**Wave Soldering**

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# Dwell Time and Immersion Depth Optimization For Immediate Defect Reduction

Studies in dwell time and immersion depth report significant opportunity for rapid improvement of wave solder repeatability and defect reduction.

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Production and process engineers have learned new insights to board-wave interaction, leading to dramatic changes in wave solder procedures. This has emerged only in the last several years, when technology was introduced which could directly measure your board's experience in your solder wave. Immediate and sharp improvements in board quality have been the result, propelling widespread acquisition of such technology.

This article discusses concepts of board-wave measurement and reports study results that employed commercially available technology to measure and respond to the key parameters of wave soldering. The purpose of the study was to determine the importance of dwell time and immersion depth measurement in wave solder quality.

By Martin Ingall and Nissim Sasson
Technology Information Corporation
204 Sportsman Way
Gaithersburg, MD 20878 USA
**1-240-631-6746**
Optimizer@WaveSoldering.com

### Centrality of Board-Wave Interaction

Your wave machine was built for only one purpose:  To cause your boards to interact with your solder wave.  You know this to be completely true; because when you look in your reflow oven you see no wave.  In the reflow oven, chemistry supports your boards as they experience temperatures.  However, this is not true for wave soldering.

In your wave machine, chemistry and temperatures are only supporting actors as they deliver your boards to your solder wave.  That is why your process window for temperatures in a wave machine is wide and forgiving in comparison to that of the surface mount oven, and why precise control of your board-wave interaction produces such large benefits.

Your leads are in the solder wave for only a few seconds or less.  Soldering is supposed to be achieved in a single pass and emerge defect-free.  Since this event is so brief and today's boards are so complex, your board must pass through your wave with precision.  Thoughtful engineers have learned that seemingly slight board-wave process variations can cause large quality variations.

### Limitations of Thermal Profiling

Many continue to adhere to the notion that wave solder process control is primarily about temperatures, and therefore choose to rely strictly on temperature stickers, pyrometers or thermal profiling.  While temperatures are important, they do not and cannot by their very nature address your board's interaction with your solder wave.

Wave soldering without accurate board-wave data is a sure prescription for consistent defects, production crises and downtime.  Experientially, production professionals understand this - they see the rework staff at their workstations and bear the brunt of management's goals for throughput and quality.

This is true despite Herculean efforts in thermal management, wonderful progress in wave solder machine quality, and the continuous development of flux and solder chemistries.  Yet ask a manufacturing engineer from where the majority of his assembly defects come and more often than not he'll point to his wave machines.

So, legions of rework staff work every day, every shift, solely to correct defects off the production line.  Rather than being viewed as compensatory activity for production failures and therefore something to be exorcised, current levels of rework are often deemed "acceptable" as part of the production process itself.  The net result, as we shall see here, is significant exaggeration of production costs and serious under performance in wave soldering.

For example, adjusting your preheaters can never eliminate bridging caused by too long a dwell.  Likewise for skipping caused by too shallow an immersion depth.  The study results presented here show that the majority of existing wave solder defects can only be eliminated through accurate, direct measurement and control of your board's interaction with the wave.

**Board-Wave Interaction**

Assuming that your board is parallel (a parameter also requiring accurate measurement) to your wave, board-wave interaction has three distinct, simultaneous facets that can be directly and accurately quantified:

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|---|---|---|
| 1. | Dwell Time | The amount of time a lead is in the solder wave. This needs to be controlled in one-tenth second increments. |
| 2. | Immersion Depth | How deep your board immerses in the solder wave. Since the very best waves have a wave height variation between 10 and 20 mil, this parameter is optimally gauged by its passage through a process window. The device used for this study employs 12 mil increments for this purpose. |
| 3. | Contact Length | The distance in which a lead passes through a wave. |

