Process-specific PCB Thickness Modeling

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Abstract
Predicting printed circuit board (PCB) thickness has not historically been a difficult task. With lower layer count boards you can afford for the prediction per layer to be wrong by a relatively large amount and still meet thickness criteria. As layer counts in multilayer boards increase, the ability to predict final thickness after lamination becomes more difficult and more important. All else equal, as the layer count increases, the error you can tolerate per layer must be reduced.

This paper discusses a method to design a thickness prediction model for a specific board shop process. This is accomplished by running carefully constructed experiments and assembling the results into a mathematical prediction model. The results will show how, in one case, thickness prediction errors were reduced by more than 25%.

Introduction
Most innerlayer travelers at PCB shops list a predicted board thickness after lamination, as well as a target for the required thickness range. A common method used to predict thickness is based upon data collected from Tedlar® pressouts, one value per glass style. Although reasonable for low technology applications, it can miss by a significant amount. In one instance errors were as large as +/- 5.25 mils. This means that occasionally, for example, a board that was predicted to be 58.1 mils thick will test out to be 52.9 mils on average. It is likely that such a discrepancy will cause scrap for tight tolerance builds.

In the spirit of purposeful process improvement we set out to improve the situation by following the Six Sigma methodology. We designed a test vehicle with well-defined copper retention and a variety of fill-loss scenarios. The DOE included all glass styles with both single and double-ply stackups in two presses. The resulting measurements were used as the parameters in a new prediction model calculator. Using the new calculator to predict historical thickness values we attained a capability of +/- 4.0 mils. For the instance stated above, this represents a 25% improvement over the current method.

Using the newly developed model we can expect, in the test case, a conservative 25% improvement in actual thickness relative to the prediction. The model, proper planning to the center of the thickness specification and a control chart to detect abherrations will improve the situation. Specifically, the combination will reduce the number of scrap investigations required and will reduce scrap caused by thickness deviations.

Background
Circuit board manufacturing requires careful planning and execution to ensure that quality products are built. One variable of increasing concern is lamination thickness. Layers of cores and prepreg are stacked together and fused under heat and pressure to form the final composite. The total thickness of the raw material stack is not a good estimate of the final pressed thickness. It is therefore important to run experiments to improve the accuracy of the predictions.

A popular method of predicting pressed thickness is to use a table of thickness values, one for each glass style used. The table is created, for instance, by pressing two plies of each glass style between Tedlar®, measuring the thickness at the center, and dividing by two to get the per-ply thickness. Pressouts are typically created at both the top and the middle of a book during regular production and averaged to capture any differences in thermal histories. As a first approximation prediction, no seating is considered.

The thickness reductions for fill-loss against etched copper layers are grouped into signal, plane and mixed categories. Losses are assumed based upon experience or direct calculation. To arrive at an expected pressed thickness after lamination, all the components are added, and then the appropriate subtractions are taken for fill-loss.

Once the expected thickness is calculated, the value is compared to thickness specification and the decision is made to accept or reject the stackup. If accepted, the traveler goes to production. If rejected, the search continues for a better stackup.

Ideally, only those stackups that yield predicted values at the center of thickness specification would be accepted. This does not happen in practice for several reasons. First, the thickness specification is an intermediate target. The end user specifies the final shipped board thickness, and the amount of plating after lamination can be controlled. This means that if the board presses out slightly thick, a little less plating can be used to hit the final product thickness requirements.

Even more can be done if the board presses too thin. Plating thick is one solution, but if the product is substantially thin the outer cap of copper can be etched away and an additional ply (or plies) of prepreg can be added to the ends in another trip through the press. There are risks with this, not the least of which is that the feedback is unlikely to make it back to the planning department, so the true problem never gets addressed.

Another reason why the center of the thickness specification is not necessarily chosen is economics. All other things being equal, with two stackup choices that both fit comfortably within the range, the cheaper one will be chosen. Yet another reason is the desire to use standard stackups. There are certainly more.

It was the aim of the project head off thickness surprises at lamination. To do so we used the Six Sigma approach of Define, Measure, Analyze, Improve and Control to characterize a specific product grade in a specific PCB process.

