To Quantify a Wetting Balance Curve

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Abstract
Wetting balance testing has been an industry standard for evaluating the solderability of surface finishes on printed circuit boards (PCB) for many years. A Wetting Balance Curve showing Force as a function of Time, along with the individual data outputs "Time to Zero" $T_{(0)}$, "Time to Two-Thirds Maximum Force" $T_{(2/3)}$, and "Maximum Force" $F_{(max)}$ are usually used to evaluate the solderability performance of various surface finishes. While a visual interpretation of the full curve is a quick way to compare various test results, this method is subjective and does not lend itself readily to a rigorous statistical evaluation. Therefore, very often, when a statistical evaluation is desired for comparing the solderability between different surface finishes or different test conditions, one of the individual parameters is chosen for convenience. However, focusing on a single output usually doesn't provide a complete picture of the solderability of the surface finish being evaluated. In this paper, various models here-in labeled as "point" and "area" models are generated using the three most commonly evaluated individual outputs $T_{(0)}$, $T_{(2/3)}$, and $F_{(max)}$. These models have been studied to quantify how well each describes the full wetting balance curve. The solderability score (S-Score) with ranking from 0 to 10 were given to quantify the wetting balance curve as the result of the model study, which corresponds well with experimental results.

Introduction
Solderability can be defined as the ability of a metal to be wetted by molten solder. Good solderability is represented by the adherence of unbroken uniform film of solder to a substrate metal. In Printed Circuit Board (PCB) manufacturing, solderability is a critical characteristic of the copper substrate as it will determine the strength and quality of the solder joints. The electronics assembly industry has gone through tremendous change since the introduction of SMT (Surface Mount Technology) since the early 80's. PCB's have gone from relatively low density plated through holes encapsulated with tin-lead solder to high density surface mount pads that may be coated with different kind of final finishes.

The final finish used on the PCB is one of the most important factors in the assembly process. The primary function of the final finish is to protect the copper surface on the board from oxidizing during storage. The final finish provides many benefits to the assembly process along with some challenges. The assembler must have information on the solderability characteristic of the final finish prior to assembly process to ensure high production yield. The surface must allow wetting by the molten solder within the time available and using the specified flux, without subsequent de-wetting. The resultant need for pre-determining solderability has become a vital necessity for both the PCB manufacturer and the assembler.

Solderability of PCB can be determined by employing various techniques such as solder dip, solder float, solder spread and wetting balance test. Among all the tests available, wetting balance test provides the most quantitative and useful information as compared to the other method. Hence, the wetting balance test is widely used in the industry for both PCB and component testing. IPC has established a test method and evaluation criteria (IPC-J-STD-003) for the wetting balance test which is available in the literature[1]. This evaluation method, even though quantitative, only allows for classifying the test specimens as pass or fail. There is a need for better evaluation method for wetting balance test results which will allow both the manufacturing and research communities to statistically validate solderability information.

Background
The wetting balance test has been utilized by PCB manufacturers and assemblers to meet this need for many years. In wetting balance testing a test specimen is inserted at high speed into a small bath of molten solder. The balance of forces, buoyancy and surface tension acting upon the specimen in the vertical dimension is measured using an LVDT (linear variable differential transformer). The resulting wetting balance curve showing total force (mN), or normalized force (mN/mm), as a function of time provides information about the speed and extent of wetting. For practical assessment of the solderability characterization a simple to use method is required that incorporates the data on both degree and speed of wetting. This is usually extracted from the wetting balance curve as shown in Figure 1[2]. The wetting balance test is fast (5 to 10 seconds), fully automated, repeatable and provides quantitative data over the whole range of the wetting action.