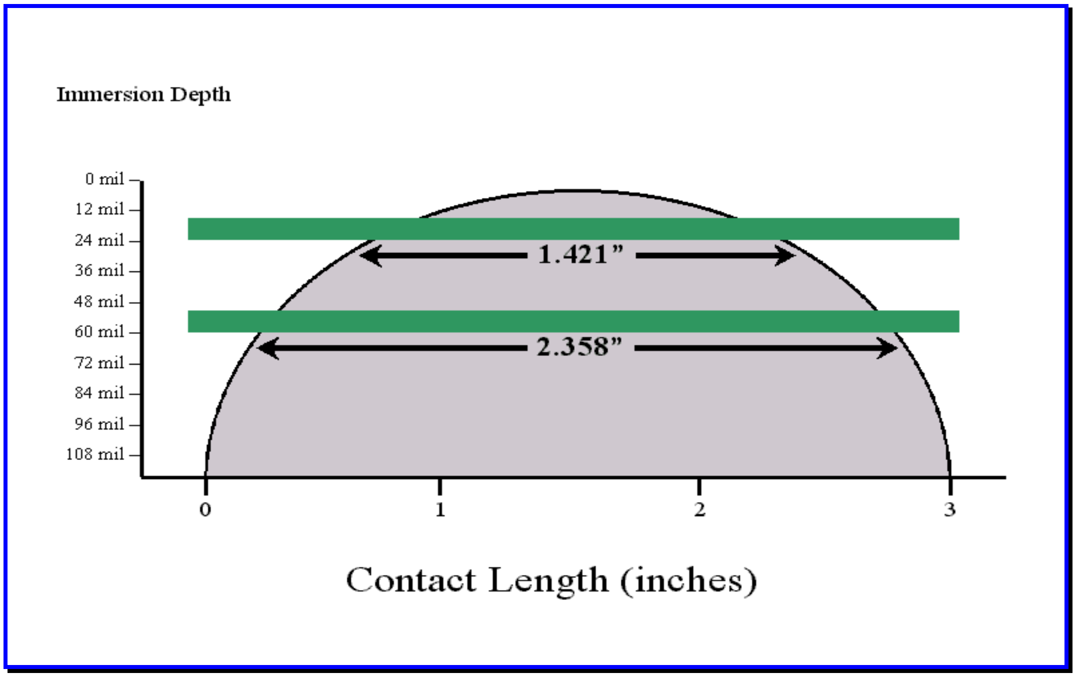


**Figure 1. Impact of immersion depth**

Figure 1 illustrates the interrelationship of immersion depth and contact length for your boards, showing that in fact your immersion depth directly determines contact length.

This in turn directly affects dwell time, since:

*Dwell Time = Contact Length ÷ Conveyor Speed*

What this means to the wave solder engineer is that your conveyor speed setting will not on its own control your dwell time in the wave. You must in fact have a means of accurately measuring and controlling your immersion depth as well.

## Wave Shape

Many of us have experienced the frustration of running an assembly on two different wave machines and seeing two very different board qualities emerge. Why do your wave machines produce different results when both are set at the same pump speed, conveyor speed, conveyor angle, solder pot height, preheat and solder temperature, are using the exact same chemistry, have the same maintenance schedules and show the same thermal profile?

As an industry, we have often retreated to accepting that "different wave machines have different personalities." Others blame operators. Yet the answer is often simple and measurable: All wave machines produce waves that are different shapes.

