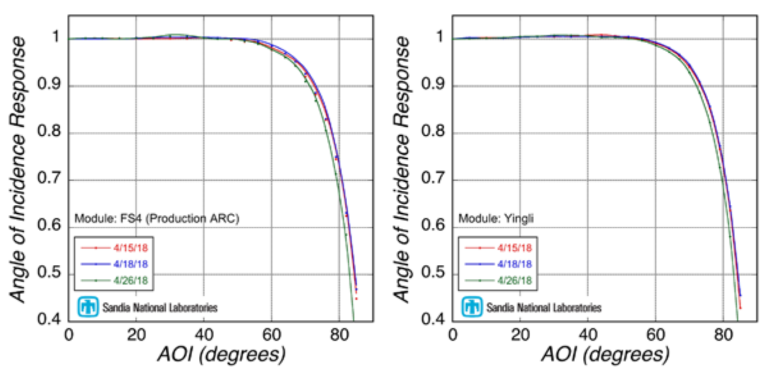

Figure 4-4. Inter-day variability observed for two commercial modules

5. DIFFERENTIAL ANALYSIS

To highlight small differences between modules, a differential analysis was performed on each module for each day of testing. A module with no known coating, FS4 (No ARC) was selected to serve as a baseline case against each of the remaining seven modules in the study. The differential at each incidence angle was found by simply subtracting the Normalized I_{sc} value for this module from that of another module. These differential values were then plotted as a function of incidence angle.

Consistent with the observations in Section 4, significant deviation was not observed until ~55°, at the point where reflection losses begin to dominate over cosine losses. However, even in the region below 55° certain modules displayed small losses relative to the baseline module. This first group displayed a dip in relative response over the range of 20 – 55° before gently rising to a peak of about 1% at 67°. Response then dropped sharply to values 4 - 5% below the baseline case above 75°. Commercial modules from Canadian Solar, JA Solar and Hanwha Q-Cells fell into this group, as did First Solar (Non-Production ARC2). These are show below in Figure 5-1.

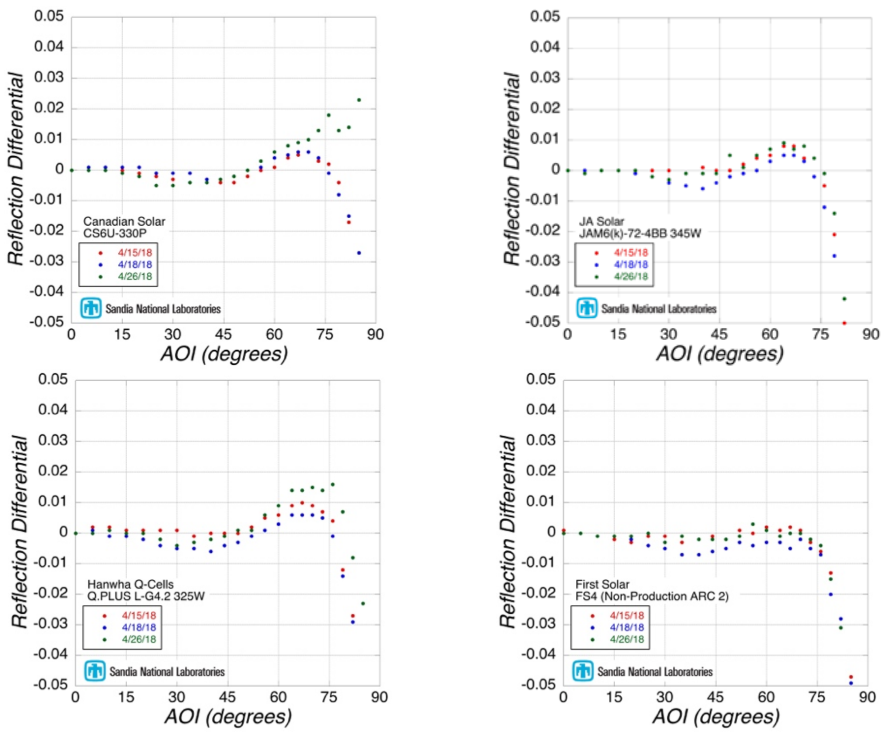

Figure 5-1. Differential AOI Response, Group 1.

