March 20, 2006

This report describes testing done at UV Process Supply using components of the UV-LED light curing system being supplied as part of the polycarbonate Assembly System.

The objective of these tests was to verify that the UV Process Supply UV-LED curing system will be capable of adequately curing adhesive the product in the given cycle time with adequate process margin.

It was not an objective of these tests to fully characterize the curing capabilities of the system or determine the exact margin available, but rather to identify any potential deficiencies of the system while there was still time to make modifications or move to a different technology.

The testing was carried out by Brian Walter of Wright Industries at the UV Process Supply's facility on March 14 2006.

Test Equipment and Setup

Testing apparatus consisted of:

- UV Process Supply power supply (built for the assembly project)
- UV Process Supply Heat Sink/ Lamp Assemblies (built for the assembly project)
- Con-Trol-Cure Radiometer with non-filtered light sensor
- Con-Trol-Cure TFC 9000 used for timer only
- Production Parts holder
- Laboratory scale for measuring adhesive weight
- Manual tensile test fixture

Figure 1 - Power Supply, Lamps on Pallet Fixture and Radiometer

Previously, UV Process Supply had used thermal imaging to measure the temperature of the LED bonds, determining the maximum allowable current for the arrays. The power supply had been set internally so that outputs can only be adjusted up to the maximum allowable value.

The power supply has four output channels which will ultimately power four heat sink assemblies, each holding two LED arrays. UV Process Supply uses the terminology “groups” for the outputs and “lamps” for the LED arrays. UV Process Supply had already set up the power supply with two groups at the maximum current setting and two groups at the minimum current setting. Since only two groups were required for this test, the first tests were done using groups 1 and 2 (at maximum), and the final tests were done with channels 3 and 4 (at minimum).

Initially, a Con-Trol-Cure radiometer with a light sensor and no filters was used to take a light power reading on each array (lamp).

Figure 2 - Taking Light Power Reading

Group	Lamp	(Max) mW/cm^2
1	1	13.8
1	2	14.7
2	1	14.0
2	2	14.1

Only Group 1, Lamp 1 and Group 2, Lamp 2 were used for curing tests. After initial tests at maximum power, the lamps were attached to groups 3 and 4.

Output measurements at minimum setting were recorded.

Group	Lamp	(Min) mW/cm^2
3	1	8.2
3	2	NA
4	1	NA
4	2	7.6

By averaging the opposing lamp outputs and comparing the “maximum” and “minimum” values, it was determined that the “minimum” setting provided 57% of the full light output power.

Adjustment between minimum and maximum is accomplished with a 20-turn potentiometer for each LED array. Ultimately, on-line radiometers can be used to balance lamp outputs at approximately 80% of full power (TBD).

The lamps were mounted to a production parts holder with spacers to mimic the “real” position of the lamps relative to the polycarbonate part.

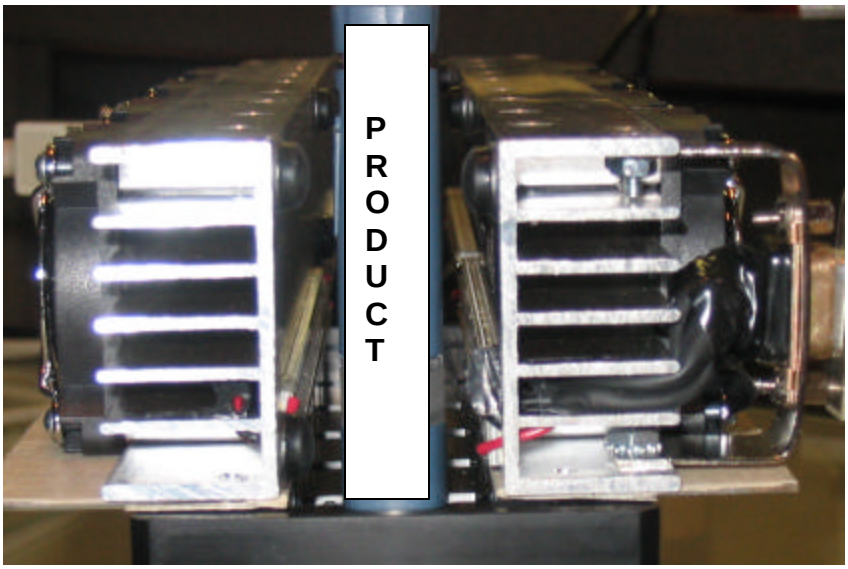

Figure 3 - Lamp Position

The lamps were centered on the six stations. The ends of the arrays were roughly even with the extreme ends of nests one and six.

Figure 4 - Alignment of Lamps to Nests

A Con-Trol-Cure, TFC 9000 instrument was used for its timer. A set of dry contacts on the instrument was used to provide a timed enable signal to the power supply.

Figure 5 – Back of Power Supply with TFC-9000 on Top

A laboratory scale with .0001 g resolution was used to measure the weight of adhesive applied to each plastic part.