Measure

There are many reasons why the measured board thickness after lamination might fall outside the thickness specification. Some key factors within a board shop's control are:

1. Errors in the predicted thickness value calculated on the traveler (i.e., the predicted thickness differs from the actual measured thickness)
2. Planning the thickness values to land off-center from the middle of thickness specification for reasons previously explained
3. Special causes (e.g., missing a ply at stackup)

All of the control charts to follow are derived from manufacturing data from several weeks of production. The data is grouped by layer, increasing in complexity from 4-layer boards on the left to16-layer boards on the right. Within a layer group the jobs are listed chronologically by release date. Data is reported in mils regardless of the actual thickness of the board. In spite of the inherent weaknesses of the graphs as displayed, all graphs contain the same weaknesses. For this reason relative comparisons can still be made.

It is reasonable to wonder how closely the calculated values match the actual measured thickness. For some insight into this, refer to *Figure 1*.

Planned Error (Expected – Actual)

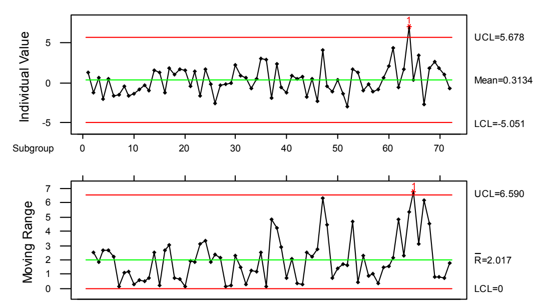


Figure 1 – Thickness Error

The metric measures the difference between the predicted value and the actual thickness in mils. As determined from the chart, the data shows stable performance with only one rule violation. The data is centered close to the origin (average = 0.3134) which means that, on average, the shop did a good job of predicting the actual board thickness after lamination. The control limits show an expected range larger than +/- 5.25 mils about the average. The question then becomes: "Is the prediction capability (considering both nominal and variation) good enough?" But, then again, that's not quite the whole story, as you can do a good job of predicting the final value but still produce scrap if you shoot too close to the edge of the thickness specification. Just how closely are the boards planned relative to the center of the thickness specification? *Figure 2* quantifies this:

Planned Offset (Planned – Center)

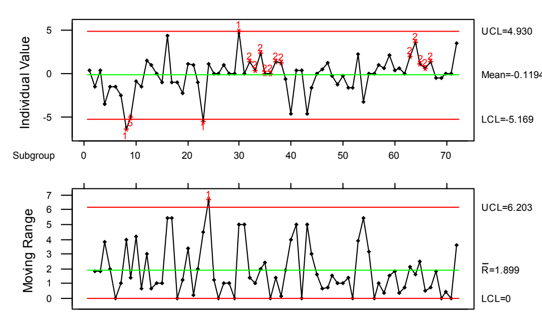


Figure 2 – Planned Thickness Offset

The difference between the planned thickness value and the center of the thickness specification is measured. The average of –0.1194 means that, on average, the planned value is tracking very closely to the middle of the thickness specification. The +/- 5.0 mil range depicted by the control limits suggests that the jobs are, at times, being planned significantly far from the center of the range. Doing so is dangerous, especially when the prediction capability is limited.

The chart also shows several rule violations, most notably strings of results on the same side of the average. This suggests a lack of standardization in the planning process. It is easy speculate that a lack of confidence, driven by predictably (after the fact) large deviations between the expectations and the actual resulting board thickness, would lead to instability in the planning process. A better prediction model will help improve this situation.

In addition to normal variation and intentional offsets, a third source of deviation stems from unusual circumstances. In control chart terminology, these are known as special causes. Knowing the inherent capability of the process is important so that you separate the signals in the data from the noise. For the historical data collected during the project, at least one special cause was identified and explained. With an error of 8.4 mils the point shows up as a special cause on the control chart. Prior to having access to the control chart, the initial discussions centered on process and/or product variation as the root cause. After further investigation and consideration, it was reported that the remaining releases of the same part pressed up just fine, and the probable cause for the thin board was a mis-ply at stackup.

There are several important lessons here. First, the control chart allowed for quick and easy detection of the special cause. Relative to typical performance, the actual thickness was so far off that clearly something went wrong. Yet, initially we were reluctant to discuss a breakdown in the process. This should not be a surprise, since without the benefit of historical data and a control chart to separate signal from noise, we have only to rely on memory and intuition – a shaky endeavor at best. It is likely that in the past investigations were launched for thickness results that were within the noise (+/- 5.25 mils), and it wouldn't take but a few wild goose chases for people to grow tired and skeptical.

Second, there were other special causes that were not discovered and investigated in real time. The opportunity is certainly lost as the trail is now cold.

Third, and most importantly, the stability of the control chart in *Figure 1* suggests that the process is performing reliably and predictably to within +/- 5.25 mils of the calculated prediction. Whether or not you can be satisfied with +/- 5.25 mils is a different issue altogether. It depends upon your willingness to target the center of the thickness specification and your expectation of the spread between the highest and lowest value.

