NEMI Tin Whisker Projects

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Introduction:

By 2001, it was clear that the move to (lead) Pb-free electronics would require removing Pb from component terminals and the preferred terminal finish was pure tin (Sn). But pure Sn has a long history of a proclivity to tin whiskers, a potential reliability issue. There was no industry accepted method for evaluating the propensity of any given plating or terminal finish design to forming whiskers. Suppliers were being asked for test data by their customers, and each customer had different requirements. The first NEMI project was established to develop a set of test conditions that could be used throughout the industry for evaluation of tin whiskers. A second goal was, if possible, to define accelerated test conditions that would allow for short test durations with high confidence level in predicting whisker growth.

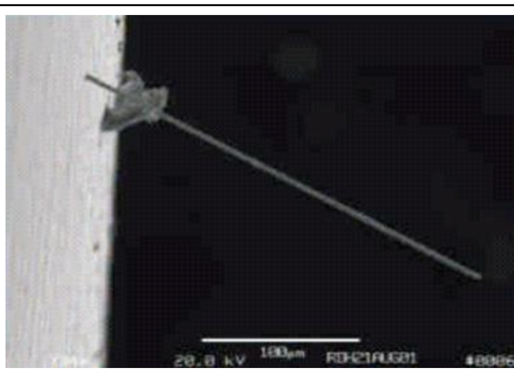


Figure 1 - Tin Whisker

Since the project goal was to develop industry standards or specifications, the project members decided to invite non-member participation in order to speed both the development and acceptance of such a specification. From the beginning, over 20 companies were actively involved in the project.

With this broad range of participation, a lot of knowledge sharing took place. A number of companies with broad plating experience (e.g. Shipley, Lucent, FCI-Connect, Motorola, etc.) contributed insight into the plating process, itself. The team also consulted with a number of experts in the field (i.e. Prof. K.N. Tu, UCLA), did a rudimentary literature search, and explored what was known about the tin whisker phenomena.

Several things were learned from these explorations:

1) Whiskers would grow at room ambient conditions (~25 C, 50-80% RH).
2) Whiskers would not grow at temperatures above ~90 C.
3) "Bright" tin seemed to grow more whiskers faster than "matte" tin.
4) There did not seem to be any bias or electric field contribution to whisker growth.

Typically, environmental testing on electronic components has encompassed high temperature (e.g.150 C storage) or temperature and humidity (e.g. "pressure cooker" test); Bias or electric field testing (e.g. for corrosion products); and broad range temperature cycling (-45 or -55 C to +125 or +150 C). So the findings above greatly limited the "accelerated" test conditions that could be employed.

First Experiments (DOE #1):

The first set of experiments employed temperature storage at ambient, 50C and 85 C; high humidity 85% RH at both temperatures; thermal cycling -40C to +90C three cycles/hour; and combinations of these conditions. Eight lead SOICs and brass coupons were plated with bright Sn and a control cell used SnPb plating.

Whiskers formed only on the bright Sn-plated coupons and were far fewer than expected, possibly because the level of impurities and/or contamination were very low (samples plated in the lab). The results of the Phase 1 study were inconclusive.

The DOE1 experiment demonstrated the need *t*o specify the physical and visual characteristics of a tin whisker for use in inspection. The following definition for tin whiskers was adopted:
"*A spontaneous columnar or cylindrical filament, which rarely branches, of tin emanating from the surface of a plating finish.*" For the purpose of inspection, then, tin whiskers have the following characteristics:

- an aspect ratio (length/width) > 2;
- can be kinked, bent, twisted;
- generally have a consistent cross-sectional shape;

– rarely branch;
– and may have striations/rings around it.

See examples in the figures below.