A second group tracked more closely to the baseline case until ~45°. At this point, relative response climbed until reaching a sharp peak around 75°. Here, boost over the baseline case ranged from 2 – 5%. Commercial modules from Yingli and First Solar (Production ARC) fell into this group, along with First Solar (Non-Production ARC 1). These are shown below in Figure 5-2.

A few exceptions to the above generalities were noted. First, FS4 (Non-Production ARC 1) didn't reach a peak until ~80° and didn't roll off to negative values like the other modules in this study. The differential analysis confirms the earlier observation that this coating had the best performance and quantifies it. Second, FS4 (Non-Production ARC 2) had the same basic shape as the other modules in Group 1, but it never reached a peak above baseline before rolling off to negative values. This again confirms the earlier observation that this coating appears to provide no benefit over plain glass.

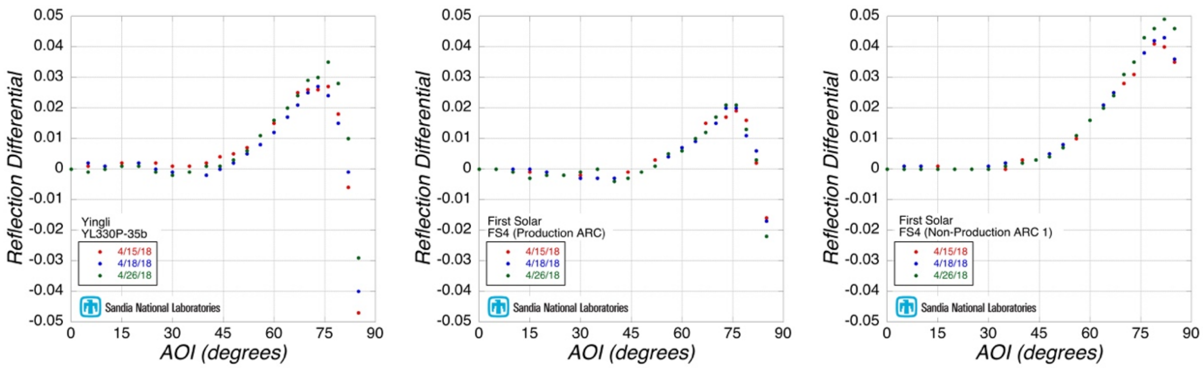

Figure 5-2. Differential AOI Response, Group 2.

REFERENCES

[1] Sravanthi Boppana, Kendra Passow, Jim Sorensen, Bruce H. King and Charles Robinson, "Impact of Uncertainty in IAM measurement on Energy Prediction," *7th World Conference on Photovoltaic Energy Conversion (WCPEC-7)*, Waikoloa, HI, 2018.

[2] Bruce H. King, Clifford W. Hansen, Dan Riley, Charles D. Robinson, Larry Pratt, "Procedure to Determine Coefficients for the Sandia Array Performance Model (SAPM)," SAND2016-5284, Sandia National Laboratories, Albuquerque, NM, 2016.

[3] IEC 61853-2:2016, "Photovoltaic (PV) module performance testing and energy rating – Part 2: Spectral responsivity, incident angle and module operating temperature measurements"

APPENDIX A. PROCESSED TEST RESULTS

Processed test results are presented below. Each entry is an average of a minimum of 5 measurements at each angle.