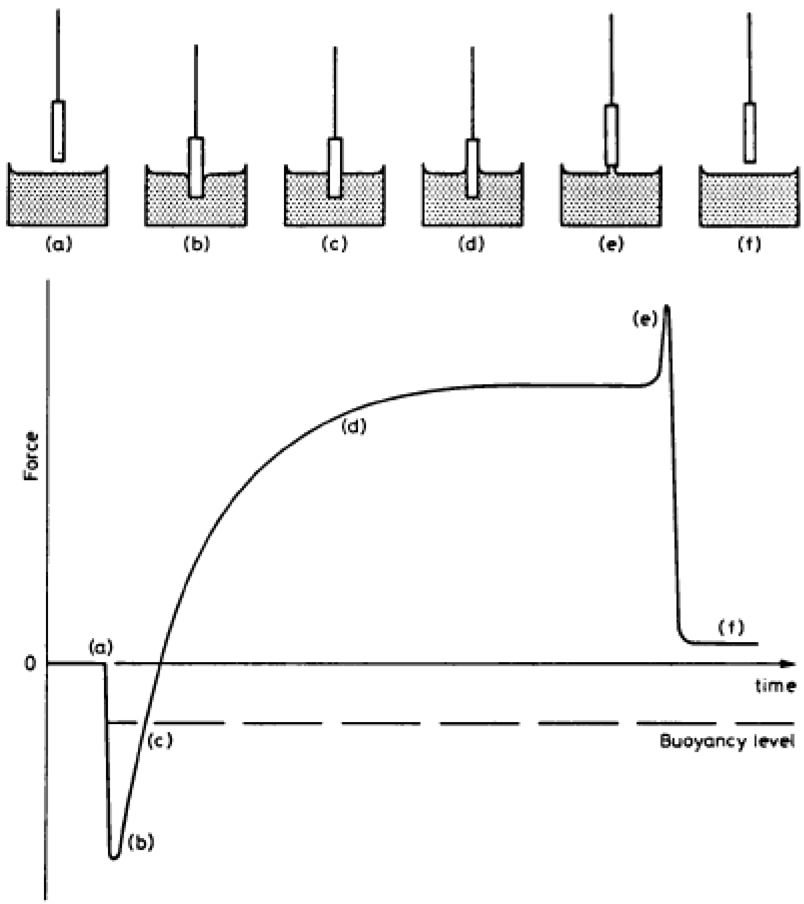

Figure 1 - Typical wetting balance curve

The major drawback has been the inability to standardize the interpretation of the wetting balance curve into a meaningful single assessment value for statistical analysis. A typical wetting balance unit provides the test results as a visual representation of the entire wetting balance curve as shown in Figure 1. Some wetting balance units also provide key quantitative parameters such as wetting initiation time, wetting rate and the maximum wetting force. Even though the wetting balance curve provides several quantitative points on the curve, interpretation of the full curve still remains somewhat qualitative. Furthermore, since all three of the fundamental components of the curve ($T_{(0)}$, $T_{(2/3)}$, $F_{(Max)}$) are equally important in assessing solderability, evaluation of a single fundamental component parameter would not provide a complete picture of the solderability. Typically, solderability assessment is made by reduction of the curve into a set of three pass/fail valuations based on criteria suggested by IPC J-STD-003. Neither of these methods provides a satisfactory solution for large scale comparative evaluations of solderability.

This paper provides a simple and fast method for obtaining a single assessment value for the entire wetting balance curve based on a model that utilizes the three fundamental components of $T_{(0)}$, $T_{(2/3)}$, and $F_{(max)}$ that are usually provided in a database format by most wetting balance units.

Wetting Balance Principle

In a wetting balance test a small bath of molten solder is raised up toward a fluxed test specimen such that the test specimen is inserted at high speed (1 to 5 mm/second) to a very shallow depth (0.1 to 0.3 mm) into the solder. The solder pot is held steady at this position for 5 to 10 seconds. The test specimen is allowed to move freely in the vertical dimension in response to the net force acting upon it.

During the test, the balance of forces acting upon the test specimen in the vertical dimension are measured with an LVDT. The resultant wetting balance curve displays the net force acting on the specimen along the Y axis, as a function of time along the X axis. Rejecting forces (non-wetting) acting in the upward direction are shown in the negative scale, and attractive forces (wetting) acting in the downward direction are shown in the positive scale. In order for individual test results to be compared with one another, buoyancy forces are generally corrected for, and the total force F (mN) is normalized against the total wettable perimeter of the test specimens and reported as mN/mm. A typical wetting balance curve from a LVDT is shown in Figure 2.

