iNEMI COLLABORATION: Pb-FREE AND ROHS TRANSITION

R. C. Pfahl, Jr., J. B. McElroy, Sr.
International Electronics Manufacturing Initiative (iNEMI)
Herndon, Virginia, U.S.A.
bob.pfahl@inemi.org; jmcelroy@inemi.org

ABSTRACT

The output of the iNEMI roadmapping process is used to establish collaborative projects to close identified gaps. The four generations of iNEMI projects to address RoHS related issues were developed to close identified gaps from the 1998, 2000, 2002, and 2004 roadmaps. This paper will review recent iNEMI findings in the areas of Pb-free wave soldering, Pb-free substrate surface finishes, and Pb-free BGAs in SnPb assemblies. In addition, details of the IPC-1752 standard, Materials Declaration Management (exchanging RoHS composition data), and iNEMI's follow-on activities to accelerate the implementation of the standards will be discussed.

Key words: Pb-free, RoHS, environment.

BACKGROUND

Since 1998, iNEMI's collaborative agenda has been increasingly dominated by projects that address infrastructure gaps that face the electronics industry as it makes the transition to be compliant with materials restrictions and end-of-life regulations. Figure 1 outlines the major iNEMI industry driven efforts that are in various stages of completion. While the original emphasis was on materials and process related issues, over time the scope broadened to include supply chain and business process issues. We expect further collaborative efforts to emerge once the industry has additional manufacturing and field experience.

