Measuring the True Wetting Time of Solders

Masato Nakamura, Keith Sweatman, Masuo Koshi, & Tetsuro Nishimura
Nihon Superior Co., Ltd.

Abstract
As the electronics industry prepares to meet the requirements of the European Community's RoHS directive on lead in electrical and electronic equipment an issue about which concern is frequently expressed is the apparently inferior wetting performance of lead-free solders. The general observation is that lead-free solders are slower to wet and then do not spread far beyond the area of direct contact. There is also much discussion of the relative merits of various lead-free solders in terms of their wetting time, which is usually reported as the time from first contact of the sample with molten solder to the time at which the net force on the sample is zero. However, the performance of some lead-free solders in this wetting balance test has been found not to correlate with their practical performance in soldering processes; an alloy with what appears to be inferior performance in the wetting balance test performs better in actual production soldering than an alloy that had a better result in the wetting balance test. In the work reported in this paper the data that emerges from a wetting balance test was studied in detail. It was found that the result of the wetting balance test could be correlated with the performance of the alloy in production soldering only if the force vs time plot is analysed in terms of five distinct stages with the performance of the alloy as a solder correlating best with time taken for the force to increase from its maximum negative value to zero and then to the maximum wetting force.

Introduction
The way in which a liquid interacts with a solid surface is important in many fields of science and technology. The underlying physical force that is in play in this situation is surface tension but while that force can be measured in most industrial applications the main interest is in finding answers to some very practical questions:

- Does the liquid wet the surface?
- If it does wet how quickly does it wet?
- If it does wet how strongly does it wet?

In all of these fields the wetting balance has found application as a basic tool for studying these liquid solid interactions.

The wetting balance test itself is simple in concept (Figure 1). A test piece is fixed vertically on a sensitive electronic balance and a container of the liquid of interest is raised vertically to immerse the test piece until the area of interest is level with the surface and held in that position until wetting is complete (usually within 5 seconds). As surface tension forces pull a meniscus above the surface of the liquid the weight of this meniscus creates a downward force. This force, typically measured as the displacement of a high modulus spring measured by a Linear Variable Differential Transformer (LVDT), is recorded as a function of time. Traditionally a chart recorder is used for that purpose but more commonly now the data is collected in digital format so that it can be more easily analysed by computer. Conventionally a downward force on the test piece is plotted as positive since that is the direction of the desired wetting force; if wetting is good the test piece should be pulled down strongly into the liquid. Ideally, to facilitate analysis of the wetting balance data the test piece should be of constant cross-section in the direction of immersion.

There are several possible outcomes to the wetting balance test each of which reveal something about the nature of the interaction between the liquid and solid surface of interest.

The first force on the test piece as it is immersed in the liquid is the buoyancy which Archimedes realised is equal to the weight of the liquid displaced. If the cross-section of the test piece is uniform along its length and the speed of immersion constant with no wetting occurring during immersion the first part of the wetting balance curve is a straight line. If no wetting occurs then that is the end of the test (Figure 2a).

If the liquid starts to wet the surface immediately the force-time relationship during immersion will not be linear and the maximum potential buoyancy force is never reached (Figure 2b).

In the case of the wetting of an initially room temperature substrate by molten solder, wetting cannot proceed until the substrate has reached a temperature sufficiently above the melting point for wetting to occur. Thus there is a period after the completion of immersion before wetting can begin (Figure 2c). This delay before the onset of wetting is the incubation period- the time over which certain processes that create the prerequisites for wetting occur.

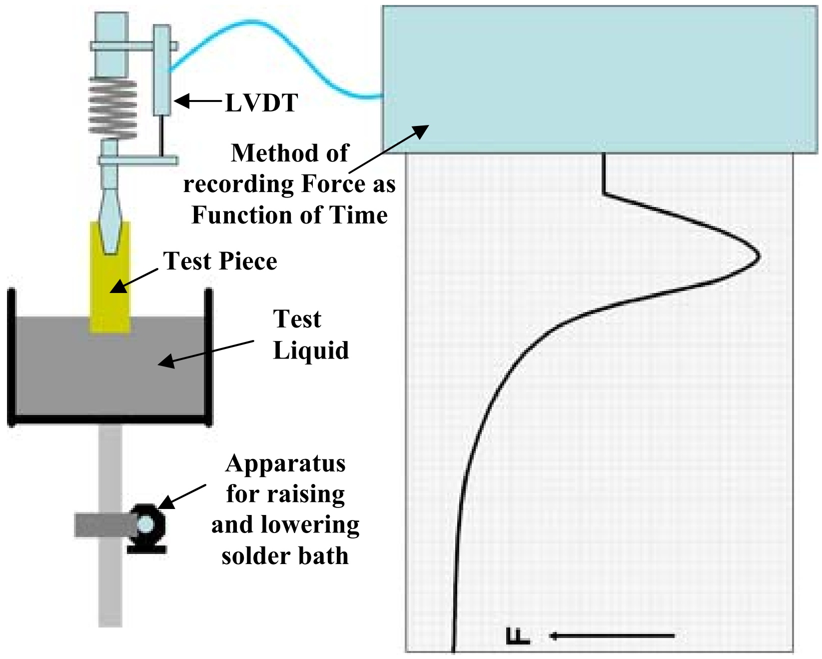


Figure 1. Basic wetting balance test set up.

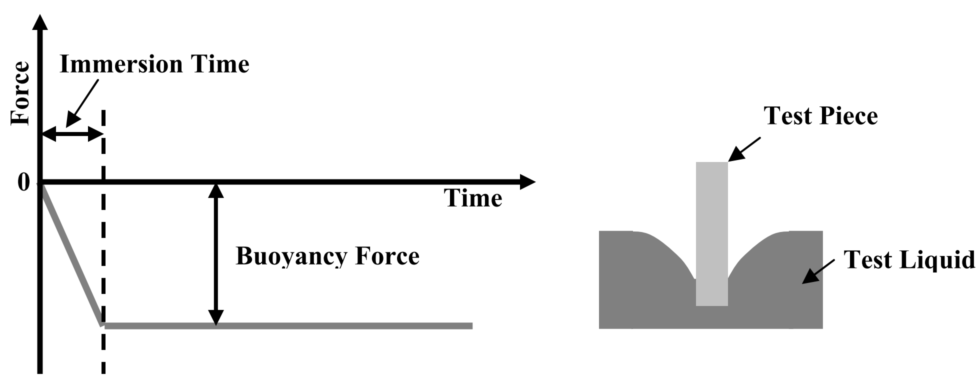


Figure 2a. Wetting balance test force-time plot in the case of complete non-wetting

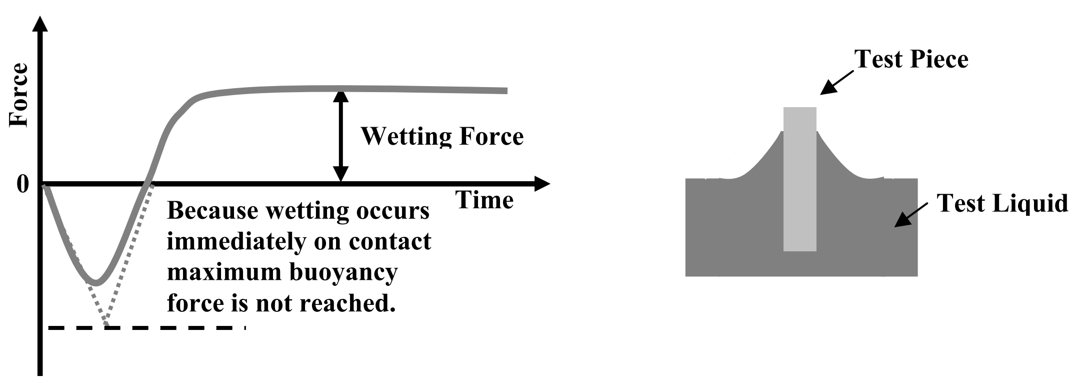


Figure 2b. Wetting balance test force-time plot in the case where wetting occurs immediately.

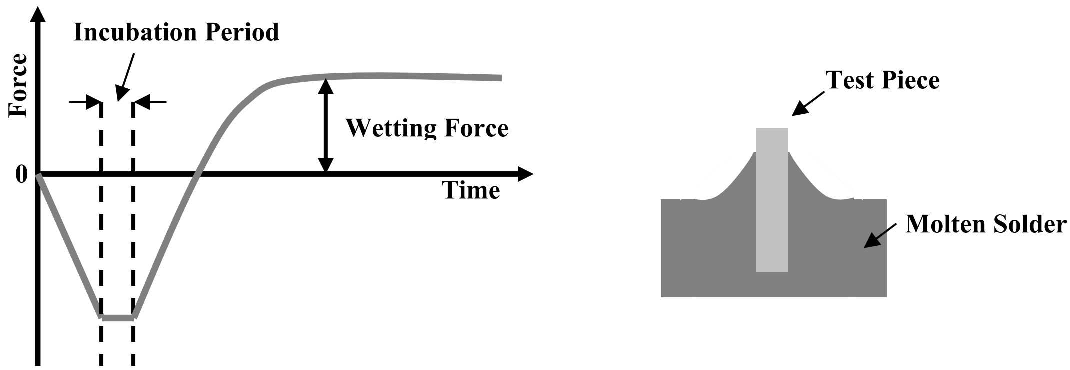


Figure 2c. Wetting balance test force-time plot in the case where wetting cannot occur until the test piece reaches soldering temperature

The Application of the Wetting Balance Test in Soldering Technology
The efficient achievement of reliable solder joints in electronics assembly processes requires that, however it is applied to the joint, with a soldering iron, wave soldering, selective soldering or reflow of solder paste, the solder wets the joint quickly and completely.

The wetting behaviour in a soldering process is affected by many factors:

- The chemistry and metallurgy of the solder alloy
- The chemistry and metallurgy of the substrate to be wetted
- The activity of the flux used to clean and protect the solder and substrate surface
- The atmosphere in which the test is undertaken.
- The temperature of the solder

By holding all the other variable constant the remaining variable can be studied. For example if the solder, substrate, atmosphere and solder temperature are held constant the wetting balance can be used to compare fluxes of different formulations. At this time when the electronics industry is obliged to select lead-free solders to replace the tin-lead solders that have effectively been banned by the EU RoHS Directive, the other variables can be held constant and the wetting characteristics of various candidate lead-free solders compared.

The wetting balance test provides measures of the two key properties of interest:

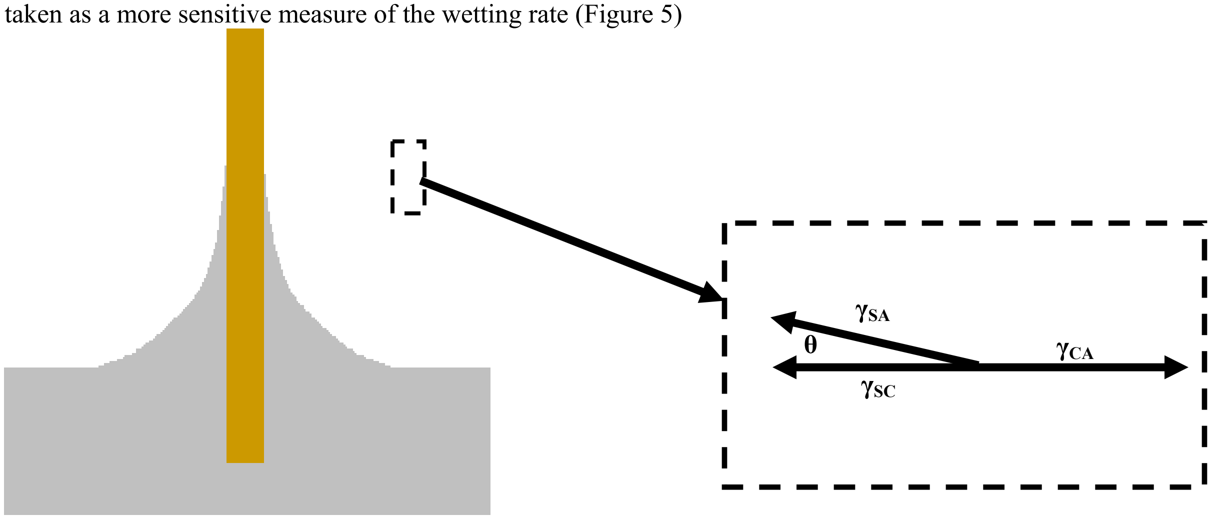
- The degree of wetting
- The speed of wetting.

The degree of wetting is indicated by the wetting force. This maximum wetting force is the strength with which the solder is being pulled onto the substrate and is the result of the balance of surface tensions known as Young's Equation (Figure 3). Hwang (1) has pointed out that for wetting to occur:

$$\gamma_{CA} > \gamma_{SC} + \gamma_{SA}\cos\theta$$

Strictly speaking, when measuring the wetting force a correction has to be made for the buoyancy force on the immersed part of the specimen. Since it is acting in the opposite direction to the wetting force that is tending to pull the test piece into the solder the effective zero is displaced downwards (Figure 4). The buoyancy force can be estimated by multiplying the immersed volume (cross-sectional area of the test piece x depth of immersion) by the density of the molten solder. Since in this study it is the rate of wetting rather than the wetting force that is of interest the buoyancy force will not be taken as negligible. In fact its magnitude does not directly affect the proposition presented in this paper.