A manual tensile tester was devised for this test. It consisted of a pair of yolks with pins to mount the samples and a 10:1 lever arrangement to magnify the manual force. A hand-held digital pull-scale was used to manually provide force for the tensile test. The construction of the tester allowed multiple degrees of freedom to prevent excessive moment loads on the samples and provide a reasonably pure shear force to the bonds.

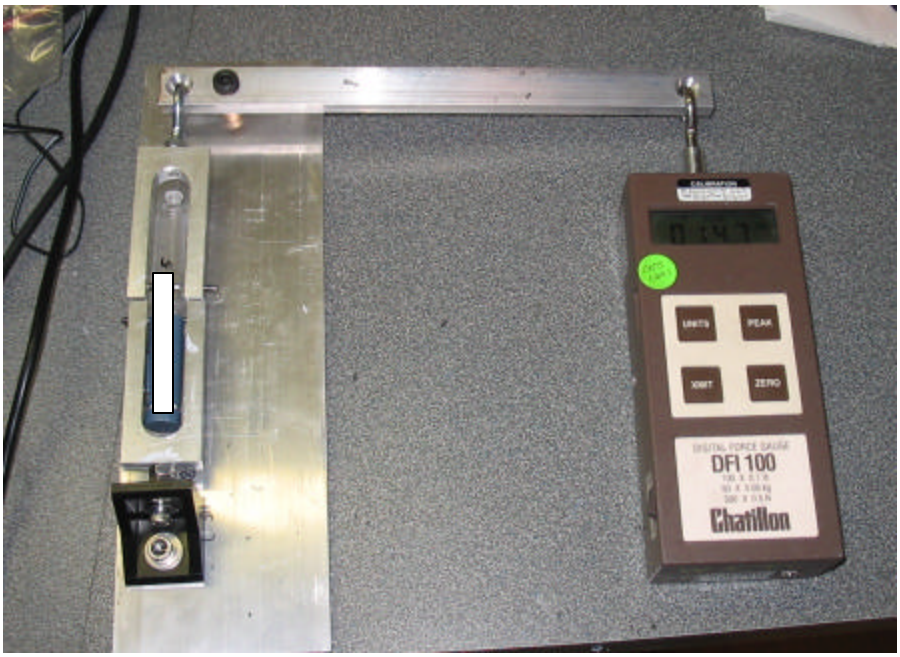

Figure 6 – Manual Tensile Test Fixture

Test Process

Using previous test data generated by UV Process Supply, (the variation of cure as a function of lot and age) lot number 4D387 was determined to be the slowest-curing sample provided for test by Loctite. Since this test was about process margin, only that particular lot was used.

1. A polycarbonate plastic part was marked with a sample number, and then placed on the lab scale.
2. When the scale had stabilized, it was zeroed with the plastic part in place.
3. Adhesive was manually applied to the four specified locations by dipping a small tool and transferring one dot at a time.
4. The plastic part was placed back on the scale and total adhesive weight was measured.
5. Adhesive was added or removed as necessary to bring the adhesive weight within spec. Although an attempt was made to visually balance the adhesive among the four locations, no effort was made to verify that it was evenly distributed.
6. Actual adhesive weight was recorded
7. The polycarbonate plastic part was immediately inverted and placed onto an assembly.
8. The assembly was placed into the specified pallet nest and exposed for the prescribed amount of time. Time between adhesive application and cure light exposure was not tightly controlled but did not exceed 30 seconds.
9. A .135” diameter hole was drilled through the plastic part for mounting in the tensile yolk fixture. The hole in the plastic part was drilled through the entire plastic part at the alignment tab just behind the bulkhead flange. This was done in an effort to force failure to the Bulkhead/Holder bond rather than the Bulkhead/plastic part Housing bond. Time between curing and tensile test was not tightly controlled but did not exceed 5 minutes.
10. .135” diameter hole was drilled through the holder approximately .75” from the bonded end of the holder.
11. The tensile tester linkage was adjusted (if necessary) to ensure that the lever bar was roughly perpendicular to the tensile pull direction.
12. The hand-held digital pull scale was set to capture peak force reading, and then re-zeroed prior to each test.
13. The pull scale was hooked to the lever bar and pulled manually with slowly increasing force to the point of part or bond failure. Tests normally took 5-10 seconds.
14. Samples were checked for uncured adhesive in the bond area.
15. Peak force, failure type and other test conditions were recorded.

Notes:

1. Initially, adhesive was applied to the old spec of 15-25 mg, using 20 mg as a target. After the first nine samples, the new spec of 13 mg +/- 3 mg was used.
2. The hole location through the plastic part was not optimum on the first two tests. Although the force values were high, the bulkhead failed near the mounting hole. After that, the hole was placed at the alignment tab and bulkhead failure was not an issue.
3. Failures were categorized into two types. Bond failures (identified as "B") were recorded when the plastic part and Holder separated at the bond line with no plastic breakage. Plastic failures (identified as "P") were recorded when the bulkhead or holder broke. In some cases, the bond failed on one side and the holder broke on the other. These were recorded as plastic failures.