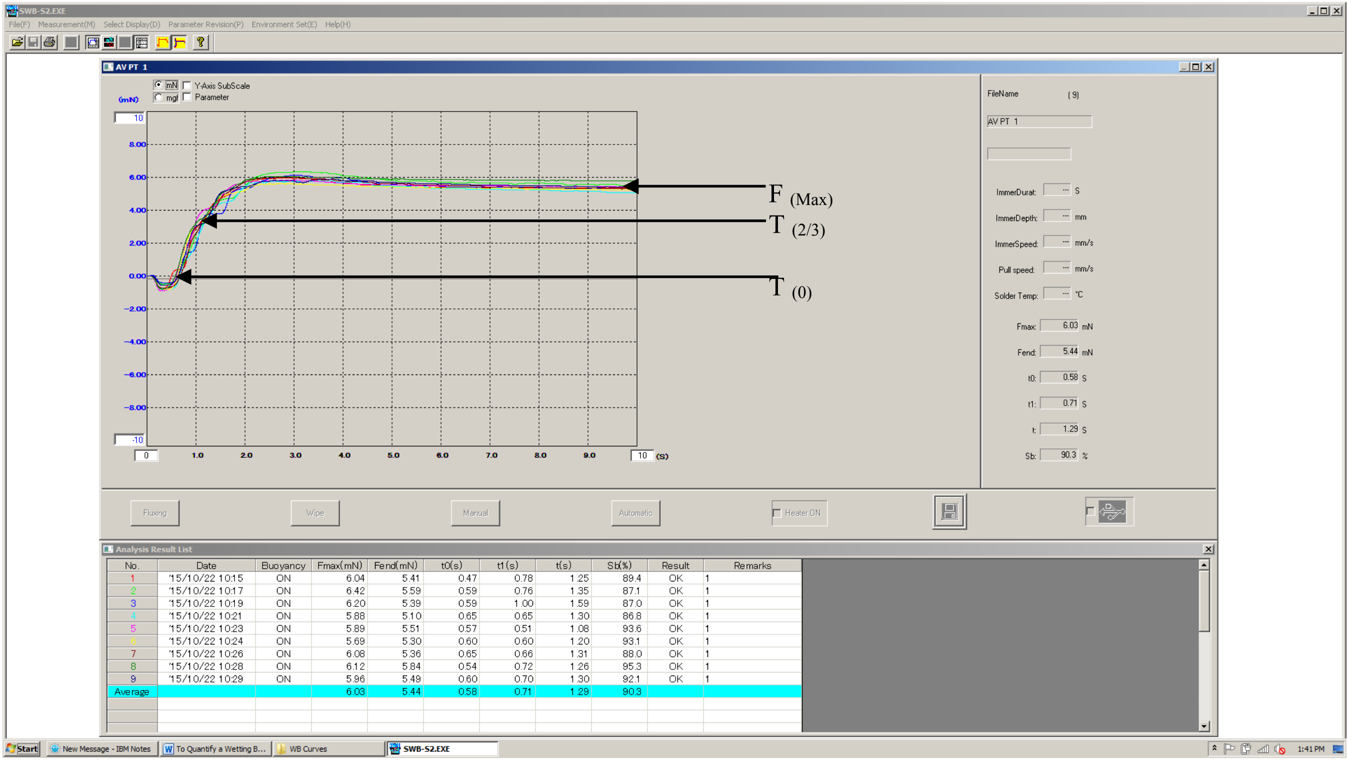

Figure 2 - Typical wetting balance curve showing three critical components of the curve

Acceptable solderability is established through evaluation of the general shape of the curve and such fundamental curve components as $T_{(0)}$, $T_{(2/3)}$, and $F_{(max)}$. In general a test specimen is inserted at such a high rate of speed that it reaches the maximum insertion depth before attractive wetting forces are initiated. Initially the net repulsive forces act in the upward direction and display in the negative on the curve. After a short time the attractive wetting forces acting on the specimen in the downward direction initiate and overtake the repulsive forces and is displayed as a rise in the positive direction. When the attractive forces match the repulsive forces the curve crosses the zero axis (or buoyancy corrected zero axis). This is recorded as the Time to Zero $T_{(0)}$. As the molten solder wicks up the surface of the test specimen drawing it down into the solder bath the curve continues to display a rise in the positive direction. The slope of the rise is an indication of the wetting rate. A typical wetting balance unit will record the time at which the positive force reaches two thirds the maximum force as an indicator of the rate of wetting, $T_{(2/3\ max)}$. Eventually, the slope of the rise levels off as the maximum wetting force is reached, and is recorded as $F_{(max)}$ as shown in Figure 2.