The <u>speed</u> of wetting is indicated by the time taken for the wetting force to increase from the maximum negative buoyancy force at the time when the immersion of the test piece is complete. Conventionally the wetting speed is measured as the time from the first contact of the test piece with the molten solder until the maximum wetting force is reached (Figure 5). Because it can be difficult to determine exactly when the curve levels off the wetting time is often taken as the time for wetting force to reach a more easily defined point, e.g. half or two thirds of its maximum value (Figure 5). Time to zero-crossing, i.e. the point at which the meniscus had just climbed back to its horizontal starting point when the immersion began is sometimes taken as a more sensitive measure of the wetting rate (Figure 5)



Young's Equation

$$\gamma_{CA} = \gamma_{SC} + \gamma_{SA}\cos\theta$$

Where
γ_{CA} = surface tension of copper/atmosphere interface
γ_{SA} = surface tension of solder/atmosphere interface
γ_{SC} = surface tension of solder/copper interface
θ = contact angle

Figure 3. Young's equation as it applies in the wetting balance test.

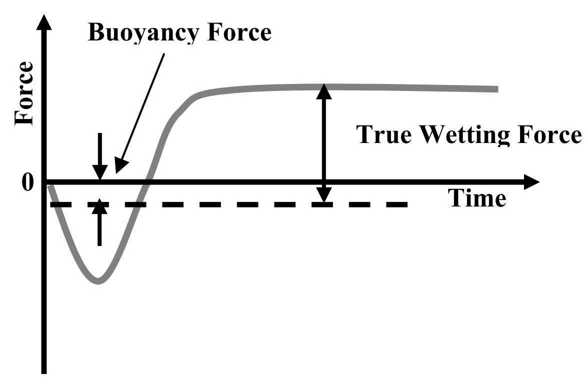


Figure 4. Correcting the wetting force for the buoyancy force on the immersed test piece

If the time that the test piece first contacts the solder is taken as the starting point, whichever of the three conventional methods of measuring wetting time are used, included in that total are three quite distinct physical processes (Figure 6):

- Immersion
- Incubation
- Wetting

During the incubation period there are at least two things happening.

- The flux is working on the surface of the test piece removing oxides and exposing the underlying metal which the solder must contact for wetting to occur.
- The test piece is being heated to the temperature required for wetting to occur.

For the purposes of this paper the flux action is taken as a constant and the point of interest is the time taken to get the test piece to soldering temperature. The determinants of the incubation period are, therefore:

- The temperature of the solder
- The melting point of the solder

The hotter the solder in the wetting balance the faster will be the heating. The higher the melting point of the solder, the hotter the test piece will have to be before the solder in immediate contact with it is molten and able to wet. Thus if the wetting time is measured from the time at which the test piece first contacts the solder these two factors additional to the actual rate of wetting are affecting the reported wetting time.

The effects of those two factors, solder temperature and the melting point, on the wetting balance curve are similar in that they affect the incubation period before wetting commences but in opposite directions (Figure 7)

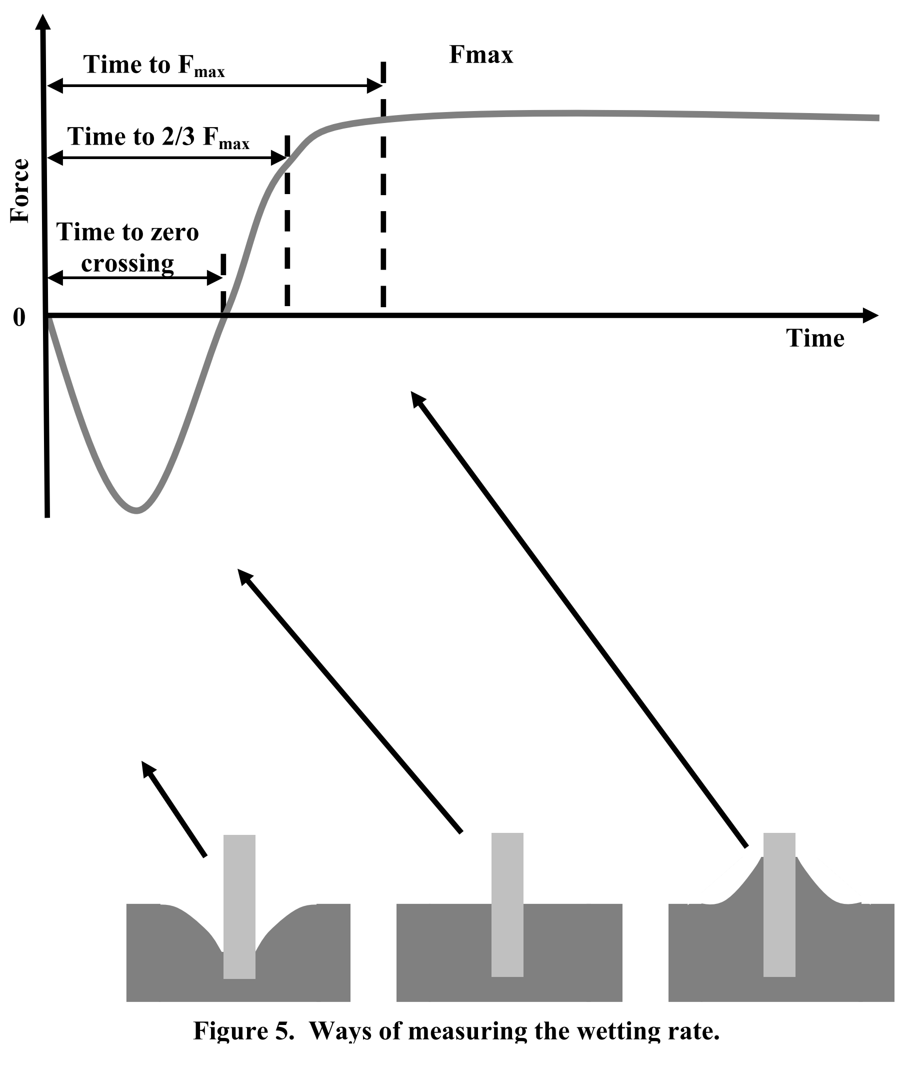


Figure 5. Ways of measuring the wetting rate.

Measuring the True Wetting Time

While wetting balance test data can be very useful in studying properties of solders and fluxes and component and printed circuit board finishes relevant to soldering processes, in its conventional form it does not simulate what typically happens in production soldering. In particular there is no provision for the preheating that is a normal part of wave, selective and reflow soldering processes. For example, in a production soldering process an incubation period that was so long as to significantly interfere with the process would be dealt with by preheating the joint substrates or by increasing the solder temperature. In both cases the increase in the temperature to which the assembly is exposed during the soldering process is relatively small and is unlikely to compromise the reliability of the circuitry. In fact the reliability is likely to be enhanced because of the better quality joints that are formed when the solder wets well.

What cannot be so easily dealt with is the intrinsic wetting behaviour of a solder after the joint assembly has reached the optimum soldering temperature for that particular solder alloy. This is where real differences in the rate and quality of wetting distinct from melting point differences become apparent. It is, therefore, the contention of the authors of this paper that when analysing the data from a wetting balance test the wetting time considered when assessing the properties of a particular solder alloy and optimising a process should be measured not from the time that the test piece contacts the solder but from the time that wetting commences (Figure 8). These true wetting times are not affected by heating rates that can be adjusted in practical soldering but by the actual wetting properties of the solder in relation to the test piece surface.

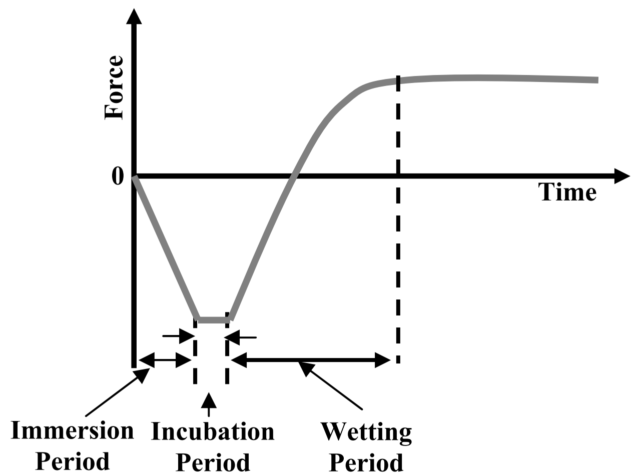


Figure 6. The three components of a wetting time measured from the time that the test piece first contacts the solder.

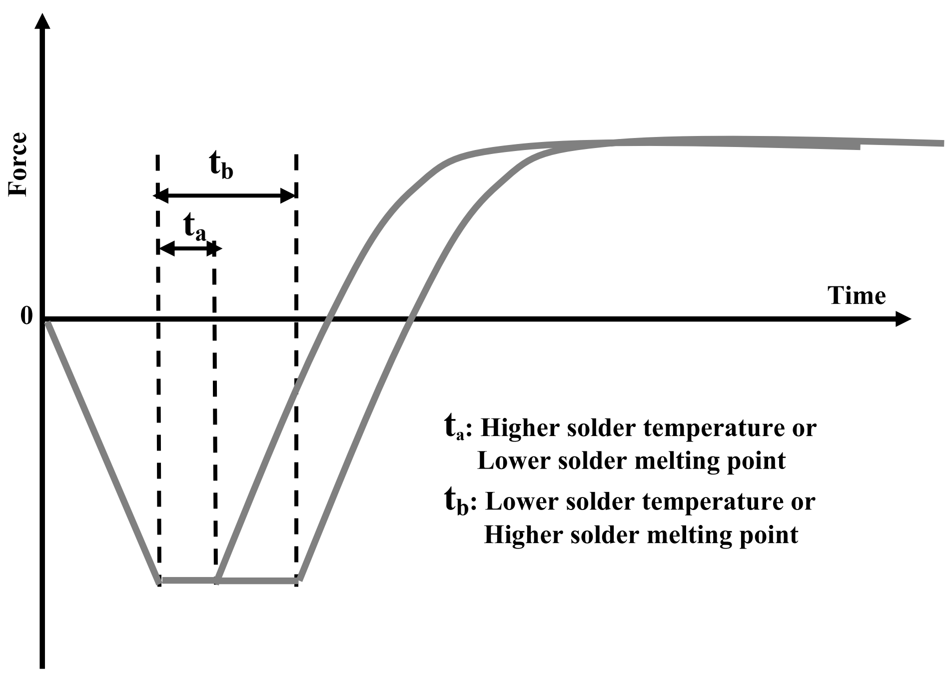


Figure 7. Effect of solder temperature and solder melting point on the incubation period in a wetting balance test.

Comparing the Wetting Rates of Some Practical Lead-free Solders
To determine the effect of this alternative measurement method on the ranking of some widely used lead-free solders wetting balance tests were carried out on the wetting balance pictured in Figure 9. The two solders tested were the Sn-3.0Ag-0.5Cu alloy that is widely known as SAC305 and the Sn-0.7Cu+Ni+Ge alloy patented by Nihon Superior Co., Ltd and marketed under the name "SN100C". Test parameters are set out in Table 1. Results, which are the average of three readings, are set out in Table 2 and plotted in Figure 10.

Although the total wetting time from the point of contact of the test piece with the solder until the wetting force reaches two thirds of the maximum wetting force is shorter for the Sn-3.0Ag-0.5Cu alloy, when measured from the point of onset of wetting the wetting time of the Sn-0.7Cu+Ni+Ge alloy is shorter by 25%. This is consistent with the observation in practical soldering that the Sn-0.7Cu+Ni+Ge alloy wets and flows better than the Sn-3.0Ag-0.5Cu alloy.

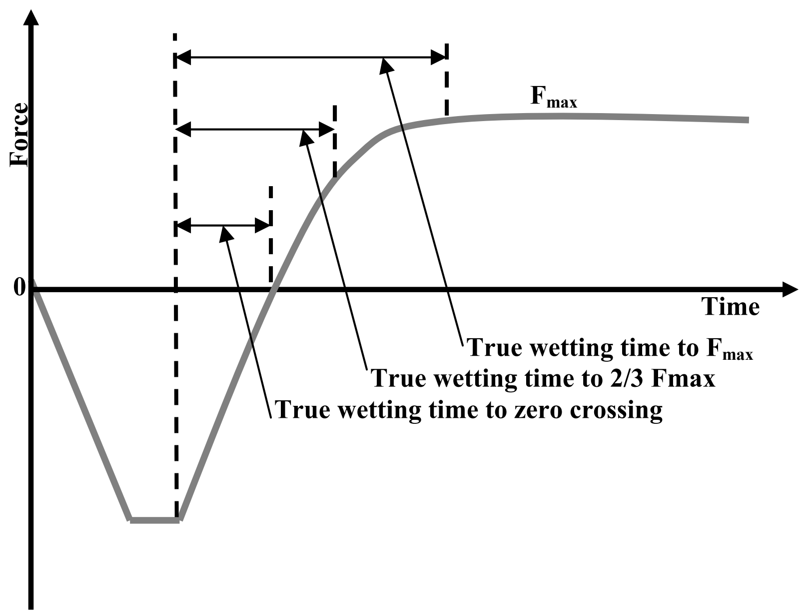


Figure 8. Options for measuring the true wetting time

Figure 9. Wetting balance test apparatus

Table 1. Analysis of wetting balance curve for two lead-free solders

Wetting Balance Test Parameter	Time (sec)		Ratio
	Sn-3.0Ag-0.5Cu	Sn-0.7Cu+Ni+Ge	(Sn-0.7Cu+Ni+Ge)/(Sn-3.0Ag-0.5Cu)
t_1: Immersion Period	0.50	0.50	100%
t_2: Incubation Period	0.03	0.62	2067%
t_3: Interval to Zero Wetting Force	2.25	1.77	79%
t_4: Interval to 2/3 Fmax	2.35	1.7	72%
Start of Wetting (t_1+t_2)	0.53	1.12	211%
Zero Crossing Time ($t_1+t_2+t_3$)	2.78	2.89	104%
Total Wetting Time ($t_1+t_2+t_3+t_4$)	5.13	4.59	89%
Total Time since Start of Wetting (Total Wetting Time -(t_1+t_2))	4.60	3.47	75%