Results and Notes

The production system will provide at least 4.5 seconds of cure time for each pen. Roughly 100% margin was designed into the system, so based on Led cure profile by UV Process Supply; we expected a full cure in less than two seconds at full power.

Samples 1-2

The first tests were set up to verify that the cure system could produce a full cure at 2 seconds. Pin placement through the plastic part was not optimum and the plastic part broke at the pin on both tests. However, pull force values of 770 N and 552 N indicated that the adhesive was fully cured.

Samples 3- 5

The test time was then dropped to one second and the pin location changed to reduce the chance that the bulkhead would fail in the tensile test. Previous UV Process Supply's, UV-LED cure profile data indicated that adhesive may not be fully cured at one second. Tensile test results showed bond failure rather than plastic failure, although tensile forces were still over 500N and there were no obvious areas of uncured adhesive.

Samples 6-7

The first test was then repeated with the new pin location. Pull forces were very high (1161 N and 1143 N) and resulted in broken plastic – one at the bulkhead and one at the holder.

Samples 8-9

For the next test, the sample was placed in nest #2. The pull force of 783 N broke the holder. Then, a dummy pen was added on either side of the pen being cured to see if there was any reduction due to slight shading caused by the other pens. Pull force was 556 N and broke at the bond, so there may have been a slight reduction in curing (insufficient data).

Samples 10-11

The same time and pen configuration were used for the next four samples, but the adhesive weight was dropped to 13 mg nominal. All subsequent tests were done with the lower adhesive volume. Break forces were 556 N and 974 N.

Samples 12-14

The exposure time was raised to 3 seconds, still at 100% power. Pull forces were 756 N to 996 N with two out of three breaking plastic.

Samples 15-17

Lamps were connected to power supply groups 3 and 3, resulting in a power setting of 57% of maximum. Exposure time was left at 3 seconds. Pull forces were 734 N to 912 N with all samples breaking plastic.

Samples 18-19

Cure time was raised to 4 seconds and tests were run on nests 1 and 2 with adjacent dummy pens. Pull forces were 654 and 912 N and both broke plastic.

Samples 20-21

This was estimated to be a process that can produce good bonds with approximately 4X margin (2X time and 2X power). Failures were at the bonds rather than plastic, but pull forces were 552 N and 654 N and no uncured adhesive was detected. Twelve samples were then produced for tensile tests.

Twelve additional samples were produced for tensile tests with this same configuration, except with a cure time of 3 seconds.

Summary:

Tests support the design margin of at least 2X for full cure of adhesive. Further testing will be required to accurately define the minimum safe process parameters, but the system proved to have ample process margin.

Sample	Time sec	Power %	Power, mW/cm^2	Adhesive Weight, mg	Meter Force N	Multiplied Force, N	Multiplied Force, Lbf	Failure type	Notes
1	2	100	13.95*	22.4	77.0	770	173	P	Pin placement for tensile test not optimum
2	2	100	13.95*	21	55.2	552	124	P	Pin placement for tensile test not optimum
3	1	100	13.95*	25.3	52.9	529	119	B	Better pin placement starting here
4	1	100	13.95*	24.3	65.4	654	147	B	
5	1	100	13.95*	20.9	77.0	770	173	B	
6	2	100	13.95*	21.8	116.1	1161	261	P	Bulkhead failed
7	2	100	13.95*	20.8	114.3	1143	257	P	Holder failed at pin
8	2	100	13.95*	15-25	78.3	783	176	P	Holder broke near bond line
9	2	100	13.95*	22.1	55.6	556	125	B	Shaded by positions 1 and 3
10	2	100	13.95*	15	97.4	974	219	P	Broke a chunk off of holder
11	2	100	13.95*	12.1	59.6	596	134	B	
12	3	100	13.95*	12.6	93.4	934	210	P	Broke a chunk off of holder
13	3	100	13.95*	12.3	75.6	756	170	B	
14	3	100	13.95*	14.8	99.6	996	224	P	Broke a chunk off of holder
15	3	57	7.9*	12.4	73.4	734	165	P	Broke a chunk off of holder
16	3	57	7.9*	15.8	91.2	912	205	P	Broke a chunk off of holder
17	3	57	7.9*	14.6	65.4	654	147	P	Broke a chunk off of holder
18	4	57	7.9*	14.5	71.6	716	161	P	Broke a chunk off of holder
19	4	57	7.9*	12.9	65.4	654	147	B	
20	2	57	7.9*	12.4	55.2	552	124	B	
21	2	57	7.9*	15.5	72.1	721	162	B	

* Value is the average of the two opposing lamps

Failure types: B=adhesive bond failure P=Plastic failure (broke)