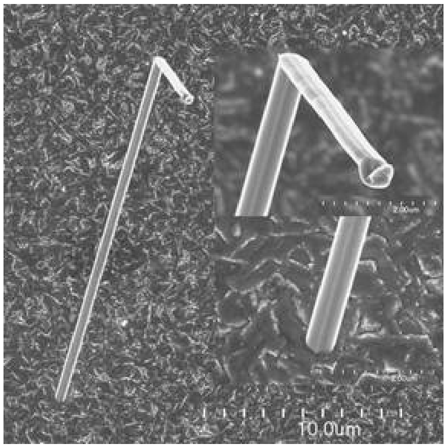


Figure 2 - Needles

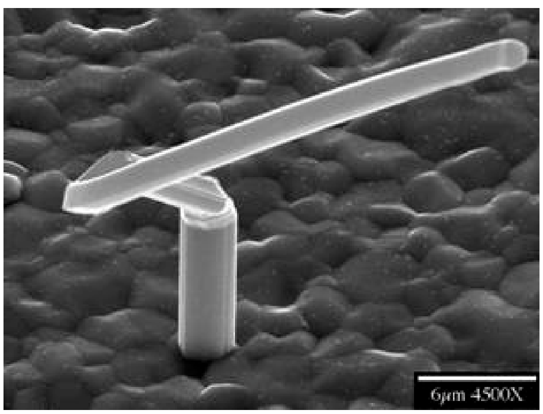


Figure 3 – Kinked

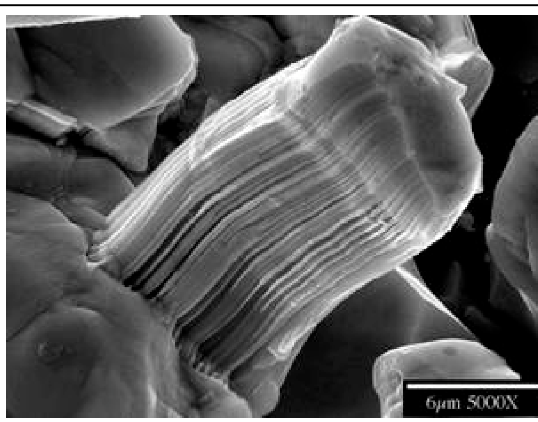


Figure 4 - Striations

It was also necessary to establish an inspection method to quantify the propensity of an electroplated component terminal to develop tin whiskers. To be able to compare experimental data from various sources, it was decided to recommend the equipment, locations and area of inspection, sample size, and procedure for inspection. The overall proposal is available on the NEMI web site (www.nemi.org) and was provided to IPC/JEDEC for consideration as an industry standard. It is currently in the review process.

Second Experiment (DOE #2):

A second set of experiments was undertaken using production plating lines and components (SOIC packages with Olin 194 Cu terminals). Matte pure tin was plated from both MSA and Sulfate baths. Again 90Sn/10Pb alloy was used as a control. Passive components in the form of fuses, and flat brass coupons were also tested. Test Conditions were modified slightly based on what was learned from the Phase 1 tests:

– Ambient exposure (30 C) for 5 months
– Temperature + humidity exposure
  • (30 C/90%RH and 60 C/95%RH) for 4 weeks
– Thermal cycling (500 cycles; -55 C to 85 C, 20 min cycle with 7 min dwell)
– And a combination of all of the above conditions

Results:

In general, more whiskers grew with the -55C/85C temperature cycle method, followed by 60C/90%RH storage. Some whisker growth was also observed in the ambient environment storage test cell. There is no indication in this experiment that thicker deposits are less prone to whisker than thin deposits. Bath chemistry/plating process parameters seem to have the most significant influence on whiskering. A slight advantage was seen in the sulfate-based chemistry comparing to a good-practice MSA bath. But there was a significant difference between the two MSA-based processes provided by two suppliers. Examination of the processes, chemistries and impurities in the baths (see Table 1 at end of paper) did not explain the differences seen on test. This means it is not clear which variables are the most significant to control.

It appears there are some unknown factors that influence whisker growth more than the aging conditions in the testing. One conclusion is that whisker growth phenomenon is a multi-factorial event and the theory/model describing it must take into consideration numerous parameters.

Another conclusion was that development of an accelerated test may not be possible until the underlying theory of whisker formation is fully understood. However, the industry needs an interim approach until the theory is developed.