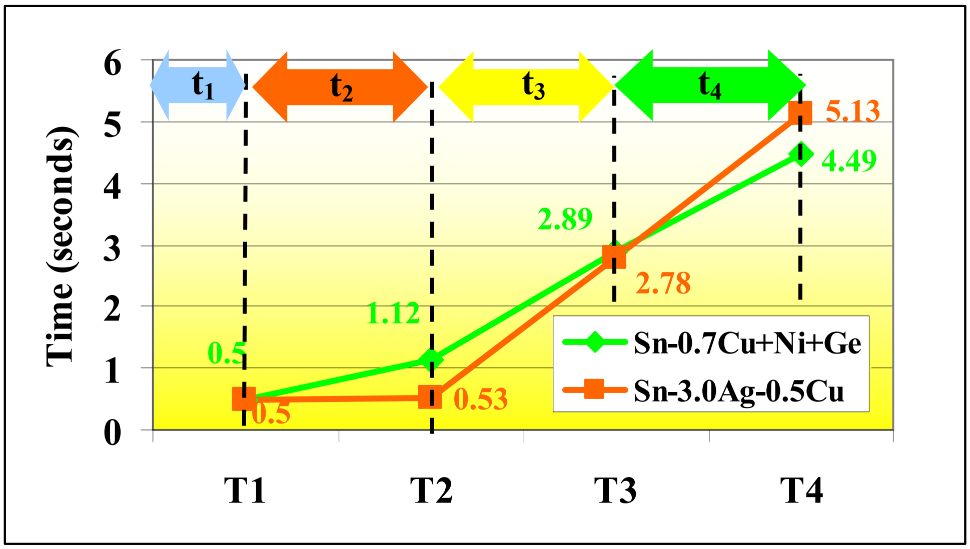


Figure 10. Plot of the individual components of a wetting balance curve

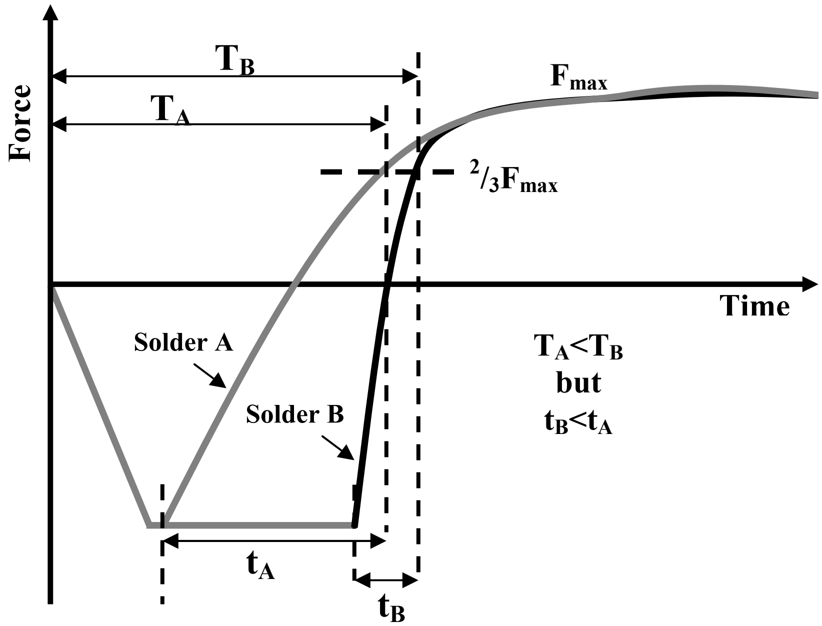


Figure 11. The relative ranking of solders A and B in regard to wetting time is reversed when the wetting rate is measured from the onset of wetting rather than from the time when the test piece first contacts the solder

Conclusions

Analysing the wetting balance curve to find true the wetting time provides a more correct impression of the wetting behaviour of the solder that is so important in the soldering processes of electronics assembly. In the hypothetical example in Figure 11 the ranking of solders A and B in regard to wetting speed is reversed when the true wetting time is considered rather than the total wetting time.

The information that can be extracted from a wetting balance test that is of greatest value in comparing solders and, most importantly in optimising a soldering process is the rate of wetting during the period from the onset of wetting to the achievement of maximum wetting force.

References

1. Jennie S Hwang, "Modern Solder Technology for Competitive Electronics Manufacturing", McGraw-Hill, 1996. p 148.

NIHON SUPERIOR

Measuring the True Wetting Time of Solders

Masato Nakamura,
Masuo Koshi, Keith Sweatman &
Tetsuro Nishimura
Nihon Superior USA

Objective

To present that case that:

- **In interpreting wetting balance test results**
- **And, in particular, when comparing the wetting rates of different alloys**

It is essential that account be taken of the melting points of the alloys

Justification

As part of normal process optimization differences in melting point can be compensated for by adjustment of:

- Preheat settings in wave soldering
- Thermal profiles in reflow soldering

Agenda

1. Introduction
2. The Wetting Balance Test
3. Interpreting the Results
4. The Test
5. Test Results
6. Conclusion 1
7. Recommendation
8. Conclusion 2

Introduction

The Wetting Balance Test

Introduction

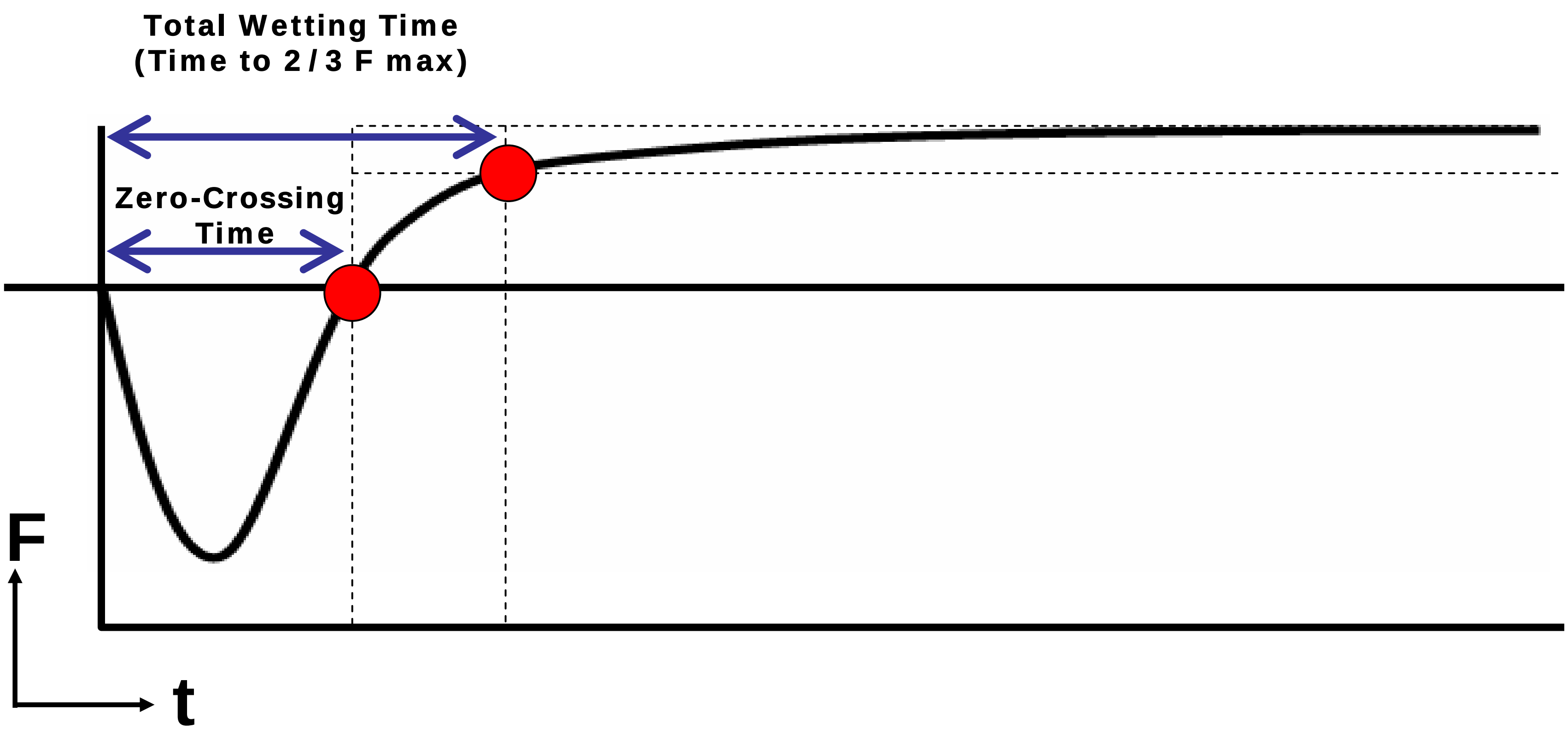
The wetting balance can be used in three general ways:

1:Fix the substrate and the flux and look at the wetting properties of a solder

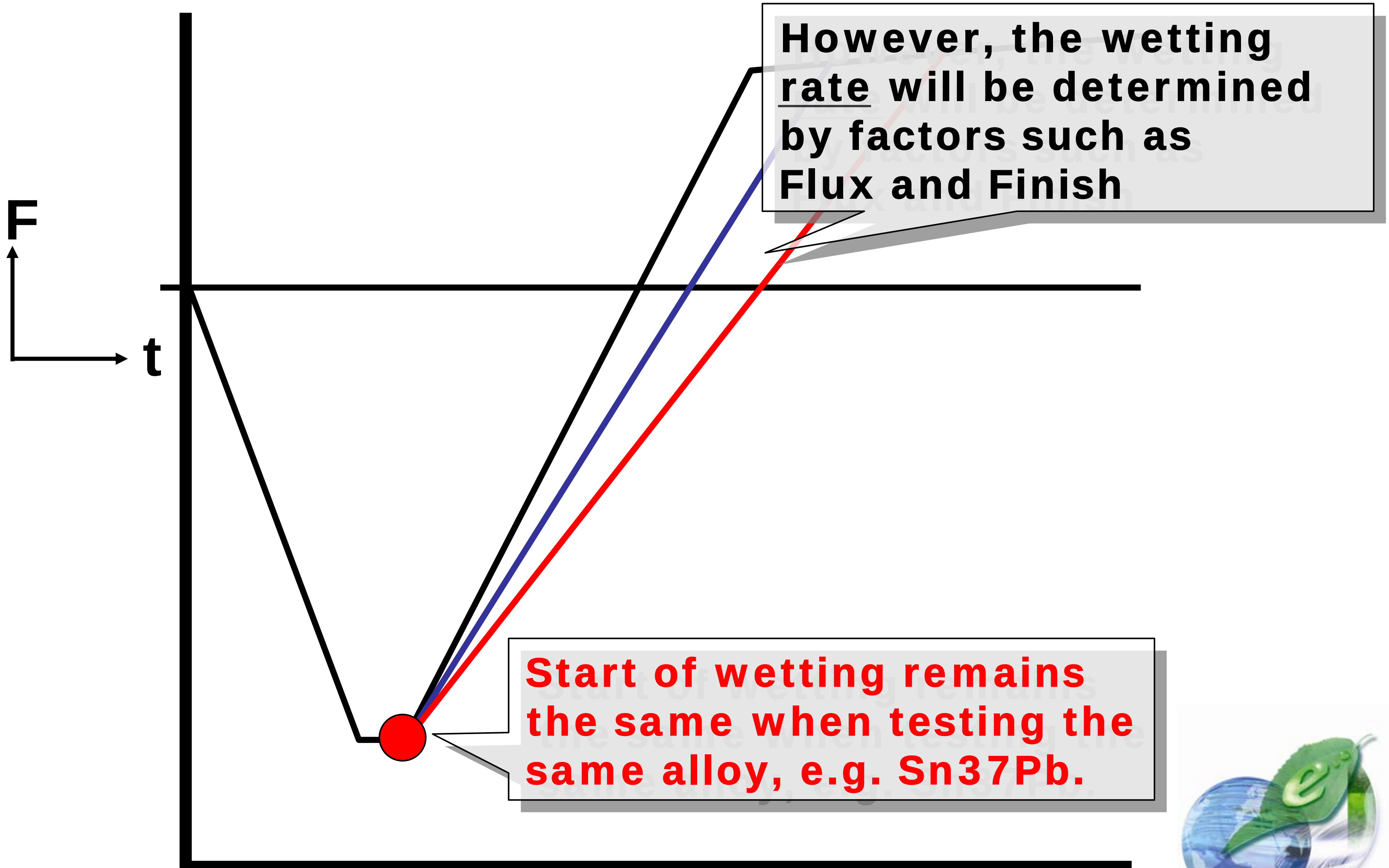
2:Fix the solder and the flux and look at the solderability of a substrate