A.1. Canadian Solar

AOI	Test Date					
	4/15/18		4/18/18		4/26/18	
	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation
0	1.000	0.000	1.000	0.001	1.000	0.001
5	1.001	0.001	1.001	0.000	1.002	0.001
10	1.002	0.001	1.001	0.000	1.002	0.001
15	1.001	0.001	1.001	0.001	1.002	0.001
20	1.001	0.001	1.003	0.001	1.002	0.001
25	1.001	0.001	1.004	0.001	1.002	0.001
30	1.001	0.001	1.006	0.001	1.005	0.001
35	1.001	0.001	1.006	0.001	1.004	0.001
40	1.002	0.001	1.004	0.001	1.002	0.001
44	1.001	0.000	1.003	0.001	1.000	0.001
48	0.998	0.001	1.001	0.000	1.000	0.001
52	0.994	0.001	0.999	0.001	0.995	0.001
56	0.989	0.001	0.994	0.000	0.989	0.002
60	0.977	0.001	0.985	0.000	0.978	0.002
64	0.962	0.000	0.969	0.001	0.961	0.001
67	0.944	0.001	0.952	0.001	0.943	0.002
70	0.920	0.001	0.926	0.000	0.910	0.002
73	0.882	0.000	0.886	0.000	0.869	0.002
76	0.828	0.002	0.831	0.000	0.806	0.002
79	0.745	0.002	0.750	0.003	0.713	0.002
82	0.625	0.001	0.631	0.001	0.585	0.003
85	0.449	0.000	0.469	0.005	0.381	0.003

A.2. JA Solar

AOI	Test Date					
	4/15/18		4/18/18		4/26/18	
	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation
0	1.000	0.001	1.000	0.001	1.000	0.001
5	1.002	0.001	1.000	0.000	1.001	0.001
10	1.003	0.001	1.000	0.001	1.003	0.001
15	1.002	0.001	1.000	0.001	1.003	0.001
20	1.002	0.001	1.001	0.001	1.004	0.000
25	1.003	0.002	1.003	0.001	1.004	0.001
30	1.003	0.001	1.003	0.001	1.007	0.001
35	1.004	0.001	1.001	0.000	1.007	0.001
40	1.006	0.000	1.001	0.000	1.005	0.001
44	1.005	0.001	1.001	0.001	1.002	0.001
48	1.002	0.001	1.001	0.001	1.006	0.010
52	0.998	0.000	0.999	0.000	0.996	0.003
56	0.993	0.001	0.994	0.001	0.991	0.001
60	0.981	0.001	0.984	0.001	0.979	0.002
64	0.966	0.001	0.969	0.001	0.962	0.001
67	0.947	0.001	0.951	0.001	0.940	0.001
70	0.918	0.000	0.923	0.001	0.908	0.002
73	0.877	0.002	0.880	0.001	0.859	0.001
76	0.820	0.001	0.820	0.001	0.787	0.006
79	0.728	0.001	0.730	0.003	0.686	0.002
82	0.592	0.003	0.593	0.000	0.529	0.004
85	0.371	0.001	0.391	0.006	0.263	0.002

A.3. Hanwha Q-Cells

AOI	Test Date					
	4/15/18		4/18/18		4/26/18	
	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation
0	1.000	0.001	1.000	0.001	1.000	0.001
5	1.003	0.000	1.001	0.000	1.002	0.001
10	1.005	0.001	0.999	0.002	1.004	0.001
15	1.003	0.001	1.000	0.002	1.003	0.000
20	1.004	0.001	1.000	0.001	1.004	0.001
25	1.004	0.001	1.001	0.001	1.004	0.001
30	1.005	0.000	1.002	0.001	1.006	0.001
35	1.004	0.002	1.001	0.001	1.006	0.001
40	1.006	0.002	1.001	0.001	1.004	0.001
44	1.005	0.001	1.001	0.001	1.002	0.001
48	1.002	0.001	1.000	0.001	1.002	0.002
52	0.998	0.001	0.999	0.001	0.996	0.001
56	0.994	0.002	0.994	0.001	0.992	0.001
60	0.982	0.001	0.984	0.002	0.981	0.002
64	0.967	0.001	0.970	0.001	0.967	0.002
67	0.949	0.000	0.953	0.001	0.947	0.002
70	0.923	0.001	0.927	0.000	0.915	0.003
73	0.885	0.001	0.887	0.001	0.869	0.007
76	0.829	0.001	0.831	0.001	0.804	0.003
79	0.737	0.004	0.743	0.003	0.706	0.002
82	0.615	0.003	0.617	0.001	0.563	0.005
85	0.418	0.005	0.437	0.005	0.335	0.003