At this point we have a good understanding of the scope of the problem. For the test case, the thickness values are currently being planned, on average, closely to the center of the thickness specification, and the actual thickness readings are, on average, very good relative to the prediction. The main problem with both is the variation about the average. To address the problem, we need a change to the common cause system that retains the accuracy (ability to hit nominal) and improves the precision (the variation about the nominal). For planning purposes, we should choose to build as close to the center of the thickness specification as possible. For the prediction part we need an improved prediction model.

Analyze

The first attempt to improve the prediction capability focused on a slight modification to the current method. We decided to update the thickness table by using 1- and 4-ply pressouts for all glass styles in all presses. The thickness readings were collected using a 5-point method – all four corners, approximately 1.5" to 2.0" diagonally inward, and one reading from the center. The results are tabulated below in *Table 1* and listed next to the values currently used:

Table 1 – Thickness Values

Glass	Current	Tedlar® 1-ply	Tedlar® multi-ply
106	2.1	2.53	2.34
1080	3.3	3.29	3.11
1652	6.4	6.24	6.19
2113	4.2	3.87	3.53
2116	5.1	4.89	4.53
7628	7.8/7.2	7.55	7.18
7629	8.7	8.80	8.32

The data was averaged over all presses to capture the variation typical in the lamination process. No obvious press effect was detected, while the nesting effect showed up to varying degrees depending upon the glass style.

Using the Tedlar® pressout data, the following capability data (*Table 2*) was obtained when predicting the final thickness readings for the several weeks of production data discussed earlier:

Table 2 – Tedlar® Pressout Capability

Baseline Data	Average Difference from Prediction (mils)	Standard Deviation of Difference from Prediction (mils)
Maximum Tedlar® Thickness	1.6	1.5
Average Tedlar® Thickness	-0.1	1.9
Predicted Values	0.4	2.0

Neither prediction method using the new Tedlar® pressout values improved upon the current prediction capability. The first had a good standard deviation but was not centered. The second was adequately centered but with minimal improvement to the standard deviation. In order to make a fundamental improvement, we decided to run a DOE using a test vehicle designed to approximate normal design parameters.

Improve

With the failure to improve the prediction capability using new Tedlar® values, a test vehicle was designed with the help of expertise within the shop. It was decided to build actual boards under controlled conditions to see if thickness values from these boards would allow for better prediction. To utilize thickness values from boards built under controlled circumstances requires more time and resources, but the payoff is a better prediction model.

Test Vehicle Design

The test vehicle was designed to give five thickness readings per coupon of varying amounts of fill loss against 1 oz. planes. They were signal/foil, power/foil, signal/signal, signal/power, and power/power. From each of the five resultant thickness measurements the starting base thickness can be calculated. Specifically, with the copper retention known, it is a simple matter to determine the base thickness required to have given the resulting measurement as follows:

Base Thickness = Measured Thickness Value + Thickness Lost to Fill

where the amount lost to fill against 1 oz. foil is as follows:

Thickness Lost to Fill (mils) = 1.2 * (1 – Fraction of Copper Retained)

The test vehicle has the typical thickness coupon on the border of the panel. Several of these coupons should be evaluated to see how closely they replicate the data measured from cross-sections taken at the center of the board. *Figure 3* shows the location of the internal cross-section.

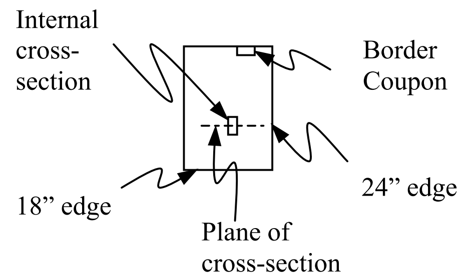


Figure 3 – Internal Cross-section Coupon

Thickness targets are selected to accommodate specific expected plating thickness. Additionally, the generally accepted average copper retention values are 80% or 75% for power layers and 20% or 25% for signal layers. It is not uncommon, however, for the actual signal copper retention to be as low as 15% or as high as 35% to 50%. Clearly, a model that takes into account actual copper retention will eliminate such variation from the prediction capability.