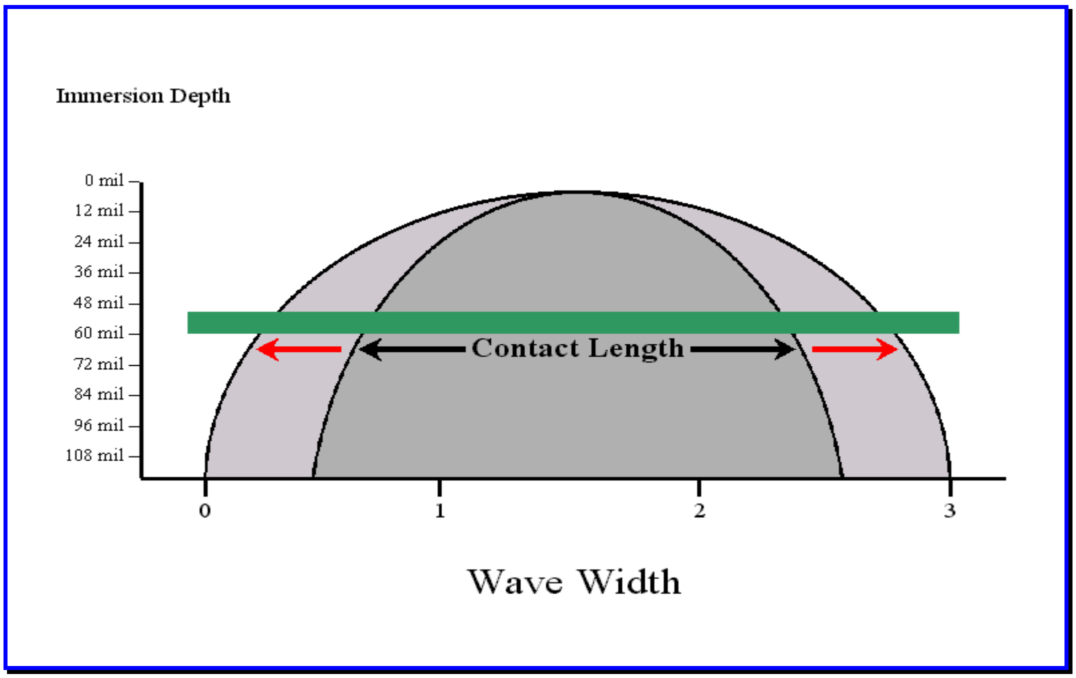


**Figure 2. Impact of wave shape**

Figure 2 shows the impact of wave shape on contact length. A wider wave will mean a longer contact length - and therefore dwell time - at the same immersion depth.

## Limitations of Machine Set-up

What this all means is that in order to control your wave process you need to directly measure what your board actually experiences in the wave. Wave machine settings can never assure repeatability. Your board does not see a conveyor speed; it does experience a dwell time. Likewise, your board does not know your pump speed; it experiences an immersion depth.

Also, your wave machine settings do not tell you the wave machine's variability. Therefore, parameters for wave soldering must be based primarily on guidelines for board-wave interaction, not wave machine settings.

Assembly plants need no longer blame their wave solder machines, flux or personnel when their real challenge is the wave solder process itself. Your wave machine does not even purport to measure your board-wave interaction.

Good equipment does not compensate for uncontrolled process. The best wave solder equipment in the world still requires a sound approach to process optimization and control.

**Dwell Time Baseline for Study**

A major consumer electronics company tasked one of its North American facilities to perform a month-long study to assess the significance of dwell time optimization and repeatability. The assembly with the greatest volume, representing 19% of all the boards produced at that location, was selected for the study.

For this purpose, the Wave Solder Optimizer was used as direct board-wave contact sensors are necessary for meaningful data. Capable of performing four runs in a row, the device offered the convenience of taking multiple readings before downloading the data to a PC. Also, the Optimizer's LCD display allowed the reading of data immediately upon its exit from the wave machine. Another important capability: Direct measurement of immersion depth. The following steps were performed:

Step 1 Parallelism was measured and established.

Step 2 Measurement of the board's current dwell time, which was 1.0 seconds.

Step 3 Measurement of the board's current immersion depth, which was 24 mil.

Step 4 Assessment of board quality, showing a defect rate at 312 ppm, a level considered normal at the facility despite the amount of rework being performed, and excellent by industry standards.

Step 5 Steps 1 through 3 were easily performed for three shifts in a row, twice per shift, since all data was obtained in a single run of the device through the wave machine. Step four was performed at the end of each shift.

If, prior to running the assembly, measurements showed a disparallelism, or a dwell time more than 0.1 second away from 1.0 seconds, or an immersion depth other than 24 mil, adjustments to the wave machine were made and additional measurements were taken to confirm that the desired board-wave experience was occurring. Areas unrelated to board-wave interaction were maintained throughout. These include, for example, flux types, preheat settings and solder temperature.

At the end of each shift, a ppm tally was made. Ppm's for this board were consistently at the 312 range. Hence, repeatability of board quality was achieved.

## Dwell Time Study Methodology

The next goal was to determine if the board's defect rate was affected by running it at different dwell times. This was achieved by running the same board type at different dwell times in half-second increments, from 0.5 seconds to 5.0 seconds, and correlating each dwell time with the defect rate it produced. Steps 1 through 5 above were followed at each dwell time.