Interpretation of Wetting Balance Curve

Most wetting balance units provide a visual representation of the curve, and they record the numerical value of the three fundamental curve components of $T_{(0)}$, $T_{(2/3\ max)}$ and $F_{(max)}$. The typical comparative evaluations for solderability involve qualitative comparisons of the general shape of the curves under investigation. In addition, IPC J-STD-003 has established a set of suggested pass/fail criteria for the values of time to zero, wetting force at two seconds, and wetting force at five seconds as; $T_{(0)} < 1$ second, $T_{(2/3)} < 2$ seconds, and $F_{(max)}$, ≥ 0.35 mN/mm. Previously, we had modified this pass/fail criteria interpretation of the wetting balance curve to a moderately qualitative interpretation by developing a "Point Model" which is described below.

Point Model Description

As it can be seen from Figure 2, it is difficult to visually compare more than a few curves at a time. While the IPC test criteria may be sufficient for a periodic check of the solderability of PCB or component in a high volume manufacturing environment, it is not sufficient to evaluate large scale testing for research and development purpose. For large scale testing, it is desirous to distill the three fundamental components of the wetting balance curve, which taken as an aggregate are a representation of the general shape of the curve. This value is here-in referred to as an S-Score (Solderability Score).

The S-Score is a method of summing up the general solderability performance of a test specimen by assigning a single numeric descriptor of the test result on a scale of 0 through 10. The scale of 0 to 10 is developed for the ease of use only. The S-Score is determined by extracting the value of the three fundamental components directly from the test unit displaying as shown in

Figure 2. The fundamental components of the curve that are displayed on the screen are $T_{(0)}$, $T_{(2/3)}$ or $T_{(0.1 \text{ and } 0.2)}$, and $F_{(max)}$. The overall scale of 0 to 10 divided into three partial values as shown in the Table 1. The three partial values are summed up to yield the total S-Score.

Table 1 - Scoring for fundamental components of wetting balance curve

Fundamental component	Possible score
$T_{(0)}$	0-3
$T_{(2/3)}$	0-4
$F_{(max)}$	0-3
Total score	0-10

Curve Component Definition

Time to zero, $T_{(0)}$

$T_{(0)}$ is defined as the time it takes for the wetting force to balance the buoyancy force. It is an indication of how fast solder has penetrated the coating and begins bonding with the Cu substrate. The range for the $T_{(0)}$ score under this model is between 0-3. The criteria for assigning a score to $T_{(0)}$ is as follows:

Table 2 - Scoring criteria for $T_{(0)}$

$T_{(0)}$ Score	Time Criteria in Sec
0	$T_{(0)} > 3$
1	$T_{(0)} = 2$ to 3
2	$T_{(0)} = 1$ to 2
3	$T_{(0)} < 1$

Time to Two-Thirds Maximum Force, $T_{(2/3)}$,

T(2/3) is defined as the slope of the rise to F(max) indicating how fast the solder spreads. The range for the $T_{(2/3)}$ score under this model is between 0-4. The criteria for assigning a score to $T_{(2/3)}$ is as follows:

Table 3 - Scoring criteria for $T_{(2/3)}$

$T_{(2/3)}$ Score	Time Criteria in Sec
0	$T_{(2/3)} > 3$
1	$T_{(2/3)} = 2$ to 3
2	$T_{(2/3)} = 1.5$ to 2
3	$T_{(2/3)} = 1$ to 1.5
4	$T_{(2/3)} < 1$

Maximum Force, $F_{(max)}$

$F_{(max)}$ is defined as the maximum net force acting on the test specimen that is attained, and is an indication of the quality of contact between the solder and the Cu surface. To determine the score the total F(max) in mN must be normalized to mN/mm divided by the wettable perimeter of the test specimen.

Table 4 - Scoring criteria for $F_{(max)}$

$F_{(max)}$ Score	Time Criteria in Sec
0	$F_{(Max))} < 0.1$ mN/mm
1	$F_{(Max)} = 0.1$ to 0.2mN/mm
2	$F_{(Max)} = 0.2$ to 0.3mN/mm
3	$F_{(Max)} > 0.3$mN/mm

The Point Model provides a way to assign a single assessment value to an individual test result which describes solderability somewhat quantitatively. Furthermore, relatively large data sets can be analyzed and evaluated, and comparisons can be made with relative ease and displayed in graphical format. According to the Point Model method, the solderability can be characterized as shown in Table 5. Corresponding wetting balance curves are shown in Figure 3.