DOE Processing

Cores (0.005” 1/1) from one lot were launched for innerlayer processing. Normal processing parameters were used for surface preparation, resist application, printing, DES and punch. The cores were not run through AOI to save time. To ensure the integrity of the test and to make sure any issues could be quickly resolved, we were present for stackup. An example of one of the stackups can be found in Appendix A. Twenty-eight total boards were built, seven glass styles each with both a single and dual-ply stackup in each press. For the 106 and 1080 single-ply stackups, two plies of prepreg were used between the two signal layers to ensure proper fill. The prepreg glass styles are as follows in *Table 3*:

Table 3 – Prepreg Glass Styles

Glass Style	Resin %
106	Standard
1080	Standard
1652	Standard
2113	Standard
2116	Standard
7628	Standard
7629	Standard

The lamination test design can be found in Appendix B. The boards were stacked up in this order: Press #2/Plate #2 (2,2), (2,1), (1,2), (1,1). One spacer was used at the bottom of (2,2) which left no room for board 2,2,1 (1 x 1080 per dielectric opening) at the top. This board was pressed in opening (2,1) at the top. For openings (2,1), (1,2) and (1,1) steel separators were used between every other board, and for opening (2,2) two separators were skipped so that the material would fit over the pins. In order to keep production moving, what was labeled as Press #2 actually went into Press #1 and vice versa. Openings labeled (2,1) and (1,1) were thermocoupled. Thin steel separators were also used where necessary to make the product fit. As a practice, having two different thickness steel separators available leads to process variation that can easily be removed by standardizing on one size or the other.

For the fill-loss DOE, the heat ramps were measured between 180° F and 280° F and the cooldown rates were measured between 350° F and 240° F. The estimates were made from the press printouts and are presented in *Table 4*:

Table 4 – Press Heat Ramp Rates

	Outer (°F/min.)	Middle (°F/min.)	Average (° F/min.)
Press #1 Heat	10.0	11.4	10.4
Press #2 Heat	8.1	9.2	8.4
Press #1 Cool	7.8	6.5	7.8
Press #2 Cool	6.6	4.8	6.0

Data

Overall thickness measurements were taken for all 28 boards produced. Readings were taken using the standard 5-point thickness method prior to flash rout. Readings after rout were also taken, but they were not used since thickness readings are normally taken prior to rout. The results can be found in Appendix C. Since the DOE was replicated for both presses, a quick comparison between identical boards pressed in Press #2 vs. Press #1 can be seen in *Figure 4* below:

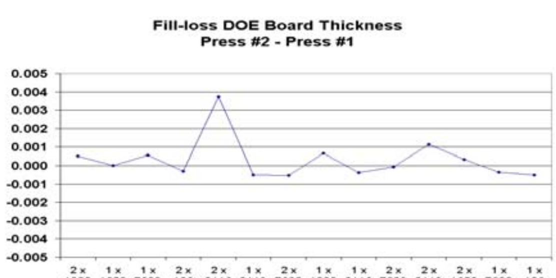


Figure 4 – Pressout Thickness vs. Press

As can be seen from the graph, no clear press bias is detected. With one exception (2 x 2116), the boards measured to be within a mil or so from one press to the other, some thicker in Press #1 and some thicker in Press #2. No explanation has been found for the 2 x 2116 discrepancy.

To retain the relative edge to center thickness weighting of the average using the 5-point measuring scheme, the overall average board thickness values were used to back-calculate the base dielectric thickness required to have given the overall board thickness measured (see the Test Vehicle Design section). For the 2 x 2116, only the thicker board was used as it fits better with the historical data. These values from the Fill-loss DOE are the ones used in the new model and are listed in *Table 5* below (in mils) next to the currently used values:

Table 5 – New Model Parameters

Glass	Current	Single-ply	Multi-ply
106	2.1	2.32	2.17
1080	3.3	3.28	3.09
1652	6.4	6.32	6.12
2113	4.2	4.08	3.94
2116	5.1	4.71	4.78
7628	7.8/7.2	7.39	7.04
7629	8.7	8.73	8.52

Once the numbers above have been identified, it is important to evaluate how useful the new numbers are for predicting actual product running in the shop. For this evaluation a thickness prediction model using the numbers above must be used to compare to historical information.

Additionally, cross-section data was collected for each board. These results can be found in Appendix D. The sample ID's are coded as follows: the first character is a "T" identifying the top of the sample, the second character is the original press design (recall that P1 and P2 were swapped), the third is the plate and the fourth is the board within the plate. The discrepancy between the two boards made from 2 x 2116 is evident in this data set also.

It would be an interesting exercise to see what the cross-section values would yield when used to create a model. The downside is that the cross-sections only capture the thickness at the center of the board, so it is likely that the method for measuring board thickness at lamination would have to be changed accordingly.