A.4. Yingli

AOI	Test Date					
	4/15/18		4/18/18		4/26/18	
	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation
0	1.000	0.001	1.000	0.001	1.000	0.001
5	1.002	0.001	1.003	0.001	1.001	0.000
10	1.003	0.001	1.002	0.002	1.002	0.002
15	1.003	0.001	1.002	0.001	1.003	0.001
20	1.004	0.000	1.004	0.001	1.005	0.001
25	1.005	0.001	1.005	0.001	1.006	0.001
30	1.005	0.001	1.006	0.001	1.008	0.001
35	1.006	0.001	1.005	0.001	1.008	0.001
40	1.008	0.001	1.005	0.001	1.007	0.001
44	1.009	0.000	1.005	0.000	1.004	0.001
48	1.007	0.001	1.005	0.001	1.004	0.002
52	1.003	0.001	1.005	0.001	1.001	0.001
56	0.999	0.001	1.001	0.001	0.997	0.001
60	0.991	0.002	0.993	0.001	0.987	0.001
64	0.979	0.001	0.981	0.001	0.973	0.001
67	0.964	0.001	0.967	0.001	0.957	0.003
70	0.940	0.001	0.945	0.001	0.929	0.002
73	0.905	0.000	0.909	0.001	0.886	0.003
76	0.852	0.001	0.857	0.000	0.823	0.002
79	0.766	0.001	0.773	0.002	0.727	0.002
82	0.636	0.003	0.645	0.001	0.581	0.003
85	0.429	0.000	0.456	0.006	0.329	0.000

A.5. FS4 (No ARC)

AOI	Test Date					
	4/15/18		4/18/18		4/26/18	
	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation
0	1.000	0.001	1.000	0.000	1.000	0.001
5	1.001	0.001	1.000	0.001	1.002	0.001
10	1.002	0.000	1.000	0.001	1.003	0.001
15	1.002	0.001	1.001	0.001	1.002	0.001
20	1.003	0.001	1.002	0.001	1.004	0.001
25	1.003	0.001	1.005	0.001	1.007	0.001
30	1.003	0.001	1.007	0.001	1.010	0.001
35	1.005	0.001	1.006	0.001	1.008	0.001
40	1.005	0.001	1.007	0.001	1.006	0.002
44	1.005	0.001	1.005	0.001	1.003	0.001
48	1.002	0.001	1.003	0.001	1.001	0.002
52	0.996	0.001	1.000	0.001	0.995	0.003
56	0.989	0.001	0.993	0.001	0.986	0.001
60	0.976	0.002	0.981	0.001	0.972	0.001
64	0.959	0.001	0.964	0.001	0.953	0.000
67	0.939	0.002	0.946	0.001	0.933	0.001
70	0.914	0.001	0.920	0.000	0.900	0.002
73	0.879	0.006	0.882	0.001	0.855	0.001
76	0.825	0.002	0.832	0.001	0.788	0.010
79	0.749	0.001	0.758	0.001	0.699	0.002
82	0.642	0.005	0.646	0.001	0.571	0.002
85	0.476	0.003	0.495	0.005	0.359	0.002

A.6. FS4 (Production ARC)