Third Experimental Matrix (Doe #3):
The third set of experiments was designed to validate and verify what had been learned and to begin collecting data that could be used to support the proposed tests recommended to industry. The test conditions were modified slightly based on what was learned.

- *Tests utilized in DOE #3:*
  - -55°C (+0, -10) / 85°C (+10, -0) air-air temperature cycle (20minutes/cycle) up to 3000 cycles (500 cycles check points)
  - 60°C, 93+2/-3%RH temperature / humidity storage 9000 hrs (~1 year) with 1000 hr check points
  - Ambient storage (~23°C, ~60%RH) up to 18000 hours (~2 years) with 1000 hr check points

Test samples were again production packages from contractors in high volume production (64 LQFP). Both copper (CDA 194) and Alloy 42 lead frames were tested. Also, SnBi, SnAg and SnCu finishes were included along with matte tin and SnPb control samples. To gather data on possible "mitigation practices" (i.e. structures that reportedly inhibit tin whisker formation), parts made with matte Ni underplate, fused Sn (confirm melting) and/or annealed Sn as well as hot-dipped Sn were included in the test.

During the first set of experiments, we had been comparing results with JEITA, who was doing similar work in Japan. We asked for, and they provided, samples of their test hardware so that we could better compare results.

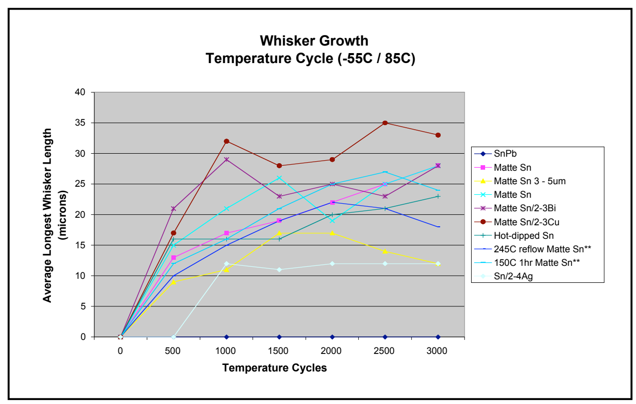
Table 2 (end of paper) provides more data on the individual cells. Failure analysis will be carried out on test completion and perhaps provide more information on what is happening within the metallurgical structures.

As of this writing, we have completed 3000 thermal cycles and 3000 hours of storage testing. Not all the data has been analyzed, and the tests are on-going. The following, then, are interim conclusions.

Thermal Cycle Results:
Figure 5 shows the average length of the longest whiskers measured at each inspection point. It was decided to inspect all leads instead of just the three leads recommended in our test protocol for added safety factor (i.e. do not miss important data. The test protocol may be revised depending on what is learned at the end of testing.

Three samples were removed from test every 500 cycles for measurement. Most cells had already formed whiskers after 500 cycles of testing. Whisker growth appears to saturate after approximately 1500 cycles with the exception of the matte Sn and hot-dipped Sn cells. From the literature, we expected the heat-treated samples to perform substantially better than shown here. As expected, grain growth is easily observable after 3000 thermal cycles.

Figure 5 - Thermal Cycle Results



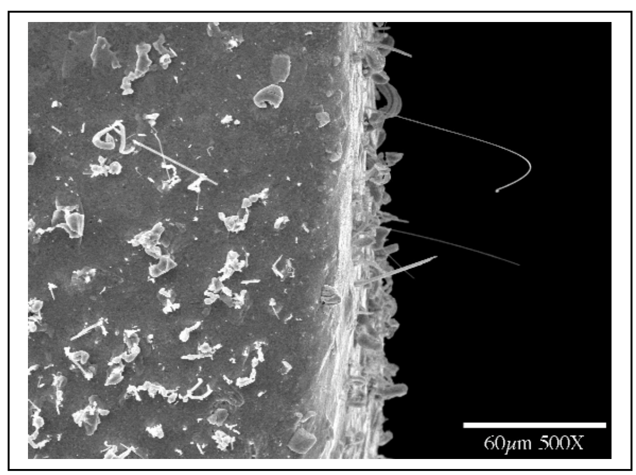


Figure 6 - Cell 10 Hot Dipped Sn

Figure 6 illustrates the whiskers seen on the hot tin dipped cell. Figure 7 & 8 illustrate the grain coarsening seen on the SnAg cell after thermal cycling.