Control

Armed with the updated thickness values, a thickness prediction calculator was created to utilize the new information. The calculator incorporates several key features:

1. Thickness values are estimated from actual production boards rather than Tedlar® pressouts
2. Seating is estimated using both single and multi-ply prepreg values
3. Actual copper retention is an available parameter
4. Actual base laminate thickness from historical data can be used

Figure 5 below shows (in mils) how the new model calculator does when compared against the same historical information discussed in the Measure section of the report.

Model Error (Model – Actual)

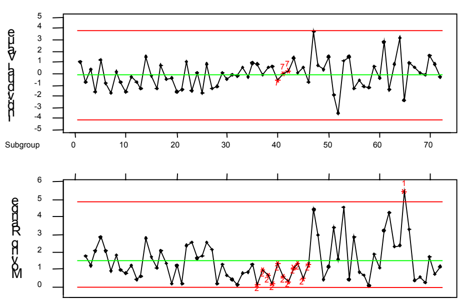


Figure 5 – Model Performance

Several points need to be made regarding the results above. The average is close to zero, meaning that the model has good accuracy. The control limits show an expected range of +/- 4.0 mils about the average, which is 20% to 25% better than the current method. Finally, there is a string of results between records 30 and 45 that show evidence of even better performance.

For a side-by-side comparison of the metrics and capabilities, see the *Figure 6* below:

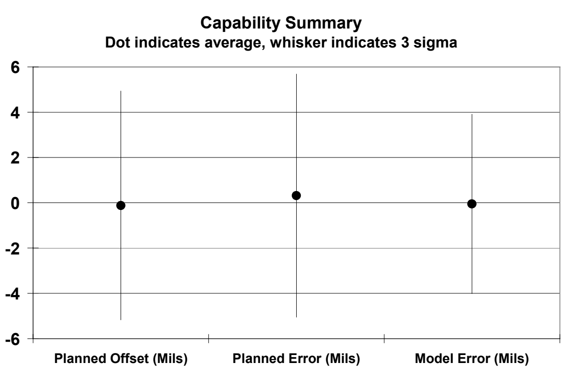


Figure 6 – Data Summary

Several conclusions can be drawn from the graph. Whisker #1 shows that the expected thickness values are planned close to the center of the thickness specification, but the wide range suggests that we are at times planning quite far from the center of the range. This is risky when the prediction capability is not good. Whiskers #2 and #3 show that both the values from the traveler and the new model calculator give good predictions on average (the centers are close to zero), but the expected range from the new model is 25% smaller than the current prediction method.

Conclusions

Based upon the data collected and observations made during the project, we make the following recommendations and conclusions:

1. The new model calculator gives reliable PCB thickness predictions, and in the test case yields a 25% improvement over the previous method.
2. Potential economic considerations aside, planning jobs to the center of the thickness specification minimizes the chances of thickness related scrap.
3. A standardized thickness measurement process is an essential element of the modeling process. Using a template would enable further improvement to the results in the test case.
4. Repeating Tedlar® pressouts every few months with analysis by control chart will aid the process of understanding the effect of process and product variation on resulting PCB thickness.
5. A control chart measuring the model's effectiveness and a reaction plan for when rule violations occur will ensure that the improvements are held. When rule violations do occur, explore first to see if the stackup is stretching beyond the model's assumptions. Explore operator error only as a last resort.

Acknowledgments

Due to the proprietary nature of the data included in this project the author chooses not to name the PCB shops involved. To those unnamed individuals who helped, my thanks to you.