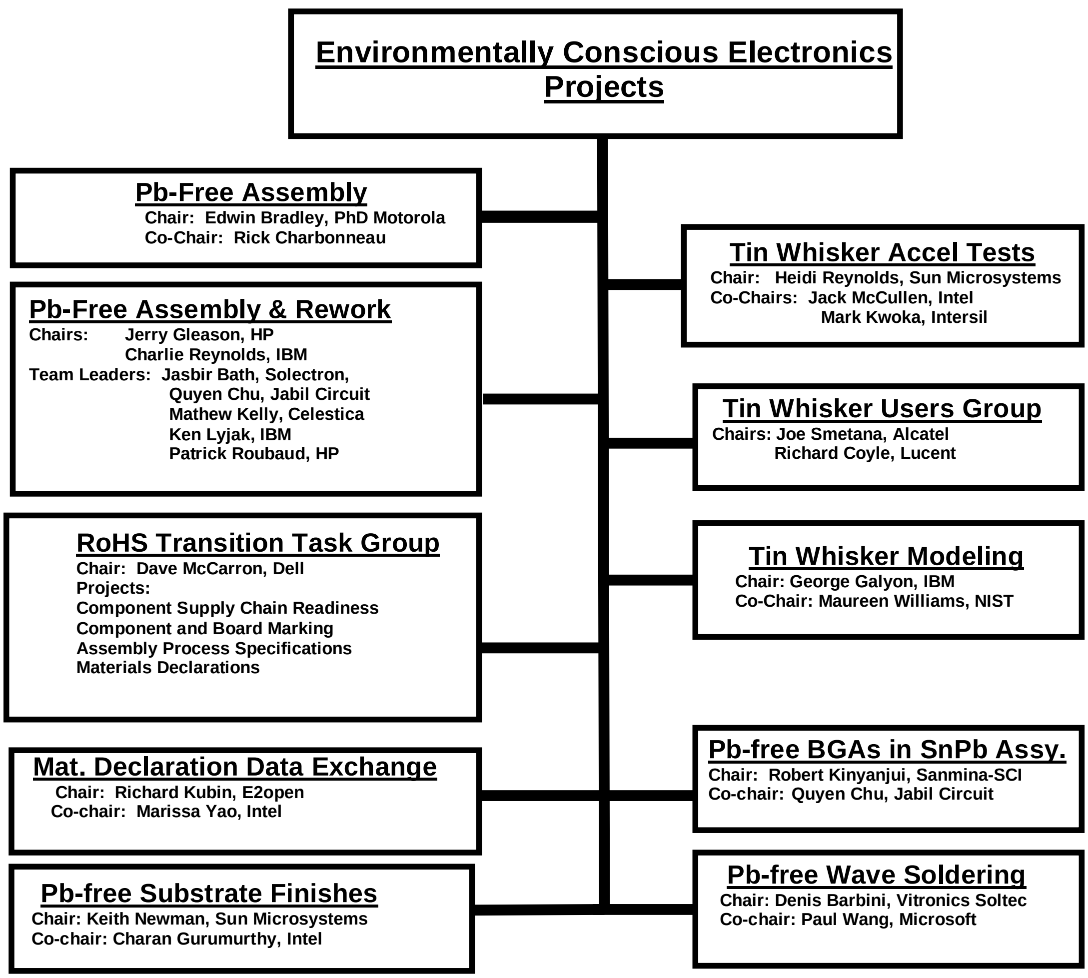

Figure 1 – Environmentally Conscious Electronics (ECE) iNEMI Projects

ECE PHASE I PROJECTS

iNEMI's 1998 Roadmap identified the need for materials and processes that would allow manufacturers to eliminate lead from electronic assemblies. In 1999, iNEMI organized its first lead-free project — the Pb-Free Assembly Project — with the goal of developing manufacturing capability to produce Pb-free products. Over the course of the next three years, the project team recommended an industry-standard alloy to replace tin-lead solders, and followed up with extensive testing to characterize the new materials and demonstrate reliability. This project moved the industry forward in knowledge and understanding of Pb-free materials and processes.

iNEMI's Phase I Efforts Accelerate Transition to Pb-Free Solder

In early 2000, iNEMI recommended the use of Sn3.9Ag0.6Cu for reflow solder based on extensive testing by iNEMI and NIST to characterize this alloy in order to demonstrate reliability and help industry implement lead-free solutions. Since that time, many lead-free solder compositions were proposed by others, causing significant confusion and dispersion of resources within industry. Today, the debate has shifted from this wide variation of materials to discussion of the best SnAgCu alloy for industry to adopt.

Although the compositions of some of the alloys being commercialized vary slightly from the iNEMI composition, the iNEMI alloy is representative of the acceptable range of lead-free solders. Tin-silver-copper formulations with silver content between 3.5% and 4.1% and copper between 0.5% and 1.0% are virtually indistinguishable in terms of melting point and process features. The iNEMI alloy provides a model system for industry that is extremely well characterized, and several iNEMI members currently are using the alloy in production. Clearly, the iNEMI focus on a single Pb-free alloy has helped to accelerate industry convergence on standard solder formulations, manufacturing processes and, ultimately, the timely and cost-effective conversion to lead-free assembly. To further push the industry toward a common solution, the IPC Solder Products Value Council is driving single alloy choice for industry standardization.

A number of iNEMI OEMs have made announcements in the past two years about new Pb-free products that are in full production including Motorola, HP, and Intel. A number of iNEMI EMS providers have announced Pb-free manufacturing capabilities including Celestica, Foxconn, Jabil Circuits, Sanmina-SCI, and Solectron.

ECE PHASE II PROJECTS

A second phase of projects was initiated by iNEMI to continue to fill in knowledge gaps. iNEMI's Pb-Free Assembly and Rework Project extended the Phase I project's work into new areas including the issue of board re-work with the higher temperature SnAgCu solder. The project's extensive testing of tools and processes to re-work SnAgCu soldered components on thick (up to 0.130") boards found that assemblies built with existing tools and processes threatened to reach temperatures exceeding 260^{o}C during rework. The team developed new tools and processes with the potential for keeping component temperatures in the range of 245^{o} to 250^{o}C. This work showed, however, that more extensive development would be required to come up with a robust rework process. Testing was on several assemblies, using two board thicknesses and a variety of representative components manufactured with the new procedures. Reliability evaluations were conducted on boards with and without rework.