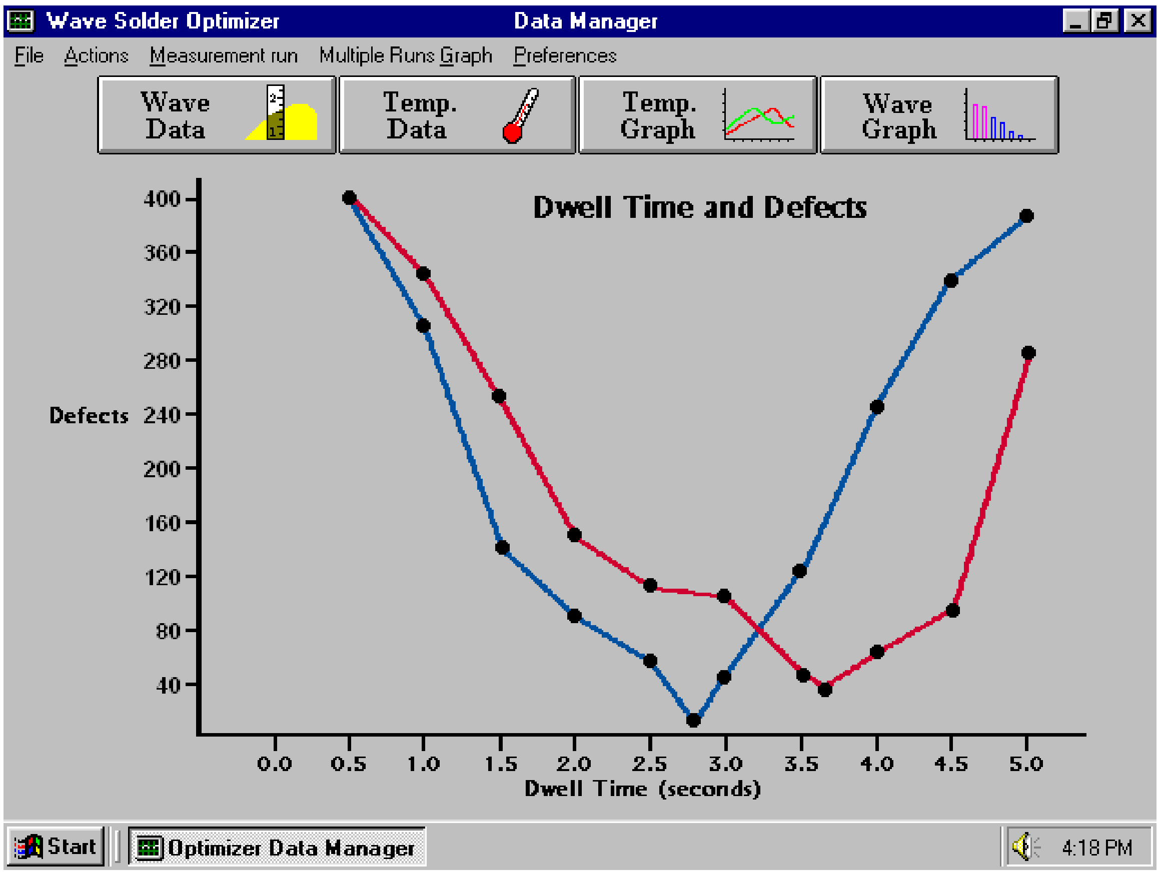


**Figure 3. The firsts study's dwell time and defect results**

The blue line of figure 3 shows the results. It was determined that the dwell time which produces the lowest defect rate for this particular board was between 2.5 and 3.0 seconds. Further study of this board was then performed. It was determined that defects are consistently lowest at 2.8 seconds. As a result, this board is now only run at the 2.8 second dwell time with 24 mil immersion depth. Machine settings are now incidental regardless of the wave machines being used. Optimization of dwell time was achieved, as was the flexibility to assemble the board on virtually any wave machine with predictable quality.