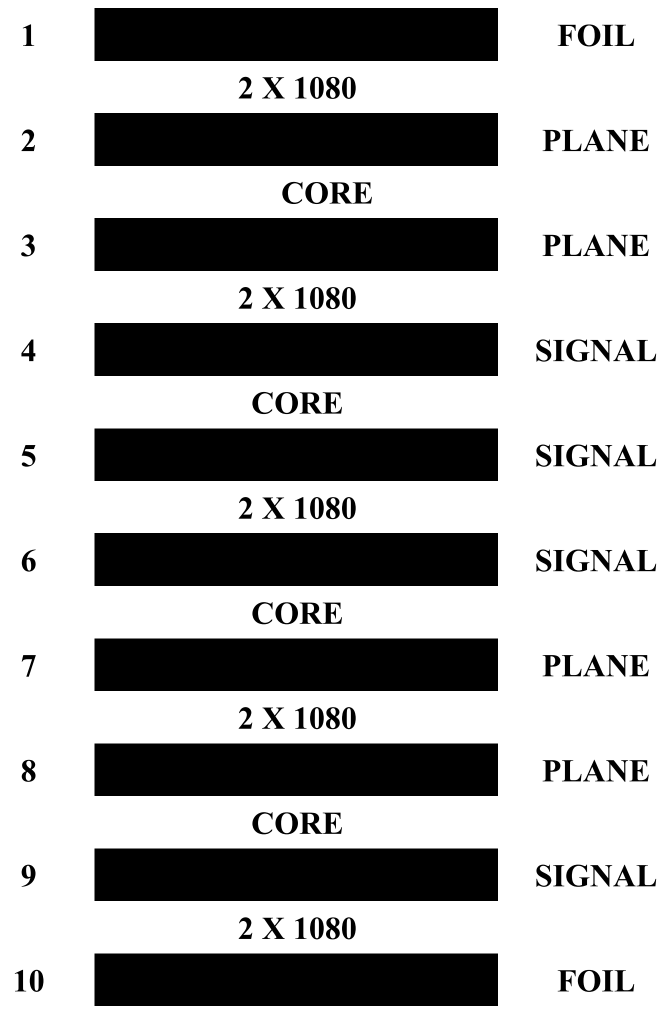
Tedlar® is a registered trademark of E.I. DuPont De Nemours and Company.

Pacothane® is a registered trademark of Paper Corporation of America.

Appendix A

PRESS #1, PLATE #1

1ST PANEL



Appendix B

Prepreg Fill Loss Testing -- Pin = 1.5" (product <= 1.25") Press 1					
Opening	**Sample**	**Glass Style**	**Board Thickness**	**Prepreg Plies**	**Thickness**
Plate #1	Caul Plate				
	Pacothane® Pad				0.050
	Steel separator plate/Tedlar® (key)				0.063
	1	1080	0.063	2	0.063
	Tedlar®/Steel separator plate/Tedlar®				0.063
	2	1652	0.064	1	0.064
	Tedlar®/Steel separator plate/Tedlar®				0.063
	3	7629	0.078	1	0.078
	Tedlar®/Steel separator plate/Tedlar®				0.063
	4	106	0.055	2	0.055
	Tedlar®/Steel separator plate/Tedlar®				0.063
	5	2116	0.083	2	0.083
	Tedlar®/Steel separator plate/Tedlar®				0.063
	6	2113	0.052	1	0.052
	Tedlar®/Steel separator plate/Tedlar®				0.063
	7	7628	0.111	2	0.111
	Steel separator plate/Tedlar®				0.063
	Pacothane® Pad				0.050
	Caul Plate				
				Sum =	1.104

Prepreg Fill Loss Testing -- Pin = 1.5" (product <= 1.25") Press 1					
Opening	**Sample**	**Glass Style**	**Thickness/ply**	**Prepreg Plies**	**Thickness**
Plate #2	Caul Plate				
	Pacothane® Pad				0.050
	Steel separator plate/Tedlar® (key)				0.063
	1	1080	0.050	1	0.050
	Tedlar®/Steel separator plate/Tedlar®				0.063
	2	2116	0.057	1	0.057
	Tedlar®/Steel separator plate/Tedlar®				0.063
	3	7629	0.125	2	0.125
	Tedlar®/Steel separator plate/Tedlar®				0.063
	4	2113	0.073	2	0.073
	Tedlar®/Steel separator plate/Tedlar®				0.063
	5	1652	0.096	2	0.096
	Tedlar®/Steel separator plate/Tedlar®				0.063
	6	7628	0.071	1	0.071
	Tedlar®/Steel separator plate/Tedlar®				0.063
	7	106	0.045	1	0.045
	Steel separator plate/Tedlar®				0.063
	Pacothane® Pad				0.050
	Caul Plate				
	Sum =				1.117

Prepreg Fill Loss Testing -- Pin = 1.5" (product <= 1.25") Press 2					
Opening	**Sample**	**Glass Style**	**Board Thickness**	**Prepreg Plies**	**Thickness**
Plate #1	Caul Plate				
	Pacothane® Pad				0.050
	Steel separator plate/Tedlar® (key)				0.063
	1	1080	0.063	2	0.063
	Tedlar®/Steel separator plate/Tedlar®				0.063
	2	1652	0.064	1	0.064
	Tedlar®/Steel separator plate/Tedlar®				0.063
	3	7629	0.078	1	0.078
	Tedlar®/Steel separator plate/Tedlar®				0.063
	4	106	0.055	2	0.055
	Tedlar®/Steel separator plate/Tedlar®				0.063
	5	2116	0.083	2	0.083
	Tedlar®/Steel separator plate/Tedlar®				0.063
	6	2113	0.052	1	0.052
	Tedlar®/Steel separator plate/Tedlar®				0.063
	7	7628	0.111	2	0.111
	Steel separator plate/Tedlar®				0.063
	Pacothane® Pad				0.050
	Caul Plate				
				Sum =	1.104