iNEMI's Tin Whisker Accelerated Test Project was an open program to devise industry standard tests for predicting tin whiskers. The project team completed several rounds of experiments in an ongoing effort to identify an accelerated test method to help predict the propensity for tin whisker growth. Comparing results with Soldertec of Tin Technology Ltd (Europe), and the Japan Electronics and Information Technology Industries Association (JEITA), the three groups concluded that temperature-humidity (up to 60C/90% RH) and thermal cycling accelerate whisker growth. Based on these results, the iNEMI project submitted definitions of tin whiskers and measurement techniques to JEDEC for consideration as industry standards. Recently JEDEC has approved JESD22A121.01 – Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes.

iNEMI's Tin Whisker Modeling Project is attempting to understand why whiskers form, and how to control them. The group continues to pursue an understanding of the mechanism(s) that cause tin whiskers to form. The team published an annotated bibliography of tin whisker literature, written by project chair George Galyon (IBM), and developed a consensus position on whisker theories. A set of experiments is currently underway to look at stress, crystal orientation and material movement within tin film, using carefully prepared laboratory samples (to avoid the variations seen in commercial processes). The project team applied to Lawrence Livermore National Laboratory to use their synchrotron X-ray diffraction tool to gain insight into how whiskers form.

iNEMI's Tin Whiskers User Group Initiative was formed to develop recommendations for Pb-free surface finishes on components that would minimize the risk of failure from tin whiskers in high-reliability electronic applications. Although the modeling project has made significant progress, the root cause of tin whiskers is not yet totally understood. Thus, this initiative focused on developing standards for acceptance testing as well as mitigation strategies to reduce risk. The group has prepared and kept current a status report which is on the iNEMI web site. Recommended mitigation practices include: use of nickel-palladium or nickel-palladium-gold instead of tin; use of a nickel underlay; heat treatment (150°C for one hour) or reflow the tin coating within 24 hours of plating. Proposed standards for acceptance testing and mitigation were provided to JEDEC and IPC for development of industry standards. JEDEC has approved a document on acceptance testing for tin whiskers – JESD 201. JEDEC and IPC have released JP002 that provides basic whisker formation theory and mitigation practices that inhibit whisker growth.

ECE PHASE III PROJECTS

The 2002 iNEMI Roadmap highlighted the need for development of standards and requirements for collection, documentation and transmittal of material content data of components, assemblies and systems to be addressed in order to meet the requirements of the European Union RoHS (Restriction on use of certain Hazardous Substances) and WEEE (Waste from Electrical and Electronic Equipment) Directives. The European Union's RoHS directive will ban several substances from electronic products sold in Europe, beginning in July 2006; and the WEEE directive requires product marking and providing of hazardous material data to recyclers by July 2005. Manufacturers will be expected to prove conformity, requiring IT systems and audit trails that can cover the entire supply chain and manufacturing cycles. These systems must be able to track materials content and provide aggregate percentages at subassembly and whole unit levels.

To meet these requirements, through a series of gap analysis meetings held as open industry forums, iNEMI facilitated industry definition of infrastructure gaps and identification of several transition issues that could be addressed effectively through industry collaboration. This process led to the creation of the RoHS Transition Task Group to further define areas for standardization and develop implementation projects. This work will build on what is being addressed by other industry groups, such as EIA, AeA and IPC.

iNEMI organized five projects under the RoHS Transition Task Group. These five projects are:

- Assembly Process Specifications
- Component and Board Marking
- Component Supply Chain Readiness
- Materials Declarations
- Materials Composition Data Exchange

RoHS Assembly Process Specifications Project

As part of the ongoing industry effort to develop a Pb-free soldering process, there is a need for component standards that accurately reflect the "real world" conditions that will be encountered during soldering operations. Before these standards can be developed, a process must be fully defined that covers all aspects of assembly (SMT, wave solder, rework, manual rework, etc.). This definition must include the soldering temperatures for all component types, taking into account the solder joint, package materials and the PWB. The Assembly Process Specifications Project worked to define the Pb-free assembly process and determine the component specifications required for successful implementation of Pb-free soldering. In addition to developing a process definition document, this project identified industry standards that will need to be modified to reflect the Pb-free process.