For the consumer electronics company, this has meant meaningful wave solder process documentation, clearer instructions to operators, greater flexibility since the board can now be run reliably through any wave machine, fewer spikes in the process control chart since measurements are made before boards are run, less downtime, higher throughput, reduced pressure on process engineers and happier management. As we all know, these are the natural results whenever specific process improvement procedures are successfully implemented.

Other observations:

1. What was discovered to be the optimal dwell time was significantly different than that which had been occurring but was heretofore unmeasured.

2. Defect rates vary sharply with different dwell times.

3. Controlling immersion depth was critical to this study, since varying immersion depths mean varying contact lengths and, as a result, uncontrolled dwell times.

## Quantifying Cost Benefits

Prior to this study, yield loss was tracked on a monthly basis as a measure of the cost of production failures. Production volume for the board studied was 11,000 per month.

- With the implementation of optimal dwell time procedures using the described device, yield loss went from 3.0% (330 boards) to 1.6% (176 boards) in the first month of daily use.

- This meant a reduction in yield loss of 154 boards per month. For a 30 day month, this means 5.13 boards per day.

- At $300 for the cost of each board, cost reduction based on improved yield loss alone was $46,200 per month, which annualizes to $554,400.

- That means that the return on investment on the device used in the study was less than five days.

Conclusion: A seemingly small daily improvement in wave solder quality meant fast, very large, measurable monthly and annual cost savings. These figures do not even account for the valuable savings from benefits like reduced rework and field failures, less downtime and increased throughput, each of which in its own right can be more valuable than the rapid savings on yield loss.

## Board-by-Board Optimization

Just as each board type enjoys its own thermal profile in your surface mount oven, each board type also enjoys its own *board-wave* parameters in your *wave machine*. Hence, the above study was also performed for a second board type.

The results are recorded as the red line in figure 3. The optimal dwell time for that board was found to be 3.6 seconds, in contrast to 2.8 seconds for the first board. As you can see, the “dwell time profiles” of the two boards are different. This process resulted in dramatically lower defect rates for the second board studied (which had also been previously run at 1.0 seconds), although never quite as low as the new baseline which was attained for the first board. This strongly indicates the presence of sources of defects unrelated to dwell time, for example non-optimal immersion depth or design problems.

## Immersion Depth

Changing your immersion depth changes your contact length and dwell time. This makes the direct and accurate measurement of immersion depth critical. Your pump speed produces a wave height (although this can diminish as your solder pot empties of solder), but the actual immersion depth of your boards depends on several factors, including solder pot height, how they sit in the fingers, if your fingers are bent, broken or crooked, the angle of your conveyor and whether or not pallets are used.

Yet controlling your immersion depth - measuring it and keeping it consistent - is only one piece of the puzzle. Another is: At which immersion depth is your board quality optimized?