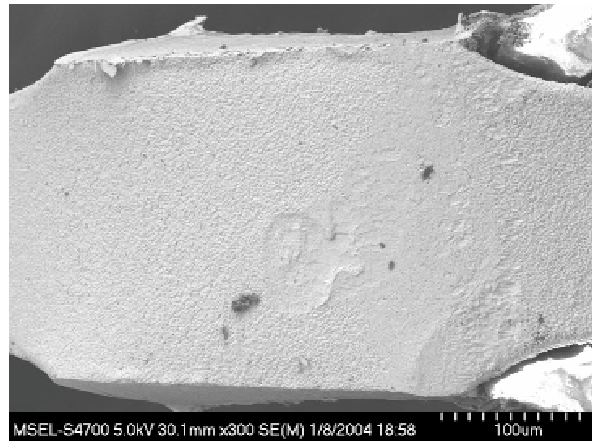


Figure 7 - Cell 14, Sn/2-4 Ag, t_0 uncycled.

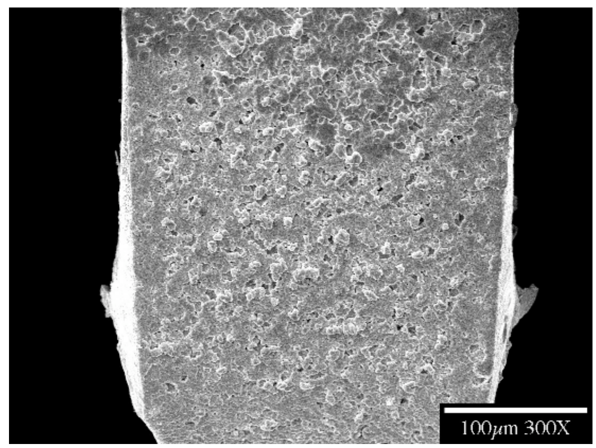


Figure 8 - Cell 14, Sn/2-4 Ag, 3000 cycles

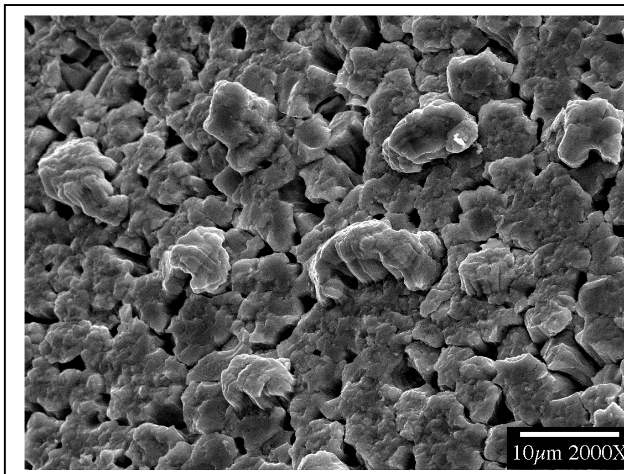


Figure 9 - Cell 2, Sn/Pb, 3000 cycles

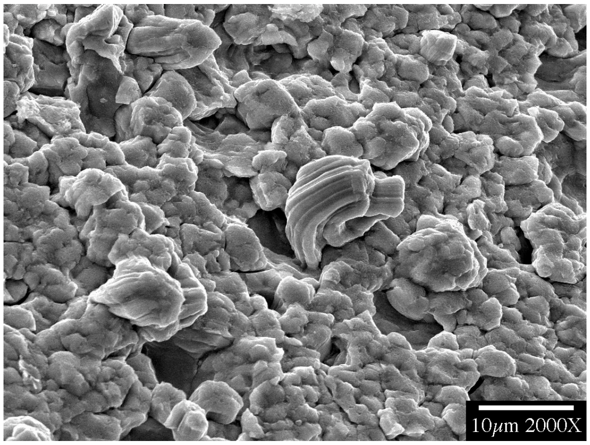


Figure 10 – Cell 14, Sn/Ag, 3000 Cycles

Figure 9 & 10 show the similarity of grain structure between the SnPb and SnAg cells after 3000 thermal cycles. Whiskers tend to be quite small on these cells, at least to 3000 cycles.