RoHS Component and Board Marking Project

One of the issues surrounding the transition of the electronics industry to lead-free assembly is marking of components, boards and end products. There are several marking schemes being used by industry and, as Pb-free manufacturing proliferates, so does the number of marking schemes. JEDEC has had a marking proposal under industry consideration; the EMS Forum has developed guidelines for transition to Pb-free assembly that include part identification; Soldertech-UK has sent out a labeling survey; and several marking schemes are currently in use by individual companies. However, there is currently no industry standard for Pb-free component and board marking. This iNEMI project worked to develop recommendations for industry standards related to Pb-free component identification. Project deliverables included specifications for a labeling and marking standard (excluding point-of-sale/retail box marking) for components, cards and motherboards, both in raw material and finished product form.

RoHS Component Supply Chain Readiness Project

The objective of this project was to assess and influence readiness of the component supply chain to support RoHS product conversions. The group looked at RoHS content compliance and Pb-free process compatibility, focusing on board-mounted components and PWBs for mainstream electronics and high-reliability applications. The first step was to develop component compliance and compatibility criteria. Based on these criteria, the group gathered data to evaluate readiness of the supply chain. The final function of this group was to address identified roadblocks, whether through their own efforts or by leveraging ongoing projects from other industry consortia.

RoHS Materials Declarations Project

Material composition disclosure is becoming a critical issue for the electronics supply chain due to the proliferation of laws and regulations that ban the use of certain chemicals in electronics. Companies need to know that the products they are purchasing do not contain banned or restricted materials, and global efforts are under way to standardize how the electronics industry will declare hazardous and other materials in products and components. The Electronic Industries Alliance (EIA), European Industry Association (EICTA) and the Japan Green Procurement Survey Standardization Initiative (JGPSSI) have drafted a Material Composition Declaration Guide, which has now been released as a JEDEC standard.

The iNEMI Materials Declarations Project ran pilot tests to identify issues relating to the Material Composition Declaration Guide, focusing on legally banned and restricted materials. Based on information from these tests, the project team recommended a standard process for materials declaration, as well as content requirements, with a goal of developing an automated reporting process with minimal supply chain impact.

Materials Composition Data Exchange

The objective of this project was to work with the appropriate international standards bodies and the Material Declaration Project team to help define and validate standards for the exchange of Material Composition data between all elements of the value chain and across the entire product lifecycle in order to support requirements of the WEEE and RoHS Directives:

- Support for bulk material, component, sub-assembly and finished product level reporting.
- Definition of standard data formats and transfer protocols.
- Automate data exchange query and response where possible, while also supporting human interaction.

The specifications developed by these projects were handed off to IPC's 2-18 Subcommittee (Declaration Process Management), for development and standardization. Altogether, more than 50 of the electronics industry's largest OEMs, EMS providers and component manufacturers helped define the business requirements and develop specifications for these standards. IPC-1752 was released in February 2006, with a number of major OEMs, EMS providers and component manufacturers declaring their support and intentions for adoption. See the following link for information: http://www.inemi.org/cms/newsroom/PR/2006/PR020806.html. Draft versions of the standard have been wrung through multiple pilots, with some companies actually using it in production for more than eight months.

iNEMI is now in the planning phase of a follow-on project that will promote adoption of IPC-1752. Efforts are likely to include:

- Working with other organizations to help promote this as a global standard (e.g., IEC TC111, RosettaNet Japan + Asia, JGPSSI, ZVEI, and EICTA).
- Identifying and promoting key elements of supply chain that are committed to using the standard: OEMs, EMS providers, and component suppliers.
- Developing a generic business case that provides cost analysis, investment required, benefits, etc.

ECE PHASE IV PROJECTS

Five projects are currently underway to address a number of remaining issues that face our industry. These include:

- Pb-Free BGAs in SnPb Assemblies Project
- Pb-Free Substrate Surface Finishes Project
- Pb-Free Wave Soldering Project
- Pb-Free Rework Optimization Project (covered by another paper in this conference)
- High Reliability Task Group

Pb-Free BGAs in SnPb Assemblies Project

For companies choosing to take the RoHS exemption and continue to manufacture SnPb products beyond July 1, 2006, there will be a growing issue with the lack of availability of SnPb components. Many companies may be compelled to use Pb-free BGAs in an SnPb process, for which the process and reliability have not yet been characterized. The objectives of this project are:

- To assess the process parameters for assembling Pb-free SnAgCu BGAs under the temperature constraints of a conventional tin-lead (SnPb) assembly process.
- To understand the reliability of mixed-alloy (SnAgCu in SnPb) solder joints.
- To develop a "generic" process guideline and risk assessment for assembling Pb-free BGAs in an SnPb assembly process.