Table 5 - Solderability acceptance criteria

Solderability	Score
Excellent	9-10

Good	7-8
Acceptable/Fair	4-6
Unacceptable/Poor	< 3

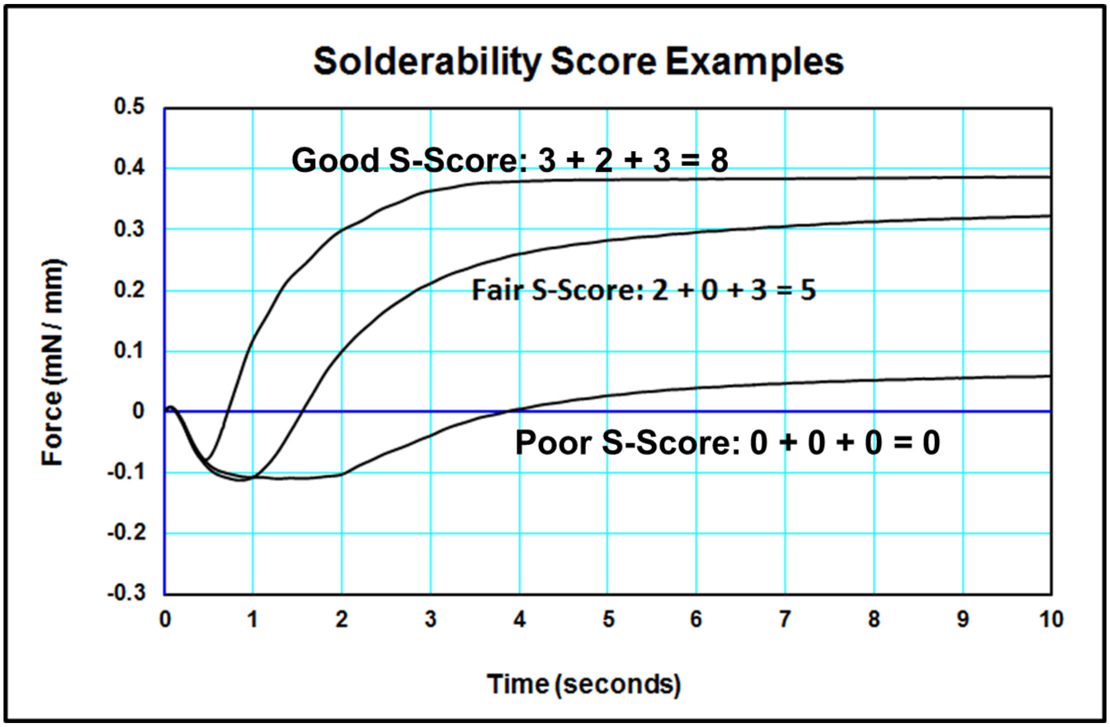

Figure 3 - The schematics of Point Model showing good, fair and poor solderability.

As stated before, evaluation of just a single fundamental component of the curve does not provide a complete and comprehensive picture of the full wetting behavior. All three of the fundamental components of the curve are equally important for assessing solderability. They need to be analyzed together to give the full spectrum of the wetting performance. The Point Model provides a reasonably good method of evaluating all three fundamental components in the aggregate and for distilling solderability into a single assessment value. However, it is a crude model at best. To overcome the deficiency of the Point Model, a new model, named "Area Model", is presented here.

Area Model Description

The most reliable assessment of solderability is to determine the integrated value of the area under the curve. The Area Model simplifies this task by utilizing already available fundamental components of the wetting balance curve. In the Area Model the values of fundamental components are used to approximate the area under the wetting balance curve. In most cases these three values are supplied by the test unit in a database format. In addition, the test unit also provides the wetting curve data which can be converted to an Excel format that can then be used to calculate the actual area under the curve. Equation 1 describes the Area Model using the three fundamental components and Figure 4 describes it in a graphical manner. Furthermore Figure 4 is used as a guide to describe the model and calculate the S-Score. A scaling factor is used in accessing the S-Score to be consistent with the Point Model.