3:Fix the solder and the substrate and look at the effectiveness of a flux

The Wetting Balance Curve



Wetting Rate for A Particular Alloy



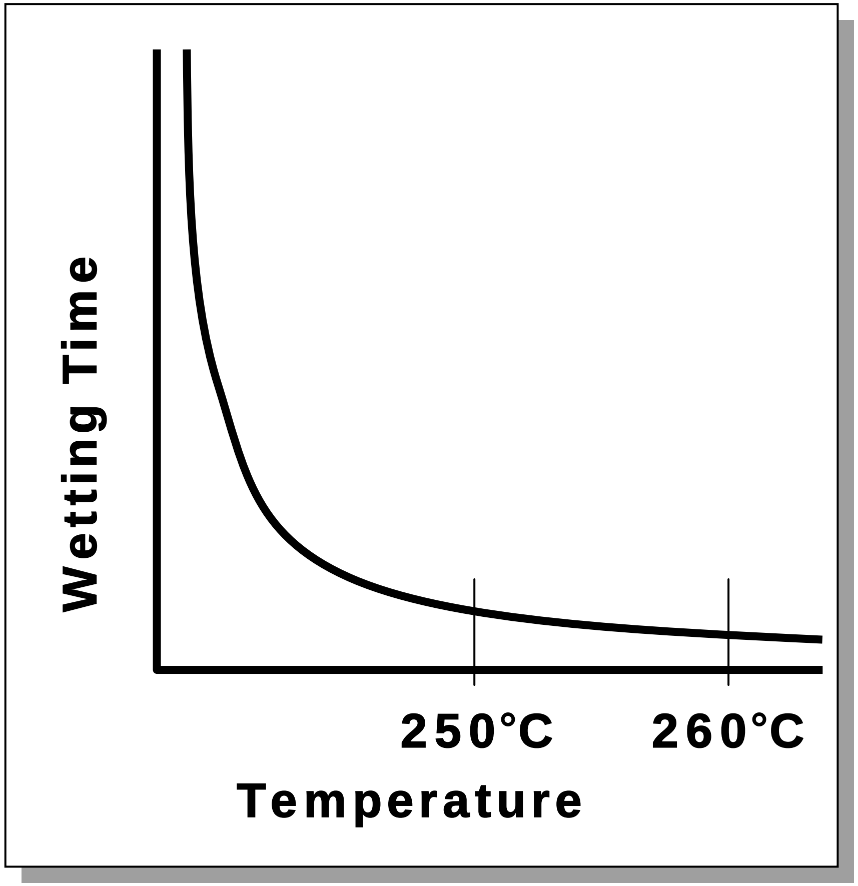
Zero-Crossing & Total Wetting Time

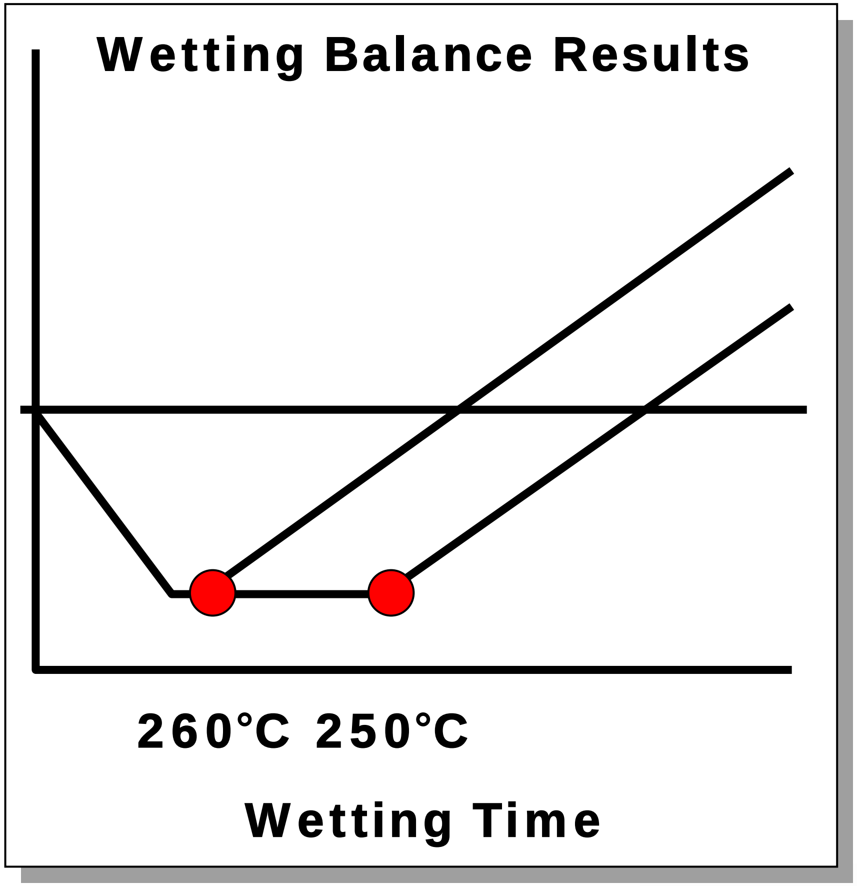
"Zero-crossing Time" & "Total Wetting Time" can be used for comparing the wetting properties of solder <u>only when testing solders that have the same melting point</u>.

The Wetting Balance Test

Interpreting the Results

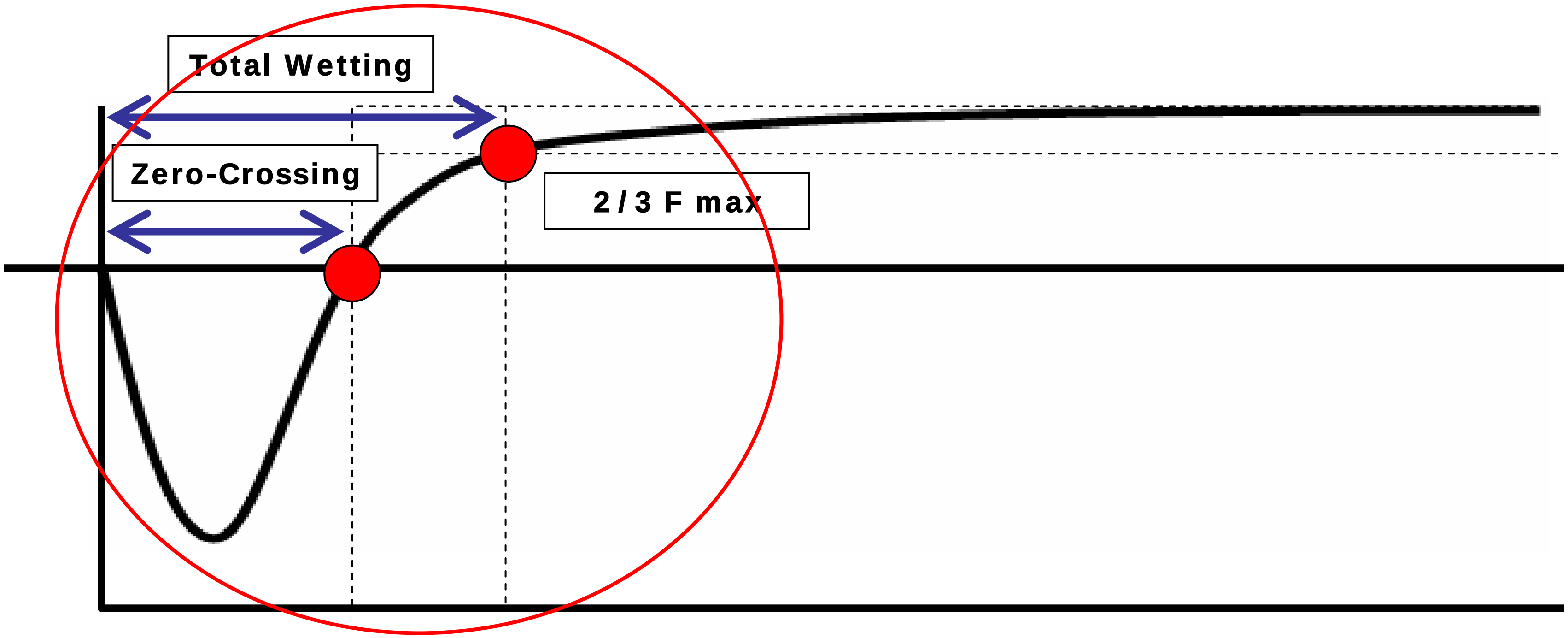
Interpreting the Wetting Balance Curve



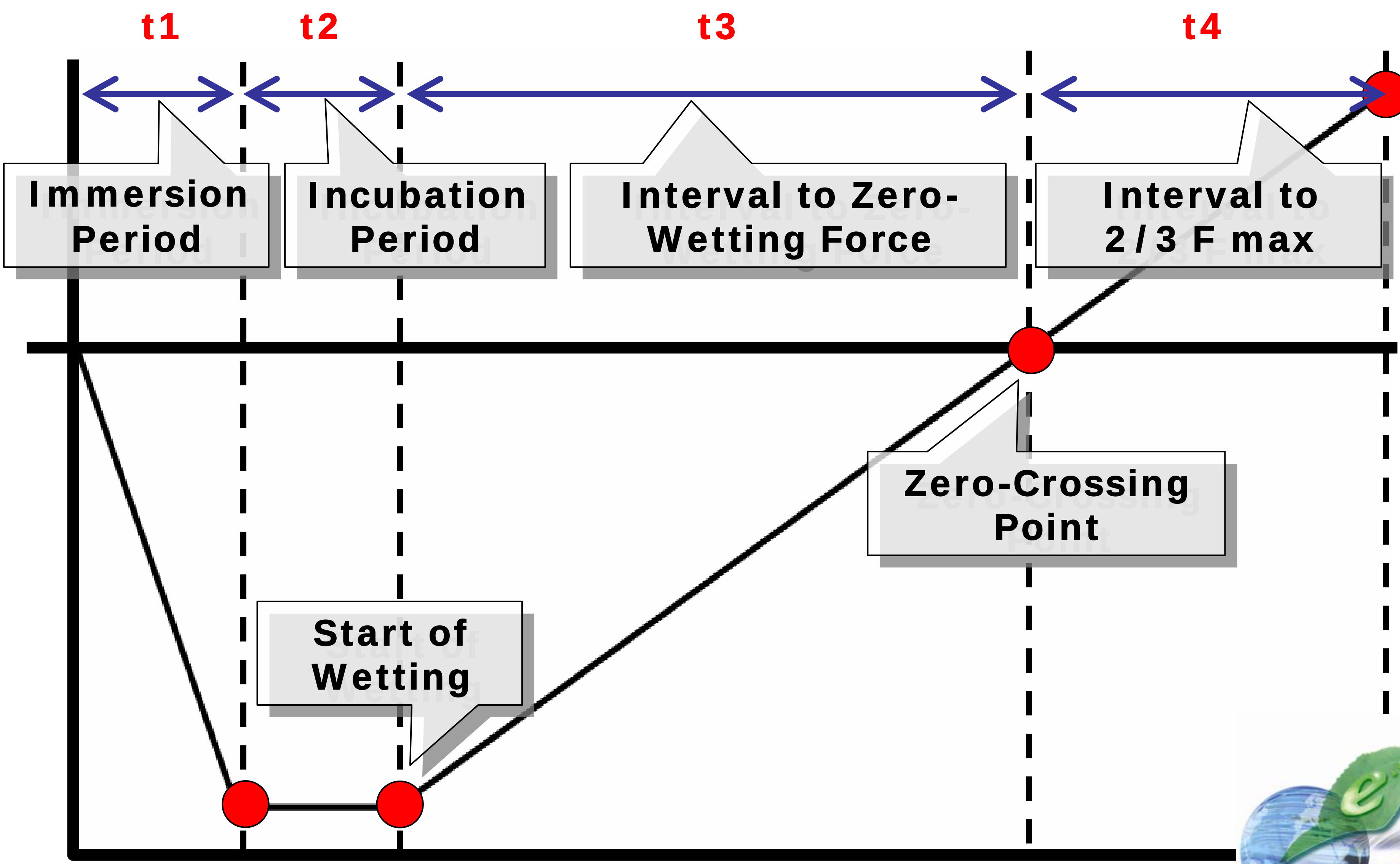


Even the same solder would yield a different result if a different solder temperature were used.