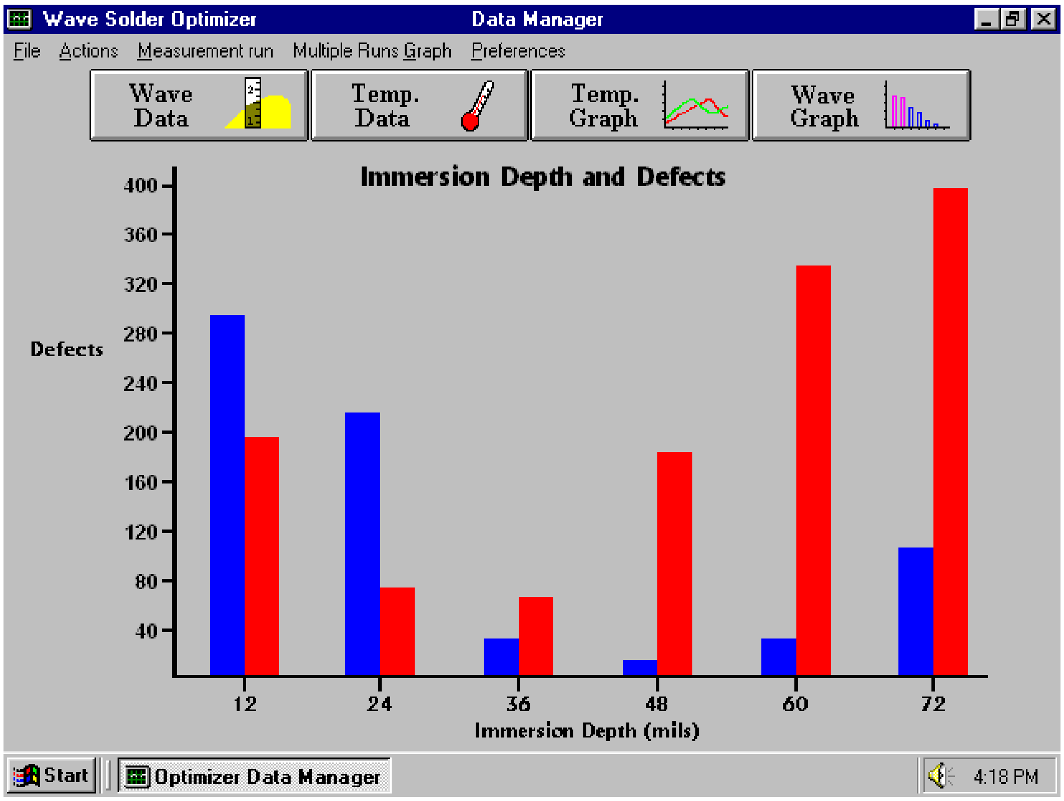


**Figure 4. The second study's immersion depth and defect results**

This point is illustrated by figure 4 above. See that the defect rate of the board represented by the blue bars is optimized over a different range (48 mil, or even 36 to 60 mil) than the board represented by the yellow bars (at 24 to 36 mil). So, different board types benefit most from different immersion depths.

## Conclusion: Prescription for Optimization

The benefits of board-wave optimization are significant, and call for a board-by-board assessment when determining wave solder guidelines. Direct measurement and management of what your boards are actually experiencing is the key. Using the same wave machine settings for all boards can never produce optimal wave solder results across a range of assembly types, and reliance on wave machine settings does not ensure repeatability of board-wave interaction.

Optimization requires adjustments that are correlated with the actual defects on the board. Just recording the machine setting will not produce the results you want; neither will exclusive focus on your board-wave data. As we already know, wave machines are not necessarily repeatable. If they were we would have already found the right settings and have no defects or even spikes in defect rates.

Getting started is simple. It will only take literally a few minutes and produce information that will help you immediately:

1. Set your wave machine as you always would for the board with which you are concerned.

2. Once you have established board-to-wave parallelism, make note of your dwell time and immersion depth readings by using a device like the one described in this article.

3. Run one of your boards and make note of its wave solder quality.

4. As a first step toward identifying your optimal dwell time, decrease your conveyor speed 0.75 feet per minute and run the device again to obtain your new dwell time reading.

5. Run one of the same board types again and make note of its wave solder quality.

If your board quality improved that means that you have identified a dwell time that is superior to that at which your have been running your boards. You can now take dwell time readings every day prior to each run of this board type, to ensure that your wave machine is delivering the desired, superior experience to your boards. Hence, you use the data to assure and document BOTH repeatability AND optimization.

If your board quality became worse, then increase your conveyor speed and follow the same procedure. You will quickly identify your optimal board-wave interaction parameters. To assess the impact of immersion depth on your wave solder quality, vary your pump speed and otherwise perform the same procedure.

Another critical aspect to understand is process windows. All wave machines have their own normal range of data variance and repeatability. This can only be identified by repeating direct measurement of dwell time and immersion depth while the machine is kept at each setting you use. Understanding your wave machines' process windows for dwell time and immersion depth (and parallelism for that matter) will help you to optimize your wave solder process for each board you run.

If you are a high mix shop, start with your most common or most troublesome boards. For high volume, low mix operations, you have the opportunity to optimize each board you run. For both types of facilities, there is the added flexibility of reliably moving production of a particular board between different wave machines and even plant locations.

Numerous facilities have combined commercially available technology with simple procedures to optimize their boards' dwell times, control immersion depth and enjoy true repeatability of their wave solder process. Facilities that want to cut costs quickly and keep pace with industry norms for wave solder quality will embrace the technology and implement the procedures reported here.

A shorter version of this study appeared in *Circuits Assembly* magazine.