AOI	Test Date					
	4/15/18		4/18/18		4/26/18	
	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation
0	1.000	0.001	1.000	0.001	1.000	0.001
5	1.001	0.001	1.000	0.001	1.002	0.000
10	1.002	0.000	1.000	0.001	1.002	0.001
15	1.001	0.001	1.000	0.001	1.000	0.001
20	1.000	0.001	1.001	0.001	1.002	0.001
25	1.001	0.001	1.003	0.001	1.004	0.003
30	1.001	0.001	1.004	0.001	1.009	0.006
35	1.002	0.001	1.004	0.001	1.008	0.005
40	1.003	0.001	1.004	0.001	1.003	0.001
44	1.003	0.001	1.003	0.001	1.000	0.001
48	1.001	0.001	1.002	0.001	1.000	0.001
52	0.998	0.001	1.001	0.002	0.997	0.001
56	0.993	0.001	0.997	0.001	0.991	0.001
60	0.982	0.001	0.988	0.002	0.978	0.001
64	0.968	0.001	0.974	0.001	0.963	0.001
67	0.954	0.001	0.958	0.002	0.945	0.001
70	0.931	0.001	0.936	0.002	0.916	0.001
73	0.895	0.001	0.902	0.002	0.876	0.002
76	0.844	0.002	0.852	0.002	0.809	0.002
79	0.765	0.003	0.769	0.001	0.712	0.003
82	0.644	0.004	0.652	0.001	0.574	0.003
85	0.460	0.002	0.478	0.008	0.336	0.002

A.7. FS4 (Non-Production ARC 1)

AOI	Test Date					
	4/15/18		4/18/18		4/26/18	
	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation
0	1.000	0.001	1.000	0.001	1.000	0.001
5	1.001	0.001	1.001	0.000	1.003	0.001
10	1.002	0.000	1.001	0.000	1.003	0.001
15	1.003	0.001	1.001	0.001	1.003	0.000
20	1.003	0.000	1.002	0.001	1.004	0.001
25	1.004	0.001	1.005	0.001	1.007	0.002
30	1.004	0.001	1.008	0.001	1.010	0.001
35	1.005	0.001	1.008	0.001	1.009	0.001
40	1.008	0.002	1.010	0.001	1.008	0.001
44	1.008	0.001	1.009	0.000	1.006	0.002
48	1.007	0.001	1.008	0.000	1.005	0.001
52	1.003	0.001	1.008	0.001	1.003	0.001
56	0.999	0.001	1.005	0.001	0.997	0.001
60	0.992	0.000	0.997	0.002	0.987	0.001
64	0.979	0.002	0.986	0.001	0.973	0.001
67	0.964	0.002	0.972	0.000	0.957	0.001
70	0.942	0.001	0.951	0.001	0.930	0.002
73	0.910	0.001	0.917	0.001	0.890	0.002
76	0.864	0.001	0.870	0.001	0.831	0.002
79	0.789	0.001	0.800	0.001	0.745	0.003
82	0.682	0.004	0.689	0.002	0.620	0.003
85	0.511	0.003	0.531	0.008	0.405	0.001

A.8. FS4 (Non-Production ARC 2)

AOI	Test Date					
	4/15/18		4/18/18		4/26/18	
	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation	Normalized I_{sc}	Standard Deviation
0	1.000	0.002	1.000	0.002	1.000	0.001
5	1.001	0.001	1.001	0.001	1.002	0.001
10	1.001	0.001	1.000	0.001	1.002	0.001
15	1.000	0.001	0.999	0.001	1.002	0.001
20	1.000	0.001	1.000	0.001	1.003	0.000
25	1.002	0.001	1.001	0.001	1.006	0.002
30	1.003	0.001	1.002	0.001	1.007	0.001
35	1.002	0.001	0.999	0.001	1.007	0.001
40	1.003	0.001	1.001	0.002	1.004	0.001
44	1.003	0.001	1.000	0.001	1.001	0.001
48	1.000	0.001	0.998	0.002	0.999	0.002
52	0.997	0.001	0.997	0.001	0.995	0.002
56	0.989	0.001	0.990	0.001	0.989	0.007
60	0.978	0.003	0.978	0.001	0.973	0.002
64	0.959	0.001	0.961	0.002	0.952	0.001
67	0.942	0.001	0.942	0.002	0.933	0.001
70	0.915	0.001	0.918	0.001	0.900	0.001
73	0.876	0.001	0.878	0.003	0.853	0.001
76	0.819	0.003	0.825	0.001	0.784	0.003
79	0.735	0.001	0.738	0.002	0.684	0.001
82	0.614	0.004	0.618	0.002	0.540	0.003
85	0.429	0.006	0.446	0.006	0.305	0.002

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