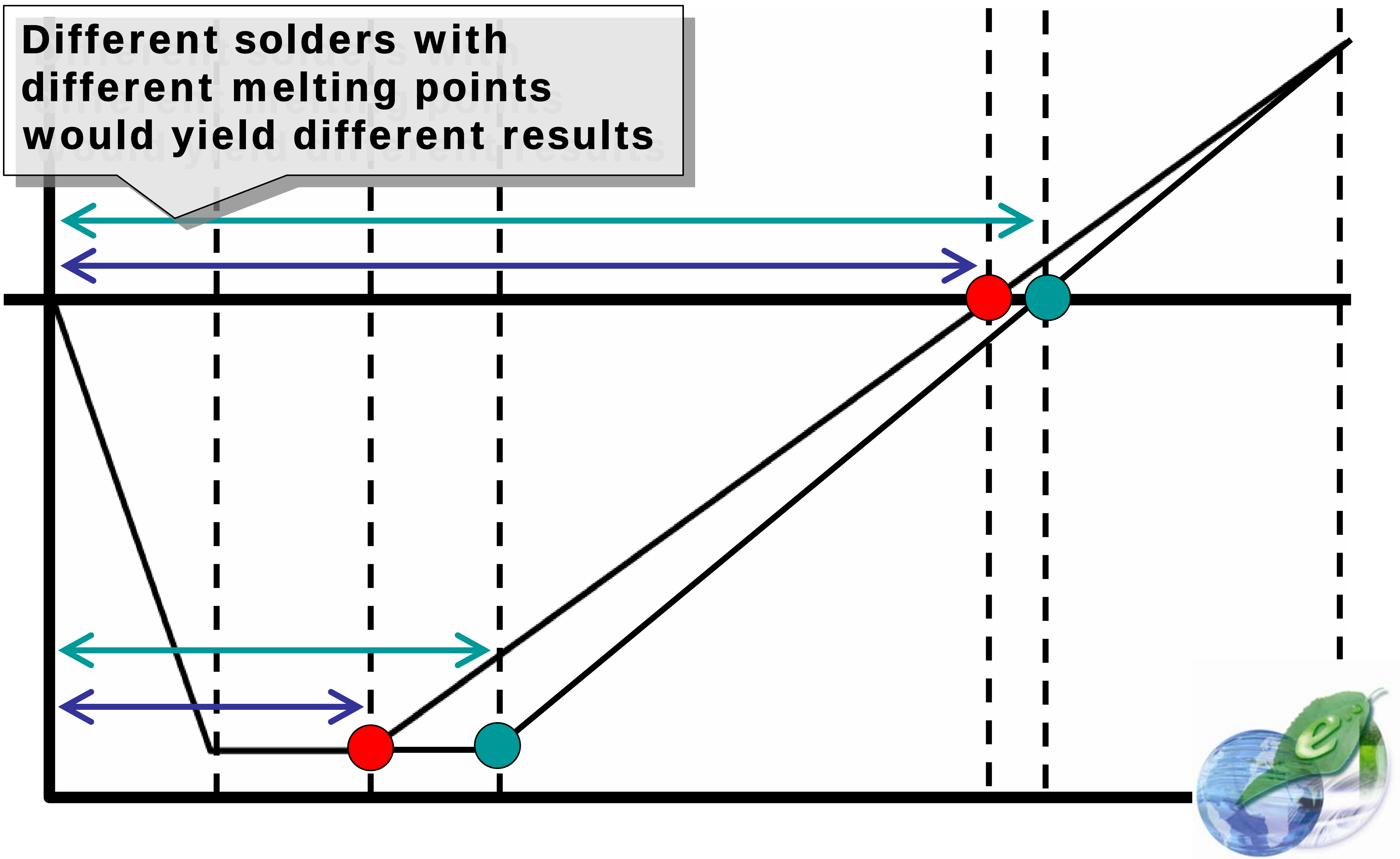
Interpreting the Wetting Balance Curve



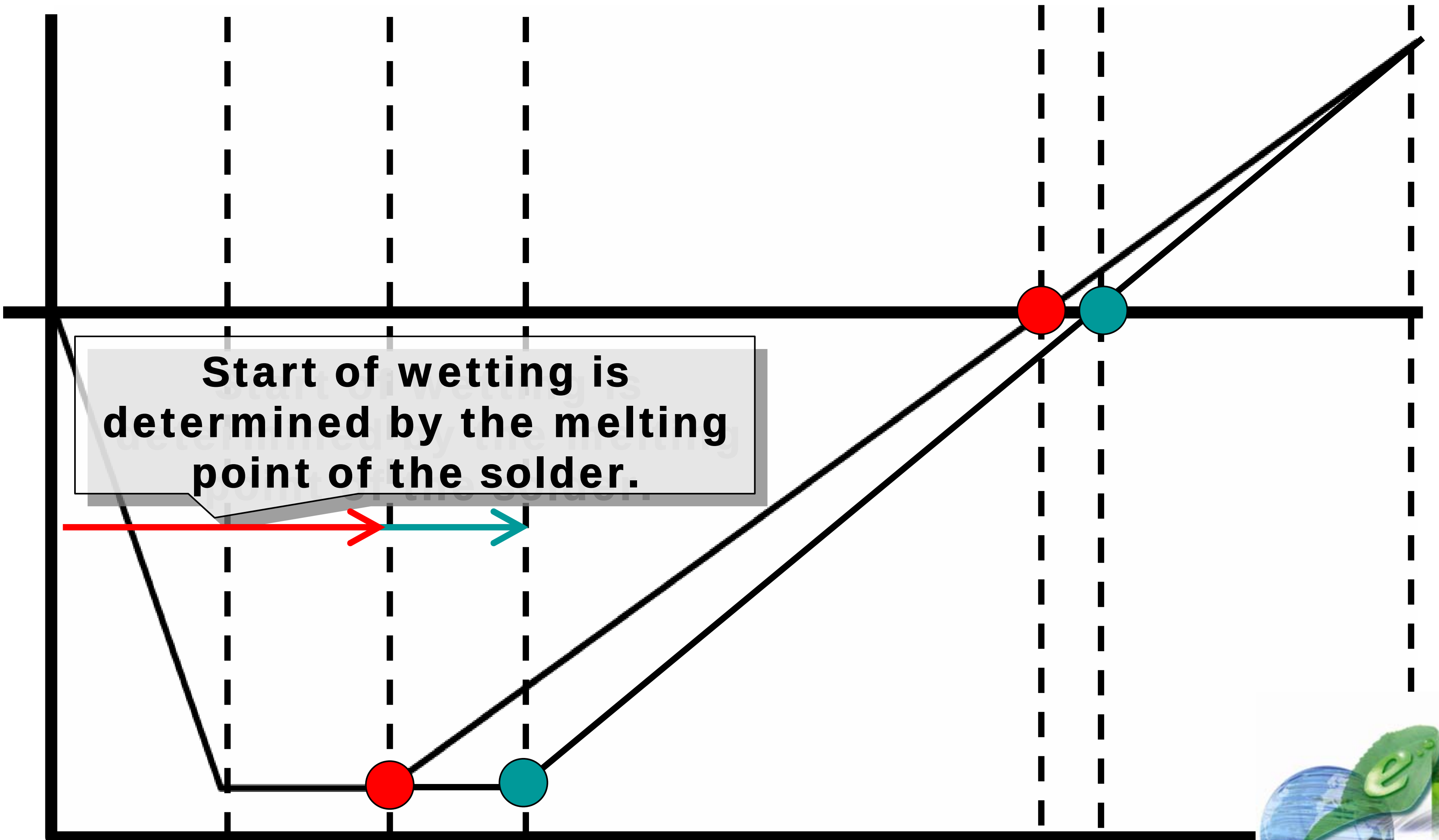
Interpreting the Wetting Balance Curve



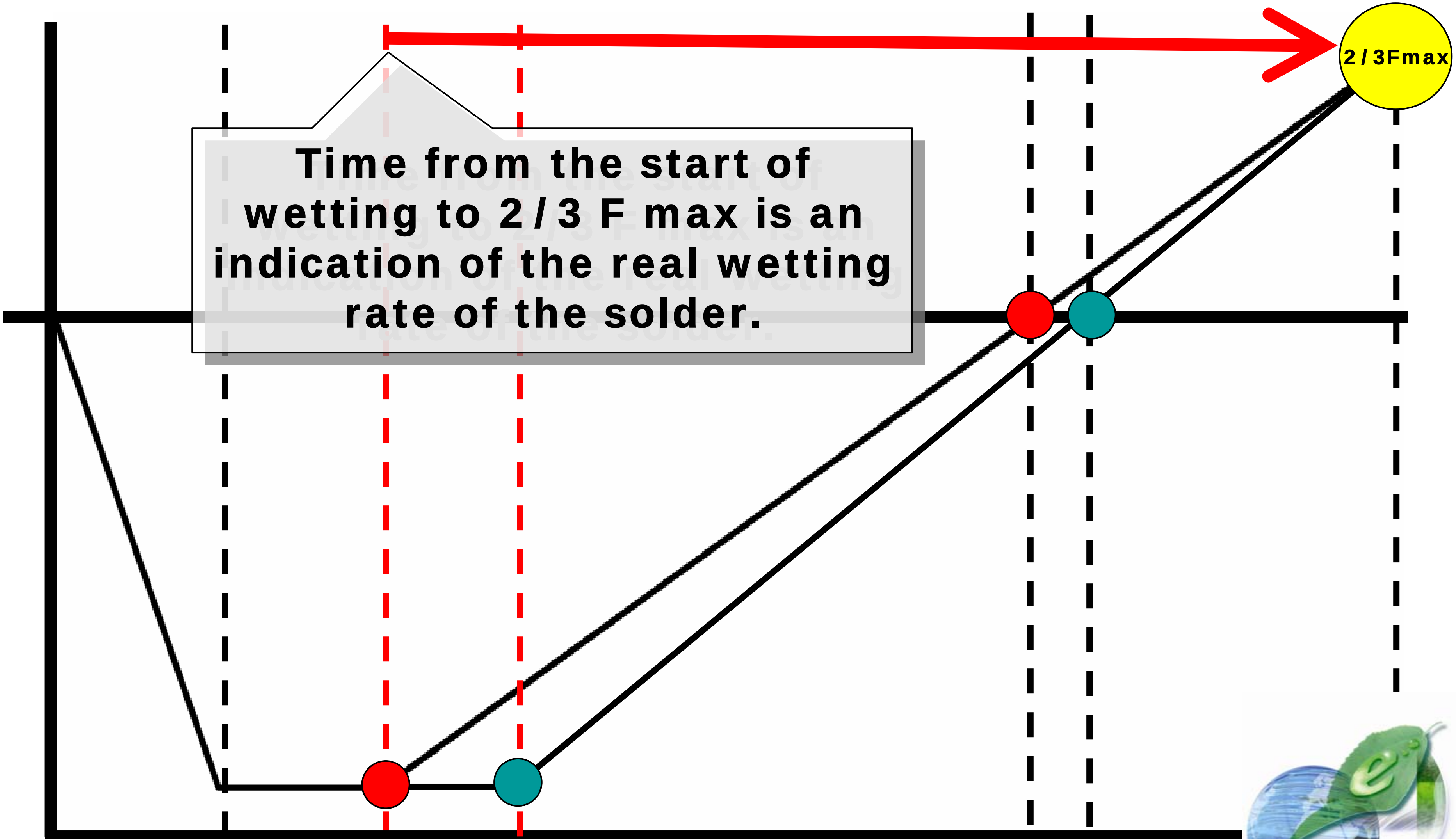
Interpreting the Wetting Balance Curve



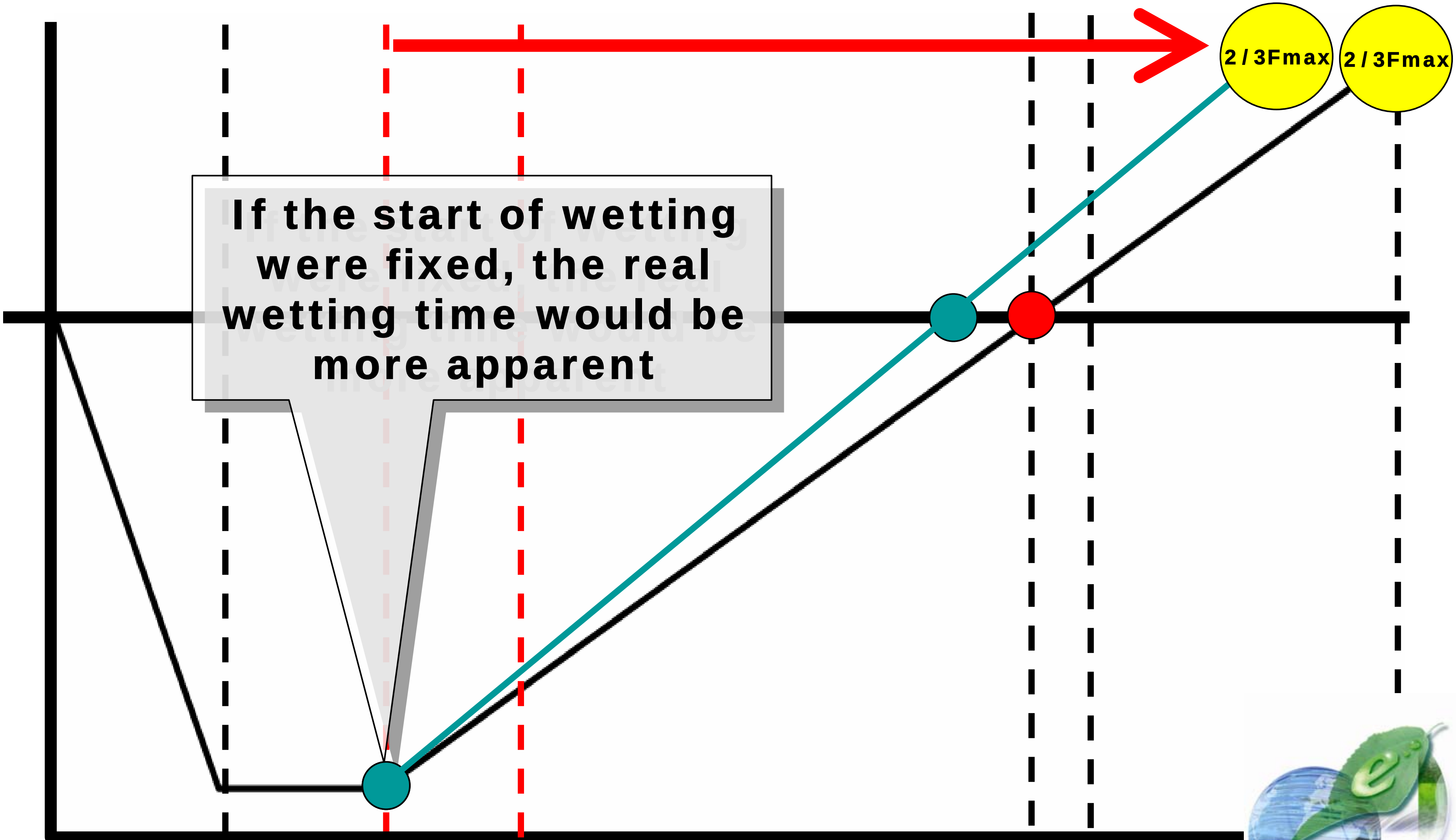
Interpreting the Wetting Balance Curve



Interpreting the Wetting Balance Curve



Interpreting the Wetting Balance Curve



The Real Wetting Rate

To measure the real wetting rate it is

the time from start of wetting to 2/3F max

that needs to be measured.