Figure 11 shows the results of 3000 hours of storage at 60C/93% RH. Inspections were carried our every 1000 hours. In some cells, substantial whiskers have formed by the 2000 hour readout. All but two cells (SnPb control & 245 C reflow) show whiskers after 3000 hours. In some case, only a portion of the packages with each finish exhibited whiskers after 3000 hours. Also, different incubation periods are observed as a function of base metal and finish type and conditioning. Some corrosion products are observed after 3000 hours in some of the cells.

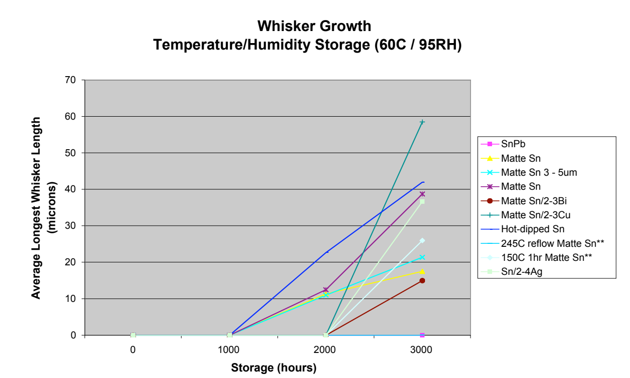


Figure 11 - Isothermal Storage Results

The Thermal cycle and isothermal storage (60C/93% RH) test methods are showing good repeatability compared to earlier experiments. This builds the confidence level that these tests can be useful to the industry. Base metal and finish type and conditioning appears to affect the whisker length observed in thermal cycle testing, as well as the incubation period in isothermal storage. It was also noted that some cells respond differently on thermal cycling, than on temperature/humidity storage (245C reflowed Sn, SnAg samples). No filament whiskers were observed after 3000 hours of aging at ambient conditions.

Coordination with JEITA in Japan and both ITRI and the E3 in Europe will continue to determine if we can establish unified whisker test methods worldwide, including pass/fail criteria and fields of application. Future work includes experimental designs to evaluate bias effects (DOE #4) and attempt to empirically determine acceleration factors (DOE #5) on the test conditions we have defined.

Modeling Project:

From the first two sets of experiments, it became obvious that whisker phenomena are a multi-factorial problem that was not going to be solved by rote testing. The theory behind whisker formation must be understood if pure Sn plated terminals are going to be reliably controlled in a manufacturing environment. The modelling project was formed with the goal of determining the mechanism of tin whisker formation and growth so that we can predict behaviour, design mitigation methods, and develop acceleration tests.

The NEMI member companies assembled a broadly discipline team (e.g. metallurgists, material scientists, chemists, etc.) to address the problem. At first, the team supported the Test project with theory to help in test design, and analysis of results to evaluate the theories. Individual member companies also continue to do their own research, which is often brought into the committee to supplement joint work.

It was soon apparent that this problem was not going to be an easy task. Dr. George Galyon, IBM, took on the task of doing a thorough literature search to determine what is known about whisker phenomena. He has published an Annotated Bibliography and Anthology which summarizes whisker publications both chronologically and by subject matter. This document is available on the NEMI web site (www.nemi.org). This provided the team with tremendous confidence that they are not re-inventing things that have been done, but are building on what is known.

In addition the team has consulted with a number of university researchers, the U.S. National laboratories, corporate research groups, and other organizations that have done work in this arena.