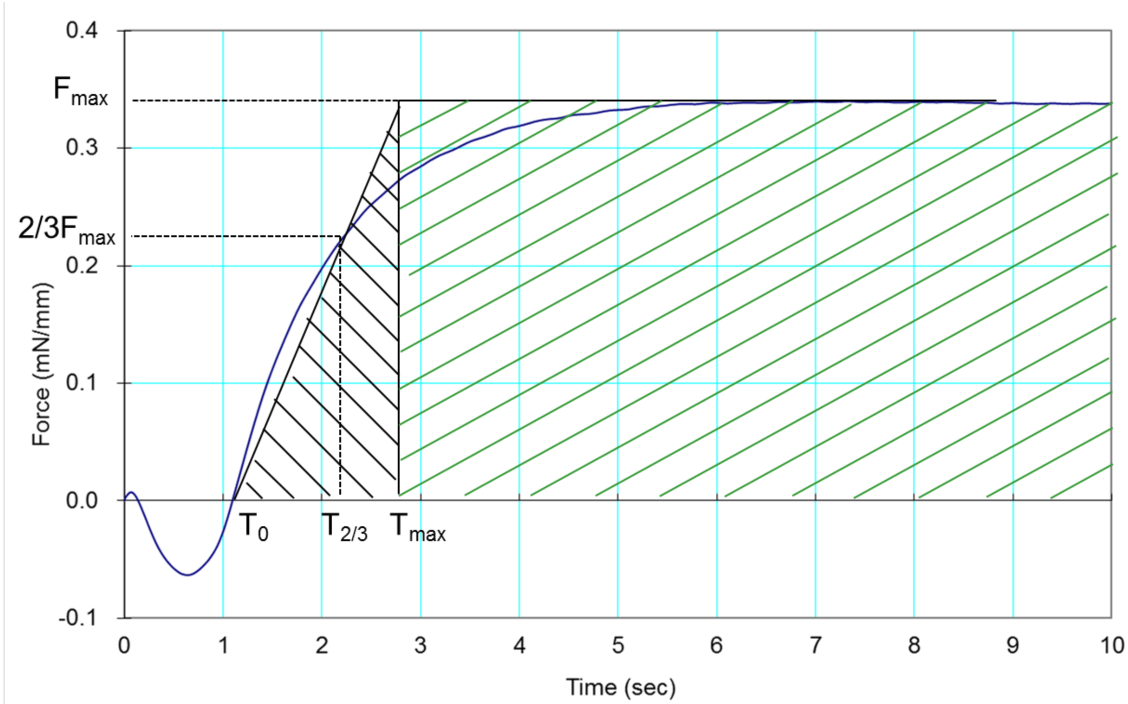

Figure 4 - Area model schematics - Three parameters used to calculate the area under the curve

As Figure 4 shows, the area under the wetting curve was approximated into two regions; a triangular region ($S_{(triangle)}$) and a rectangular region ($S_{(rectangle)}$). This is described mathematically in equation 1.

$S = S_{(triangle)}+S_{(rectangle)} = [T_{(max)}-T_{(0)}]*F_{(max)}/2 + [10-T_{(max)}]*F_{(max)}$ Eq. 1

Where,
S = Area under the curve representing Solderability score as predicted by the model
$S_{(triangle)} = [T_{(max)}-T_{(0)}]*F_{(max)}/2S_{(rectangle)} = [10-T_{(max)}]*F_{(max)}$ Eq. 2
$T_{(max)} = [T_{(0)}+1.5*(T_{(2/3)}-T_{(0)})]$ Eq. 3
$T_{(0)}$, = Time to 0
$F_{(max)}$ = Maximum force

$T_{(max)}$ was introduced for this model as the time when maximum force is achieved in a linear way (as shown in figure 4). This can be mathematically computed by, $T_{(0)}$ and $T_{(2/3)}$ as per Eq. 3.

The area "S" is calculated with a number of wetting balance curves with known excellent wetting. The area under the curve were calculated to be around 3.5 s*mN/mm. To evaluate the "area" in a scale from 0 to 10, the results were multiplied by a factor of three (3).This was primarily done for the purpose of comparing it to the point model, also for convenience of the comparison. Therefore the S-Score is calculated as:

S-Score= S*3

Table 6 - Comparison between Point Model and Area Model S-Scores

Solderability Score Calculation				
Point Model S-Score	**$T_{(0)}$ (s)**	**$T_{(2/3)}$ (s)**	**$F_{(Max)}$ (mN/mm)**	**Area Model S-Score**
9	**0.80**	**1.50**	**0.33**	**8.59**
7	**0.80**	**1.60**	**0.27**	**6.97**
1	**7.40**	**7.40**	**0.15**	**1.17**
10	**0.45**	**0.99**	**0.35**	**9.60**

Table 6 shows the S-Score comparison between the Point Model and Area Model. In order to validate the model, several sets of historical datasets were used. The true area under the wetting balance curve was calculated to compare and validate the accuracy of the Area Model as described next. The area is integrated through a series of rectangles (.01 s (x-axis) per rectangle from $T_{(0)}$ to 10 s) and included only the positive part of the curve as shown in Figure 4. This operation was conducted by exporting the wetting balance cure raw data to Excel. Resulting graph and area comparison are shown in Figure 5 and Table 7.