When the wetting rate is measured in that way comparisons between different alloys can be related to the actual performance of those alloys in production soldering processes.

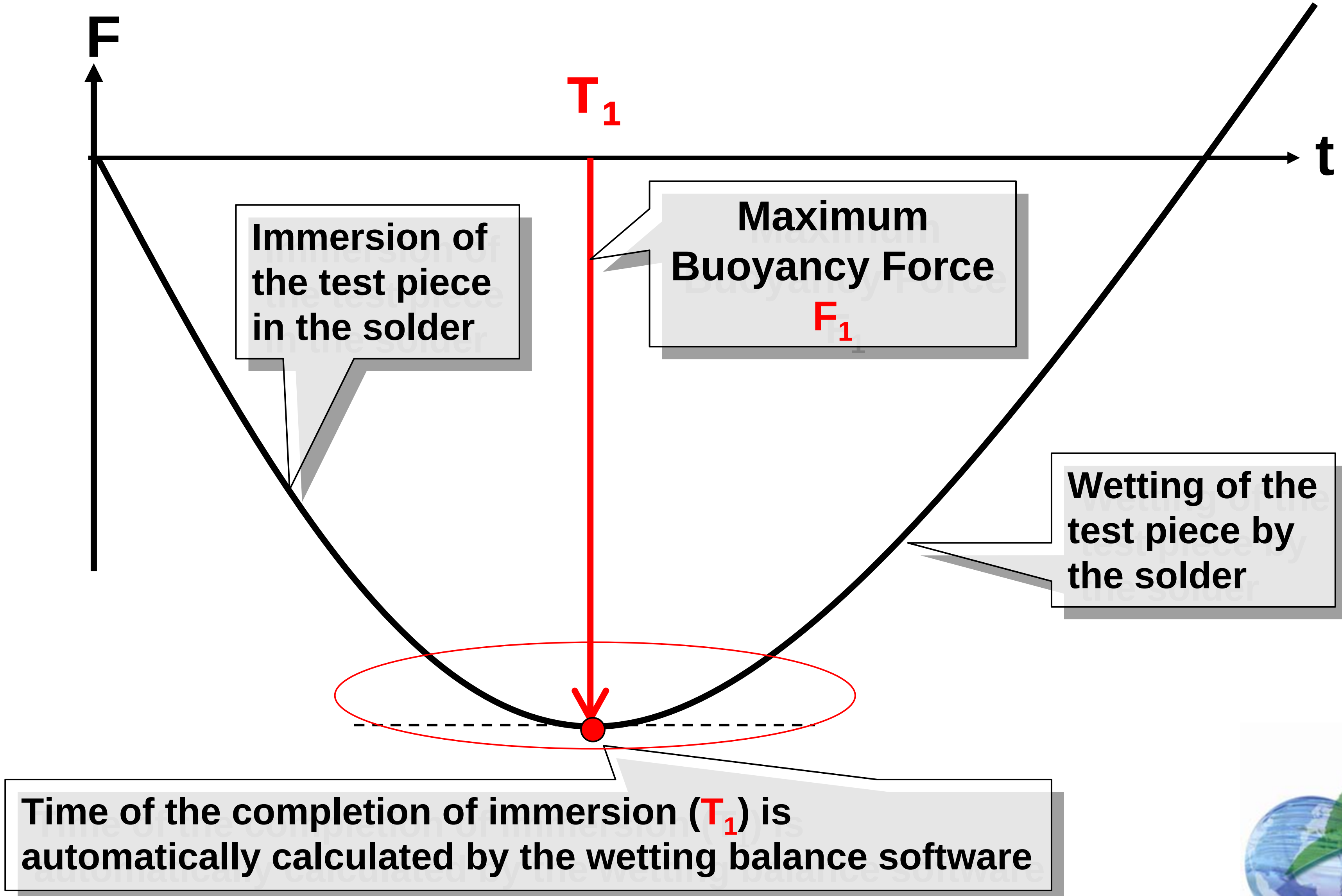
How to Measure

How to Determine the Start of Wetting

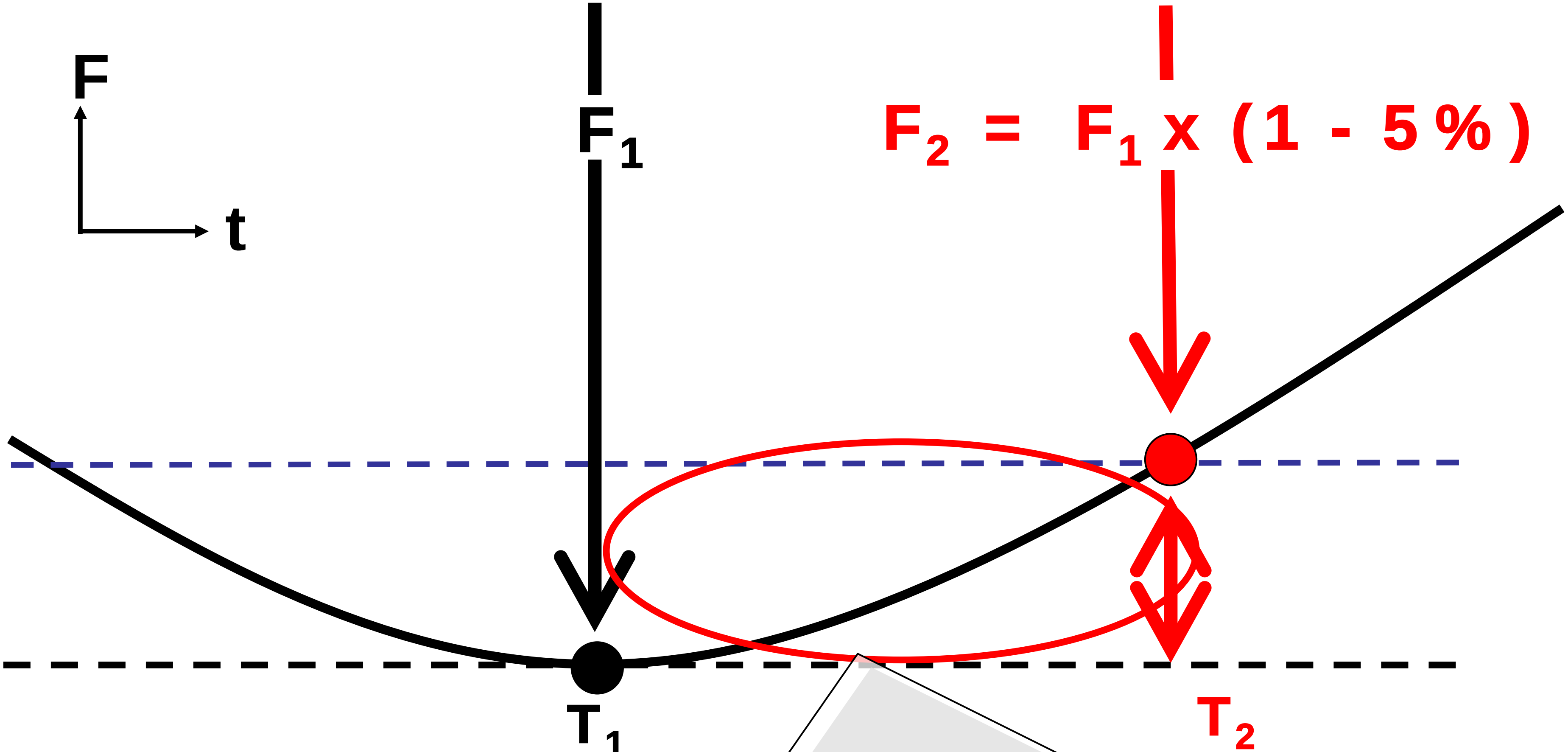
How to Measure the Real Wetting Rate

In order to measure this real wetting rate, (i.e. from the start of wetting to 2 / 3 F max), it is first necessary to define the point at which wetting starts.