All this has lead to a list of questions that must be answered if the phenomenon of whisker growth is to be resolved:

Role of Stress: There is general agreement that compressive stress in the tin film is a key driving force behind the formation of tin whiskers. Compressive stress results in atoms with a high energy state that typically manifest as dislocations or high energy grain boundaries. Stress in tin finishes as plated may be compressive or tensile in nature, however due to spontaneous recovery, the plating stresses in the material are rapidly relieved even at room temperature. Compressive stress in the tin films may be caused by intermetallic growth in the grain boundaries (such as Cu6Sn5 when tin is plated on copper base materials), thermally induced stresses (such as thermal cycling), or by mechanically induced stresses. In tin finishes over copper substrates, compressive stress typically appears quickly after plating and continues to increase with time. Reliable measurement of the stress is difficult, time consuming, and requires sophisticated tools. Even so, only the average stress in the film can be determined. It is not clear if macrostress is alone sufficient to create whiskers, or if microstresses at the grain boundaries is required.

Role of Impurities: Another theory is that impurities in the Sn film induce stress. Studies of known impurities have not, to date, provided adequate information to prove or disprove this theory. It does appear that some impurities, notably copper, do increase the overall stress levels in tin films and this usually leads to increased whisker growth. Other impurities, such as lead, appear to reduce the overall stress levels in tin films and mitigate whisker growth. How these various impurities achieve their effects is not known. Impurities are also theorized to play a role in the pinning of grain boundaries, which might contribute to the initiation or actual growth mechanism of the whisker.

Diffusion Mechanisms: Obviously whisker formation requires movement of material within the Sn film. It is generally felt that diffusion of atoms from high energy to low energy regions provides the atomic mass transfer for whisker growth. Most publications cite grain boundary diffusion as the dominant diffusion mechanism operative in whisker formation and growth. However, there are some experimental results that point to surface diffusion as the operative diffusion mechanism.

Dislocation Mechanisms: Some theoretical approaches discount the need to have any operative dislocation mechanisms involved in the whisker growth mechanism. Other approaches insist that there must be some kind of dislocation mechanism operative to move material from the whisker grain grain-boundary to the base of the whisker. Two popular theories involve Screw Dislocation and the other involves Frank-Read Source (dislocation loops). As yet, there is no direct experimental data that confirms the existence of any dislocation structures within the whisker grain.

Recrystallization: There is general agreement that whiskers do not grow from the as-plated grain structure. Instead, whiskers grow out of grains that are “different” than the bulk of the as plated grain structure. Some theorists conclude that these “different” grains are the result of a recrystallization event. There is general agreement amongst the NEMI committee members that recrystallization events do appear to be the rule for bright tin nodule/whisker growth, but the case is not so clear for matte tin whisker growth events.

Role of Substrate Material: Test results have been varied on the substrate materials in all three tests conducted so far. It is not clear if this is due to the different coefficients of expansion of the substrate materials or some other mechanism.

Role of Grain Orientation: Some recent data indicates that the film grain orientation spectra of the Sn film affect whisker growth. A. Egli of Infineon first brought this observation to the published literature. It appears that the specific dominant preferred orientation index is not critical. Rather it is the angular relationships between the dominant grain orientations that are key. To date, there is no published data that contradicts this observation.

Given all the possible variables and difficulty of obtaining data, it is very difficult to establish mechanisms of growth with certainty. One conclusion is the need for samples built in the laboratory under controlled conditions so that some of these variables can be isolated. An experimental design is currently underway using coupons and laboratory plating conditions. Even so, availability of the sophisticated tools required to see what is happening in the grain structure may limit the evaluations. The team has applied to the U.S. National Laboratories to use x-ray diffraction synchrotron facility. If successful in obtaining time on the facility, it may be possible to evaluate crystal orientation, strain (stress), and dislocation density within single grains, surrounding and including the whisker. Experiments with other tools such as focused ion bean (FIB), conventional X-RD tools, and other equipment will be utilized for maximum benefit from the experiments.