Prepreg Fill Loss Testing -- Pin = 1.5" (product <= 1.25") Press 2					
Opening	**Sample**	**Glass Style**	**Thickness/ply**	**Prepreg Plies**	**Thickness**
Plate #2	Caul Plate				
	Pacothane® Pad				0.050
	Steel separator plate/Tedlar® (key)				0.063
	1	1080	0.050	1	0.050
	Tedlar®/Steel separator plate/Tedlar®				0.063
	2	2116	0.057	1	0.057
	Tedlar®/Steel separator plate/Tedlar®				0.063
	3	7629	0.125	2	0.125
	Tedlar®/Steel separator plate/Tedlar®				0.063
	4	2113	0.073	2	0.073
	Tedlar®/Steel separator plate/Tedlar®				0.063
	5	1652	0.096	2	0.096
	Tedlar®/Steel separator plate/Tedlar®				0.063
	6	7628	0.071	1	0.071
	Tedlar®/Steel separator plate/Tedlar®				0.063
	7	106	0.045	1	0.045
	Steel separator plate/Tedlar®				0.063
	Pacothane® Pad				0.050
	Caul Plate				
				Sum =	1.117

Appendix C

							Measured Thickness Prior to Flash Rout							
Press Actual	Press Design	Plate	Board	Glass	Stack Thickness	Plies	1	2	3	4	5	Avg.	High	Range
2	1	1	1	1080	0.063	2	0.0572	0.0571	0.0591	0.0581	0.0600	0.0583	0.0600	0.0029
2	1	1	2	1652	0.064	1	0.0587	0.0588	0.0579	0.0597	0.0586	0.0587	0.0597	0.0018
2	1	1	3	7629	0.078	1	0.0710	0.0708	0.0720	0.0709	0.0704	0.0710	0.0720	0.0016
2	1	1	4	106	0.055	2	0.0483	0.0475	0.0487	0.0480	0.0509	0.0487	0.0509	0.0034
2	1	1	5	2116	0.083	2	0.0759	0.0736	0.0749	0.0743	0.0758	0.0749	0.0759	0.0023
2	1	1	6	2113	0.052	1	0.0461	0.0476	0.0475	0.0476	0.0475	0.0473	0.0476	0.0015
2	1	1	7	7628	0.111	2	0.0954	0.1006	0.0987	0.0957	0.0956	0.0972	0.1006	0.0052
2	1	2	1	1080	0.050	1	0.0469	0.0474	0.0470	0.0460	0.0463	0.0467	0.0474	0.0014
2	1	2	2	2116	0.057	1	0.0497	0.0499	0.0525	0.0500	0.0502	0.0505	0.0525	0.0028
2	1	2	3	7629	0.125	2	0.1153	0.1094	0.1142	0.1115	0.1110	0.1123	0.1153	0.0059
2	1	2	4	2113	0.073	2	0.0667	0.0658	0.0685	0.0672	0.0671	0.0671	0.0685	0.0027
2	1	2	5	1652	0.096	2	0.0881	0.0877	0.0904	0.0878	0.0881	0.0884	0.0904	0.0027
2	1	2	6	7628	0.071	1	0.0638	0.0648	0.0633	0.0633	0.0640	0.0638	0.0648	0.0015
2	1	2	7	106	0.045	1	0.0401	0.0406	0.0409	0.0407	0.0401	0.0405	0.0409	0.0008
1	2	1	1	1080	0.063	2	0.0572	0.0577	0.0580	0.0578	0.0583	0.0578	0.0583	0.0011
1	2	1	2	1652	0.064	1	0.0588	0.0594	0.0583	0.0586	0.0586	0.0587	0.0594	0.0011
1	2	1	3	7629	0.078	1	0.0704	0.0704	0.0712	0.0701	0.0702	0.0705	0.0712	0.0011
1	2	1	4	106	0.055	2	0.0492	0.0484	0.0495	0.0486	0.0492	0.0490	0.0495	0.0011
1	2	1	5	2116	0.083	2	0.0712	0.0712	0.0723	0.0707	0.0704	0.0712	0.0723	0.0019
1	2	1	6	2113	0.052	1	0.0482	0.0478	0.0477	0.0476	0.0475	0.0478	0.0482	0.0007
1	2	1	7	7628	0.111	2	0.0994	0.0956	0.1000	0.0974	0.0962	0.0977	0.1000	0.0044
1	2	1	0.5	1080	0.050	1	0.0453	0.0467	0.0462	0.0462	0.0459	0.0461	0.0467	0.0014
1	2	2	2	2116	0.057	1	0.0502	0.0516	0.0514	0.0502	0.0508	0.0508	0.0516	0.0014
1	2	2	3	7629	0.125	2	0.1163	0.1083	0.1145	0.1114	0.1113	0.1124	0.1163	0.0080
1	2	2	4	2113	0.073	2	0.0652	0.0658	0.0667	0.0656	0.0663	0.0659	0.0667	0.0015
1	2	2	5	1652	0.096	2	0.0880	0.0883	0.0896	0.0872	0.0874	0.0881	0.0896	0.0024
1	2	2	6	7628	0.071	1	0.0635	0.0641	0.0643	0.0648	0.0643	0.0642	0.0648	0.0013
1	2	2	7	106	0.045	1	0.0405	0.0407	0.0413	0.0408	0.0416	0.0410	0.0416	0.0011