Analyzing the Wetting Balance Curve

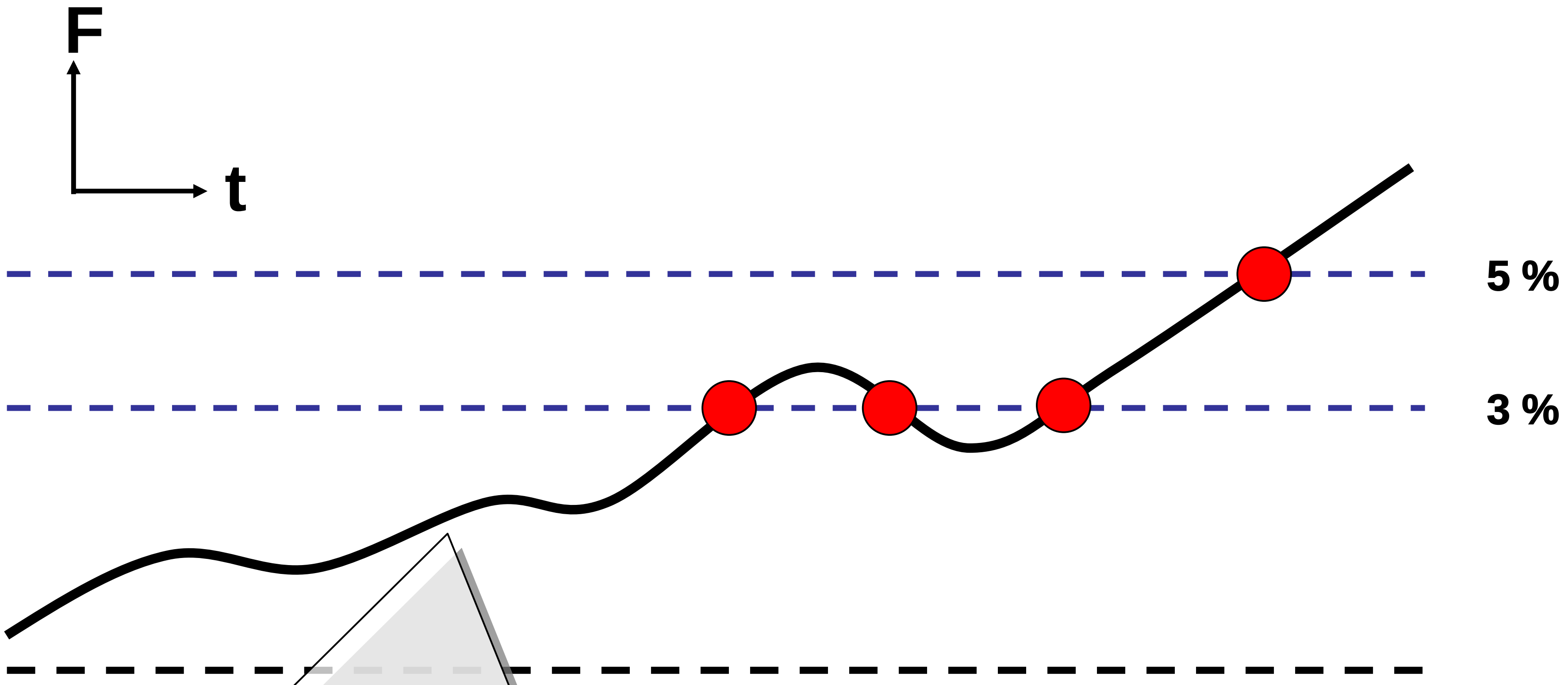


Determining the Start of Wetting



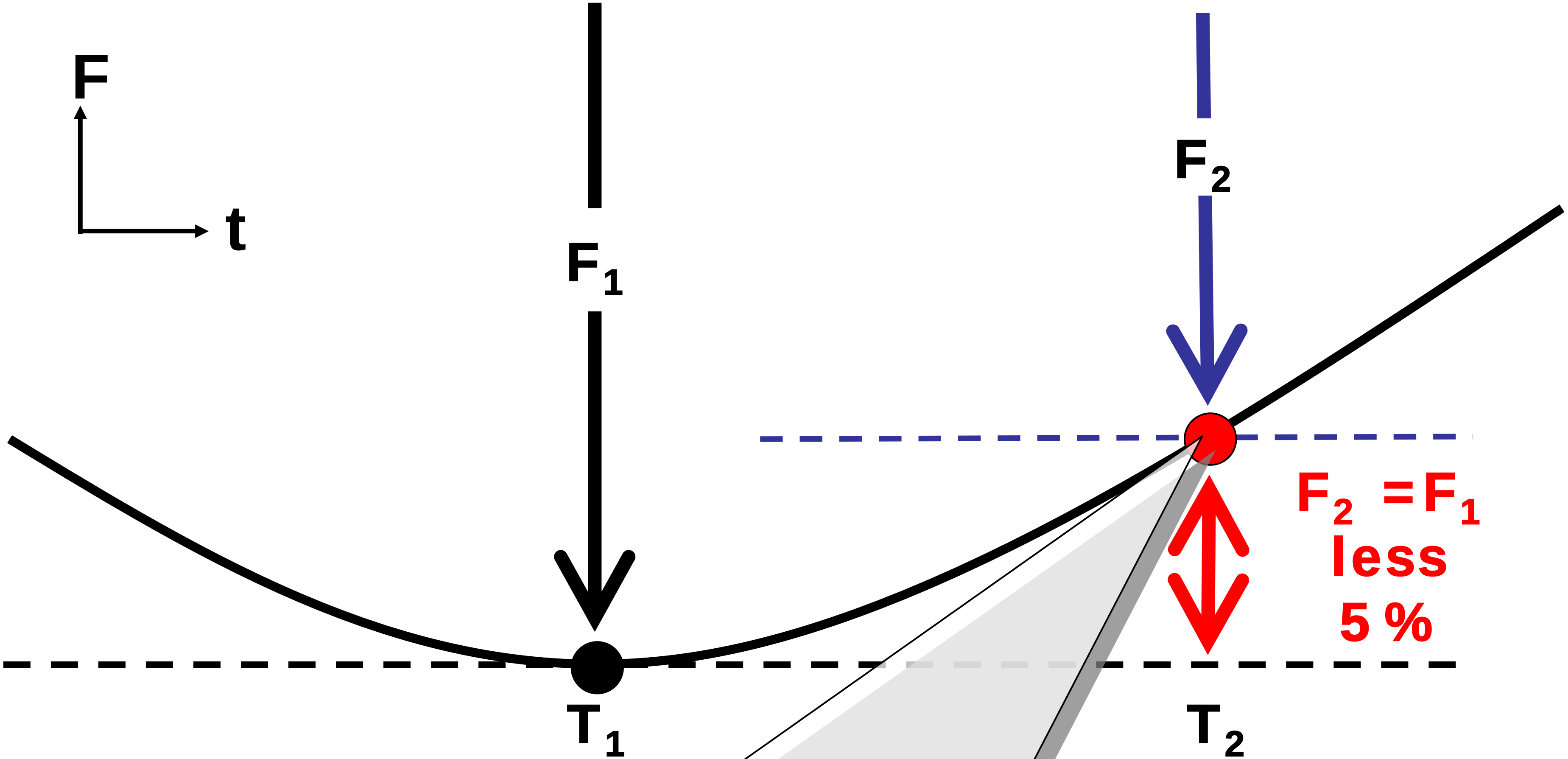
We take the Start of Wetting (T_2) as the time when the net force has fallen to 95% of the Maximum Bouyancy Force (F_1) .

Why F_1 less 5 %?



Before the buoyancy force has reduced by 5% the wetting is unstable.

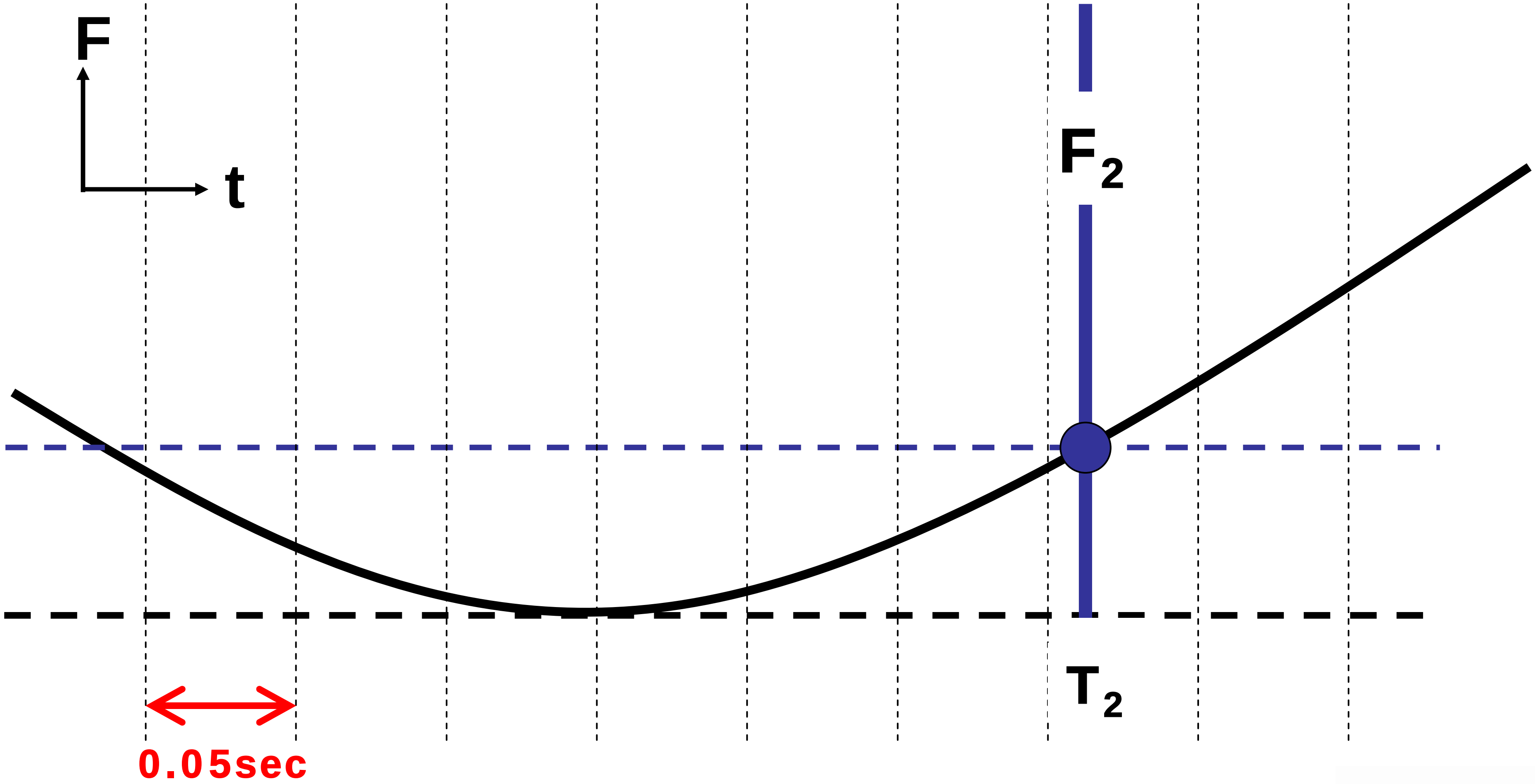
Analyzing Wetting Balance Data



The Start of Wetting T_2 is taken as the time at which the upward force on the test piece has fallen to F_2, 95% of the maximum buoyancy force F_1

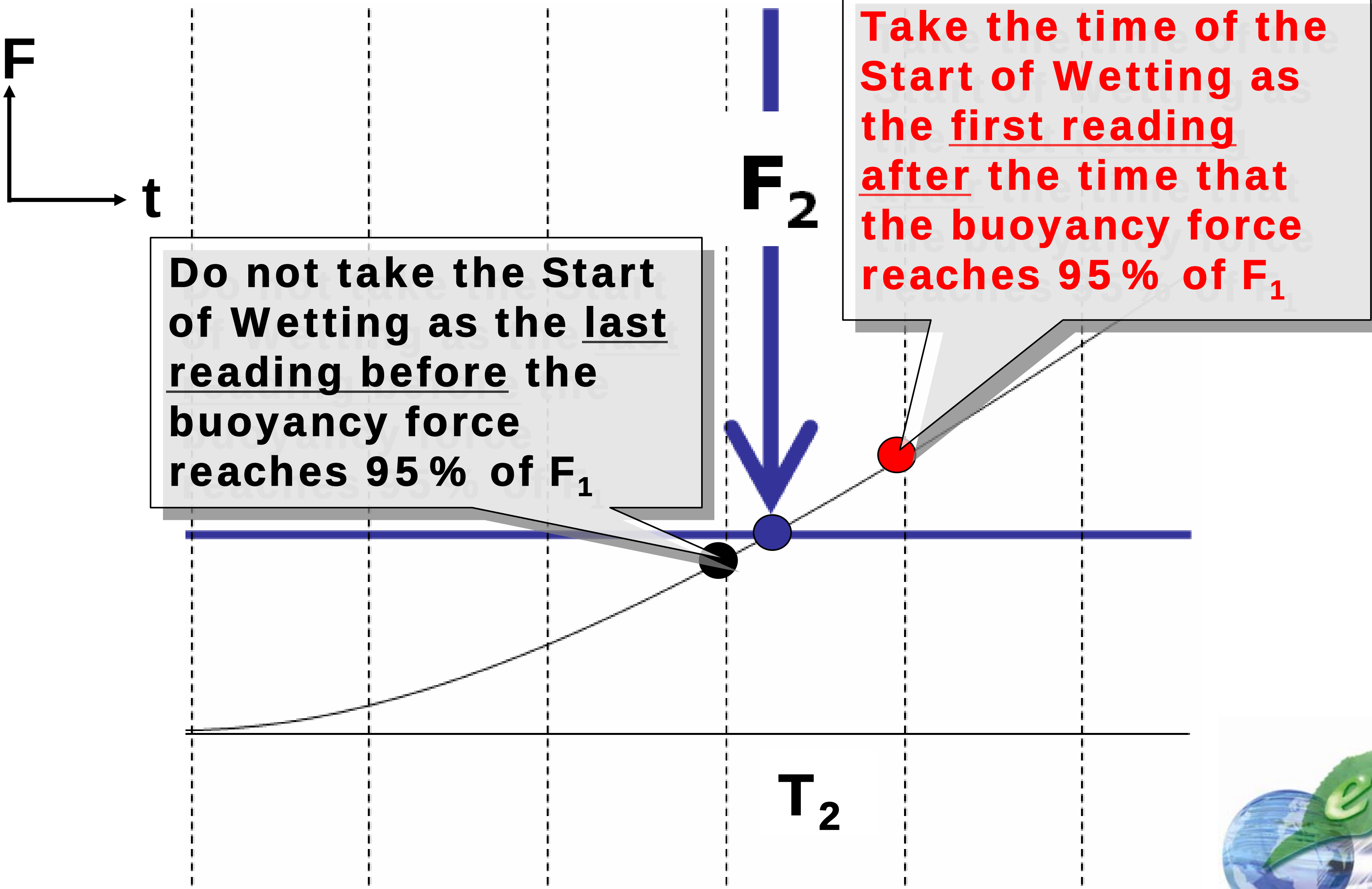
$F_2 = 95\% \ F_1$

Analyzing Wetting Balance Data



If sampling period is 0.05sec ....

Analyzing Wetting Balance Data



Analyzing Wetting Balance Data

SUMMARY

1. Note the time (T_1) at the maximum buoyancy force (F_1).
2. Determine the time at which the buoyancy force has fallen to F_2 (95% of F_1).
3. Take the time of the first reading past the time of F_2 as T_2, the commencement of wetting.
4. Wetting rate is calculated over the time interval between F_2 and $2/3F_{max}$.

The Test

Equipment & Procedures

Test Equipment

Wetting Balance Tester

Test Piece

Cu Coupon

SWET2100 manufactured by Tarutin

Test Conditions

-Cu Coupon: 0.3mm x 10mm x 30mm

-Flux: Nihon Superior NS-831M
(Halide Activated Rosin)

-Solder Temp: 255°C
-Immersion Time: 10 sec
-Immersion Depth: 2 mm
-Immersion Speed: 4 mm/sec
-Withdrawal Speed: 2 mm/sec

*Results are the average of 3 test for each solder.

Melting Points of Tested Alloys

- **Sn-3.0Ag-0.5Cu (~218-219C)**
- **Sn-0.7Cu-Ni+Ge ("SN100C") (227C*)**

***When the solder temperature is fixed solders with a higher melting point are disadvantaged if the conventional method of interpreting the test result is used.**

Test Results

True Wetting Time of Lead-Free Solders

Test Results

The wetting balance tester used in this test can measure automatically the following:

- **Immersion Period**
- **Zero-Crossing Time**
- **Interval to 2/3 F max from Zero-Crossing Point**

"Start of Wetting" needs to be determined manually

Start of Wetting

second	Force
0	-0.033
0.05	-1.284
0.1	-2.252
0.15	-3.312
0.2	-4.338
0.25	-5.302
0.3	-6.025
0.35	-7.115
0.4	-7.458
0.45	-7.722
0.5	-7.399
0.55	-7.293
0.6	-7.134
0.65	-6.948
0.7	-6.654
0.75	-6.450

F_1

Start of Wetting

This is data for Sn-3.0Ag-0.5Cu.
F_1 (maximum buoyance force) is -7.722 at 0.45sec.

"Start of Wetting" is defined as the time when the net buoyancy force has fallen by 5%.

F_2 = -7.222 x <u>0.95</u> = -7.3359

In the chart, the data point past -7.3359 is -7.293 at 0.55sec.

Therefore
"Start of Wetting" is at 0.55sec.