USER Group:

Unfortunately the date for changeover to Pb-free electronics is rapidly approaching, and industry must make decisions on terminal finishes whether tin whiskers are fully understood or not. Many suppliers started advising their customers that they planned to change terminal coatings to 100% Sn in the near future. Companies that are concerned with high reliability systems designed for long life (e.g. >5 years), harsh environments, or mission critical applications, became concerned that this change would jeopardize their products. Ten of the largest NEMI members joined together to form a user group to look at the problem and develop a course of action.

The objective of the user group is to ddevelop recommendations for lead-free surface finishes on components that would minimize risk of failures from tin whiskers in high-reliability electronic applications. Working with the Modelling and Test projects, the User Group decided to define methods and tests that minimize the probability of tin whiskers creating functional or reliability problems. This result is to be achieved by a combination of using known mitigation practices (i.e. methods to reduce the risk of whisker formation) and some level of testing.

The tin whisker mitigation practices recommended were:

- Use of nickel-palladium or nickel-palladium-gold instead of tin
- Use of a nickel underlay
- Reflow (or Hot Tin Dip of) the tin coating
- Heat treating (1 hour at 150C) plating is considered

All of the above is supported in one form or other by published studies (see whisker bibliography). The highest confidence solution is, of course, not to use Sn coatings at all, but go to the proven NiPd or NiPdAu coatings that are offered by some suppliers. The other mitigation practices (Ni underlay, reflow or heat treating) have shown mixed results on recent tests, indicating we do not totally understand the theory of whisker formation. However, in most cases, average whisker lengths have tended to be lower with these mitigation practices, so most member companies will accept one or more of them if supplemented with testing on the part of the supplier.

This information has been incorporated into a position paper that was issued March 19, 2004, and posted on the NEMI web site (see http://www,nemi.org).

The user group then developed an Acceptance Criteria document (also on the NEMI web site) and reviewed it with the supplier community on June 2, 2004. The group will continue to refine/sharpen mitigation strategies and acceptance criteria as new data becomes available.

Conclusion:

The three NEMI projects have made considerable progress in developing industry standard tests and measurement protocols for tin whiskers. And they are sharing data with European and Japanese groups in an attempt to reach world-wide consensus on these methods. Also the test group plans to investigate newly reported information on the affect of bias on whisker growth. The modelling group has made substantial headway in developing some understanding of whisker formation and plans are underway to prove or disprove many of the theories advanced. The user group is actively working with the supplier community to manage risk and find a way forward.

Table 1 – Plating Bath Impurities in DOE#2

Contaminations, ppm	Pb		Fe		Cu		Zn		Ni	
	t_o	t_e	t_o	t_e	t_o	t_e	t_o	t_e	t_o	t_e
Supplier A										
Sulfate (Samples A and B	6	6.3	9.7	11.9	0.4	0.6	0.4	0.5	0.44	0.5
MSA (samples E and D)	N/A	N/A	5.2	5.2	0.7	0.7	0.6	0.7	0.41	0.48
Supplier B										
MSA (samples E and D)	8.2	8.3	13.9	15	0.3	0.3	0.3	0.3	10	13

to – before plating te – after plating

Table 2 - Max Whisker Length

Cell	Sample	Substrate	Plating	Max Wskr Length	Comments
2	64 LQFP	CDA194	SnPb	0	Nodular multi-phase
3	64LQFP	CDA194	Matte Sn	37	Large Grain Growth
4	64LQFP	CDA194	3-5um Matte Sn	27	As above, mostly short
5	32LQFP	Cu7025	Matte Sn	37	Growth on bends, severe film damage on long cycling
7	44LQFP	CDA194	Matte Sn/2-3 Bi	42	Extensive grain reorganization
8	16SOIC	CDA194	Matte Sn/2-3 Cu	60	Extensive grain reorganization and film damage
10	8 SOIC	CDA194	Hot-dipped Sn	40	Large cracks and voids form after cycling
11	64LQFP	CDA194	245C Matte Sn	30	Large grain growth, whiskers on foot
12	64LQFP	CDA194	M Sn 150C 1hr	42	Whiskers in recrystallized areas
14	64LQFP	CDA194	Sn/2-4Ag	17	Small nodular growth similar to Sn/Pb