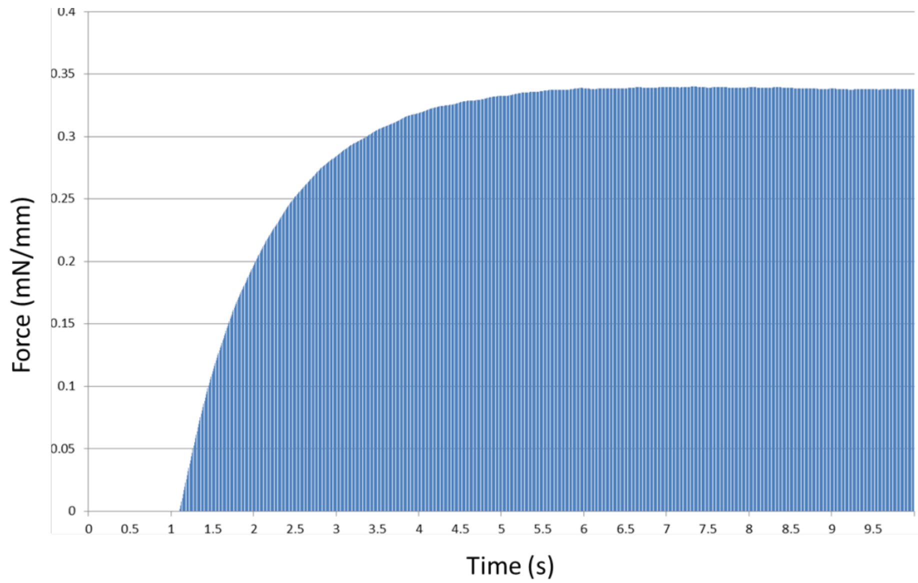

Figure 5 - Integration to acquire the true area under the wetting balance curve

Table 7 - Area Model verification

S-Score	Curve 1	Curve 2	Curve 3	Curve 4	Curve 5
Area Model	10.74	8.2	5.52	2.65	1.5
Integrated Area	10.39	8.02	5.36	2.53	1.41

The area calculated from the model using the three fundamental components is found to be less than 5% off of the true area under the wetting balance curve as shown in Table 7. This result indicates the model accuracy to be better than 95%.

Comparing the curve shapes and the three fundamental components, a generalized ranking of the S-Score result is shown in Table 8. The actual integration areas with same scaling factor are also listed in the table. It shows the area model is very close to the true area by integration. The scores from 9 and above are considered excellent wetting, and the good wetting ranges from the score 7 to 8. Both good and excellent ranking will yield good wetting behaviors during assembly process (colored green). The yellow color represents a fair wetting score (4-6) – it will still be adequate to wet but small percentage of detwetting may occur. There is high chance of dewetting in poor (red) region (0-3).

Table 8 - The S-Score ranking according to the Area Model

S-Score General Ranking Guideline					
Ranking	**$T_{(0)}$ (s)**	**$T_{(2/3)}$ (s)**	**$F_{(Max)}$ (mN/mm)**	**Area Model S-Score**	**Integration Area**
Excellent (> 9)	0.36	1.16	0.40	10.74	10.39
Good (7-8)	1.10	2.24	0.34	8.20	8.02
Fair (4-6)	0.52	1.53	0.21	5.52	5.38
Poor(2-3)	0.59	0.95	0.10	2.65	2.53
Very Poor (<2)	3.50	5.00	0.10	1.50	1.41

Summary

The Point and Area models have been discussed to quantify the wetting balance curve by utilizing all three fundamental components of the curves. The progress from point model to area model was made to better understand and utilize the wetting balance curve. The area model corresponds well with the area under wetting balance curve with high resolution. Using the area model, a Solderability Score (S-Score) from 0 to 10 was developed to quantitatively assess the wetting balance performance. The model results can be used as a reliable development tool to evaluate the existing product application as well as new product development with higher efficiency and accuracy.

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