Summary

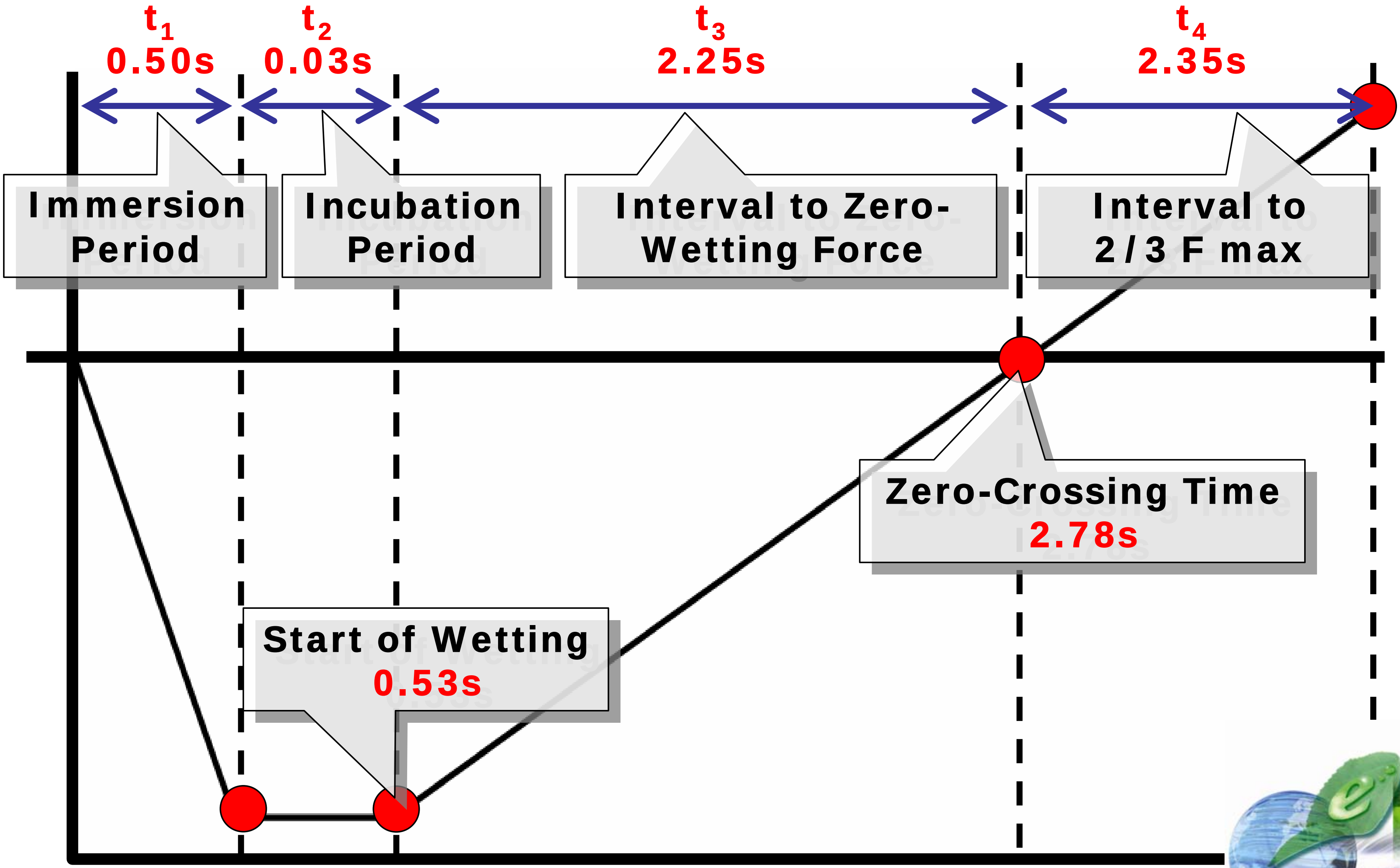
t_1: Immersion Period
(Start of Test to Complete Immersion)

t_2: Incubation Period
(Complete Immersion to Start of Wetting)

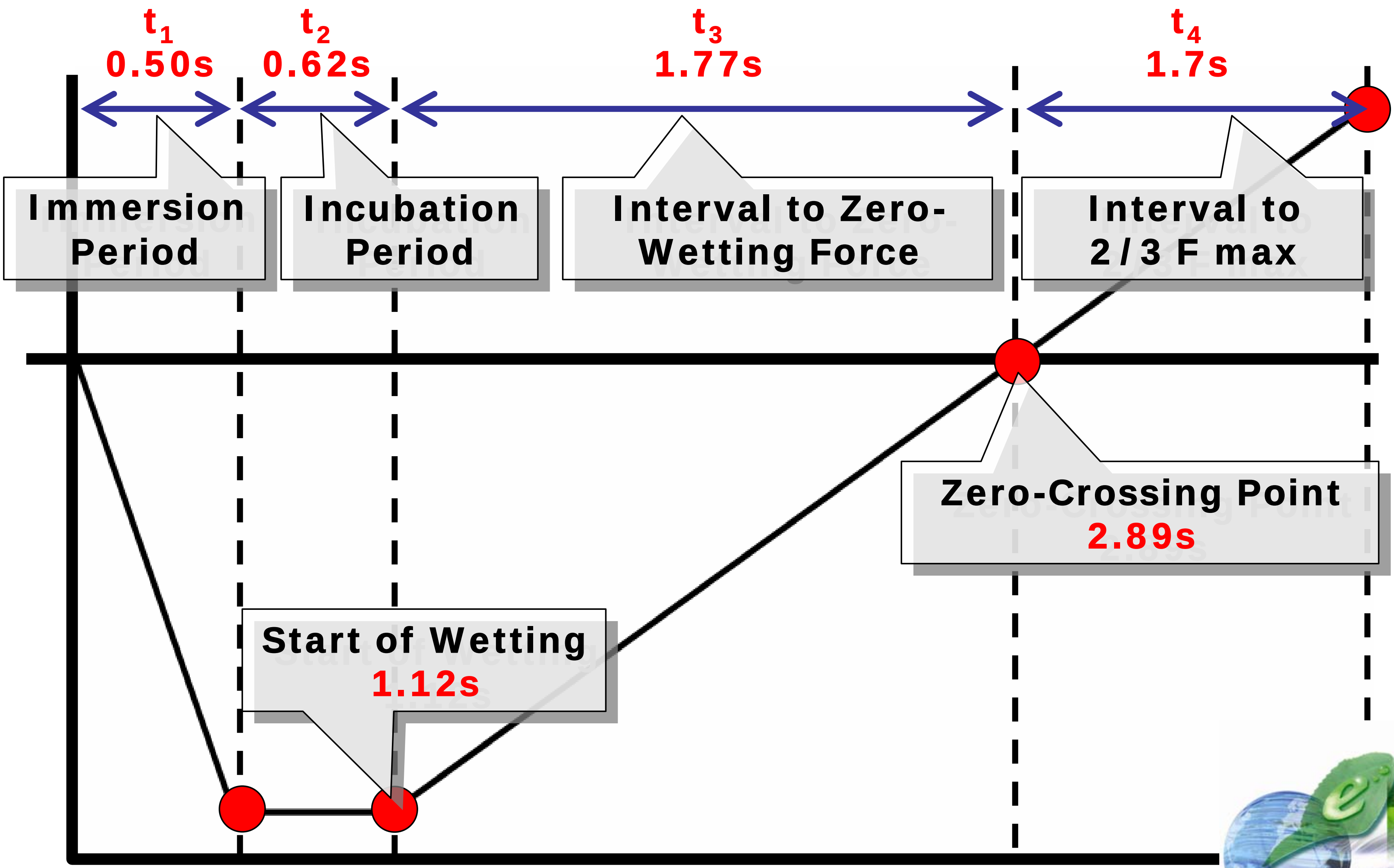
t_3: Interval to Zero-Wetting Force
(Start of Wetting to Zero-Wetting Force)

t_4: Interval to 2/3 F max
(Zero-Crossing Point to 2/3 F max)

Result for Sn-3.0Ag-0.5Cu



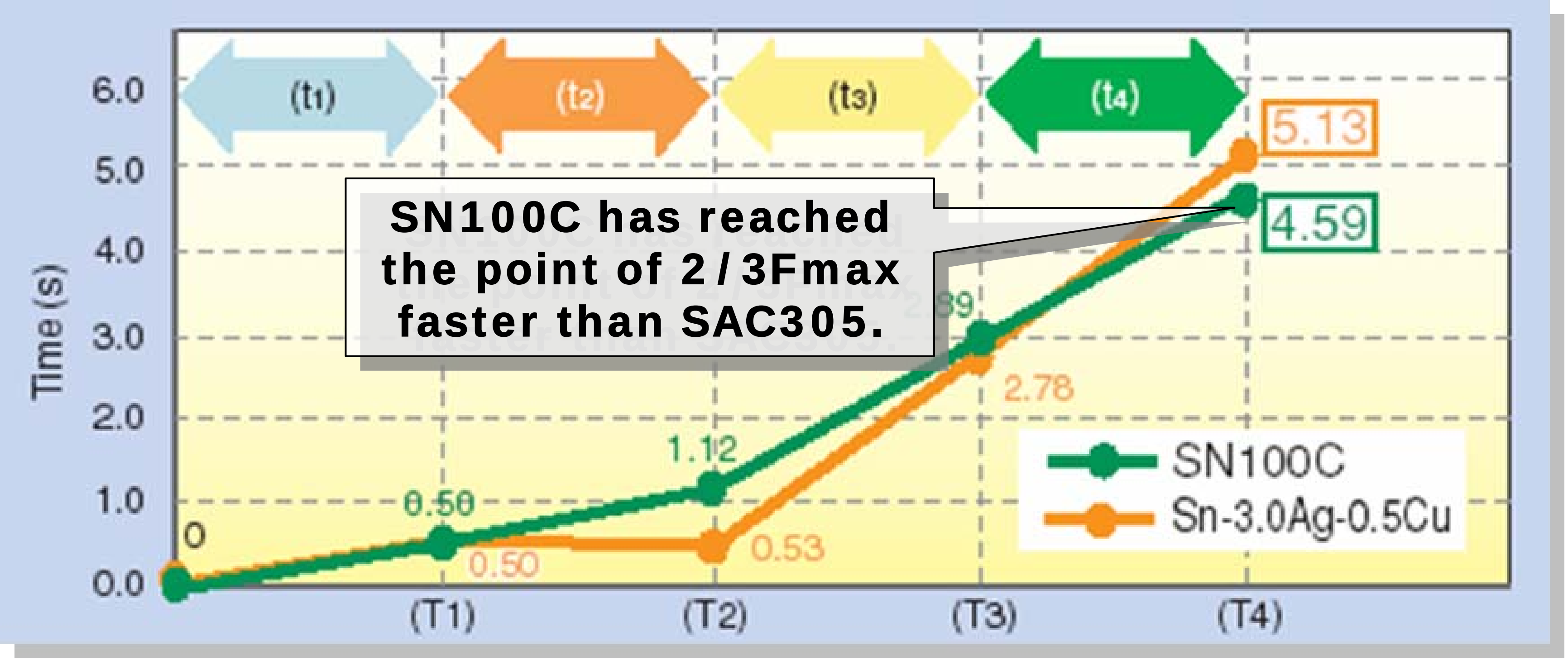
Result for Sn-0.7Cu-Ni-Ge (“SN100C”)



Summary of Test Results

		Time (sec)	Proportion
Item	Sn-3.0Ag-0.5Cu	SN100C; Sn-0.7Cu-Ni+Ge	SN100C/SAC305
t1: Immersion Period	0.50	0.50	100%
t2: Incubation Period	0.03	0.62	2067%
t3: Interval to Zero-Wetting Force	2.25	1.77	79%
t4: Interval to2/3 F max	2.35	1.70	72%
Start of Wetting	0.53	1.12	211%
Zero-Crossing Point	2.78	2.89	104%
Total Wetting Time (t1+t2+t3+t4)	5.13	4.59	89%
Wetting Time since Start of Wetting (Total Wetting Time-(t1+t2))	4.60	3.47	75%

True Wetting Times



Item	Sn-3.0Ag-0.5Cu	SN100C; Sn-0.7Cu-Ni+Ge	Proportion SN100C/SAC305
	Time (sec)		
t1: Immersion Period	0.50	0.50	100%
t2: Incubation Period	0.03	0.62	2067%
t3: Interval to Zero-Wetting Force	2.25	1.77	79%
t4: Interval to2/3 F max	2.35	1.70	72%
Start of Wetting	0.53	1.12	211%
Zero-Crossing Point	2.78	2.89	104%
Total Wetting Time (t1+t2+t3+t4)	5.13	4.59	89%
Wetting Time since Start of Wetting (Total Wetting Time-(t1+t2))	4.60	3.47	75%

Conclusion 1

The True Wetting Time

The True Wetting Time

- The wetting behavior of alloys based on Sn-0.7Cu is usually considered inferior to that of alloys based on the SnAgCu system.

- However, the wetting times from the start of wetting to F max and from the Zero-Crossing Point to 2/3Fmax are shorter for Sn-0.7Cu+Ni+Ge than those of SAC305.

- The argument presented in this paper is that comparisons of “Zero-Crossing Time” and “Time to 2/3Fmax” present a false impression of the wetting properties of lead-free solders.

Recommendations

Process Adjustments to Take Account of Solder Wetting Properties

Process Adjustment

If the true wetting time of a lead-free solder is known it is possible to determine the adjustments to process parameters required to achieve optimum results with that solder.

Process Adjustment

Optimization of Process Parameters to Take Account of Solder Wetting Properties

Example 1:

Start of wetting is slow, but wetting rate is fast.

Adjust pre-heat

Example 2:

Start of wetting is fast, but wetting rate is slow.

Use a more active flux or a more solderable surface finish

Conclusion 2

Optimizing Lead-free Soldering

Optimizing Lead-free Soldering

- Knowledge of its true wetting behavior makes it possible to find the appropriate adjustment of process parameters for each kind of lead-free solder.
- Understanding the properties of each kind of lead-free solder is the key to the achievement of the best soldering result.

NIHON SUPERIOR

Thank you very much for your attention

If you have further questions, please contact me at

m.nakamura@nihonsuperior.co.jp