Appendix D

Sample	ID	D1 (mils)	D2 (mils)	D3 (mils)	D4 (mils)	D5 (mils)	D6 (mils)	D7 (mils)	D8 (mils)	D9 (mils)
1	**T117**	13.20	5.10	12.60	5.20	11.98	5.10	13.38	5.01	12.90
2	**T116**	3.40	5.20	2.70	5.10	2.30	5.20	3.10	5.07	2.89
3	**T115**	8.85	5.16	7.93	5.10	7.24	5.13	8.61	5.19	8.17
4	**T114**	3.67	5.07	2.89	5.16	2.47	5.13	3.40	5.09	3.19
5	**T113**	7.99	5.04	7.42	5.19	6.70	5.13	7.81	5.13	7.54
6	**T112**	5.60	5.15	4.83	4.98	4.53	5.09	5.27	5.19	5.00
7	**T111**	5.33	5.15	4.41	5.15	4.11	5.13	5.15	5.13	4.59
8	**T127**	1.52	5.21	0.86	5.19	1.91	5.01	1.61	5.07	1.25
9	**T126**	6.59	5.13	5.87	4.95	5.48	5.01	6.35	5.13	5.75
10	**T125**	11.62	5.22	10.94	5.09	10.37	5.07	11.71	5.13	11.20
11	**T124**	7.27	5.33	6.47	5.12	6.53	5.24	7.00	5.27	6.59
12	**T123**	16.96	5.24	15.67	5.18	15.58	5.07	16.72	5.15	16.15
13	**T122**	3.93	5.24	3.58	5.13	3.43	5.01	3.99	5.18	3.72
14	**T121**	2.44	5.09	1.97	5.24	3.78	5.16	2.68	5.09	2.06
15	**T217**	14.01	5.21	10.19	5.24	12.57	5.18	13.08	5.01	13.17
16	**T216**	3.31	5.13	2.74	4.98	2.26	5.04	3.25	5.13	2.71
17	**T215**	8.17	5.07	7.45	5.07	7.09	5.09	7.78	5.09	7.54
18	**T214**	3.25	5.19	2.92	5.19	2.50	5.04	3.25	5.19	3.13
19	**T213**	8.19	5.13	7.33	5.13	7.09	5.09	7.51	5.13	7.60
20	**T212**	5.36	5.13	4.98	5.09	4.62	5.19	5.22	5.22	5.15
21	**T211**	5.24	5.09	4.53	5.09	4.50	5.09	4.71	5.16	5.01
22	**T227**	1.82	5.22	1.10	5.07	2.06	5.09	1.67	5.13	1.07
23	**T226**	7.03	5.22	6.35	5.13	5.39	5.22	6.76	5.13	6.17
24	**T225**	11.92	5.25	11.06	5.19	10.57	5.19	11.98	5.15	11.35
25	**T224**	7.39	5.22	6.38	5.22	6.08	5.22	6.79	5.07	6.53
26	**T223**	17.05	5.03	15.81	5.03	15.33	5.03	16.16	5.03	15.92
27	**T222**	4.17	5.30	3.58	5.19	3.22	5.27	4.02	5.09	3.84
28	**T221**	2.35	5.22	1.73	5.16	3.75	5.18	2.41	5.22	1.99