Phase I of the project is complete. Results include:

- Characterized joints at 205ºC, 225ºC, and 240ºC reflow temperature.
- Observed microstructures in agreement with predictions based on the calculated solidification path: especially, the Scheil calculations.
- SAC-Pb formed final frozen phases: (Sn) + (Pb) + ε with melting point: ~177ºC (calculated), & micro-pores observed in same area.
  - Further investigation of porosity effects may be required.
  - Results from different phase fractions compared to equilibrium microstructures.
- At 205ºC reflow temperature, there are significant differences in microstructure between the melted SAC-Pb and non-melted SAC. In addition, the primary ε phase will grow to an abnormal intermetallic compound (IMC) size if the reflow temperature is not sufficient to melt it. These features may be unfavorable to the reliability of the solder joint.

- The growth of the Cu6Sn5 IMC has less influence on the microstructures than that of the Ag3Sn IMC.

Pb-Free Substrate Surface Finishes Project

A number of surface finishes are being proposed for use in Pb-free assemblies. There are insufficient data to compare these alternatives from a manufacturing and reliability perspective. The objective of this project is to evaluate the effects of alternative surface finishes for circuit boards and package substrates on Pb-free solder joint reliability during accelerated stress testing. This group is conducting comparative four-point bend testing, drop testing and board-level thermal cycling of Pb-free components assembled on test boards, as well as comparative solder ball shear/pull testing on BGA and CSP components. The test packages include BGA, CSP and QFP devices, manufactured in a variety of Pb-free surface finishes. OSP and immersion Ag surface finishes are being evaluated for the circuit boards. Sn3Ag0.5Cu solder paste has been selected for the component attachment.

During 2005 a comprehensive test plan was developed, and the daisy-chain test packages (BGA, CSP, QFP, etc.) were fabricated and delivered. Time-zero component characterization (cross-section, X-ray, CSAM, co planarity, etc.) of these components was completed. Extensive low/high speed solder ball shear and pull testing was also completed. Thermal cycle and monotonic bend test board designs were released for fabrication.

Pb-Free Wave Soldering Project

The focus of the first two iNEMI Pb-free assembly projects focused on assembly, reliability, and rework of Pb-free joints. All participants in these two groups identified thru-hole assembly as a gap in the respective project scopes. This project aims to fill in this gap by addressing the Pb-free wave soldering issue on two levels: process and board level. The objectives of this work are:

- In phase I understand and characterize process-related challenges and material impact based on a low cost, representative test vehicle. The purpose of characterizing the Pb-free wave process is to optimize process parameters for Phase II where solder joint performance will be evaluated based on a specific, optimized Pb-free wave soldering process.
- Phase II encompasses the development of a test vehicle which is characterized by a complex network of components assembled upon varying board construction complexity. The purpose of this assembly will be to characterize joint performance.

During phase I the group designed an experiment to investigate the impact of various materials and process parameters on joint formation with specific focus on thru-hole penetration. The experiment was executed in March 2005 at Vitronics Soltec. Table 1 provides the parameters of that experiment.

Std Order	Atmosphere	Belt speed	Preheat Temp	Flux Quantity	Flux Type	Chip Wave	Solder Temp	PWB thickness
1	N2	3	100	1 low	VOC Free	on	255	0.062
2	N2	3	110	2 med	Alcohol	off	265	0.094
3	N2	2	130	3 high	WS	on	275	0.135
4	N2	3.5	90	1 low	Alcohol	off	275	0.135
5	N2	4.5	110	2 med	WS	on	255	0.062
6	N2	4.5	130	3 high	VOC Free	on	265	0.094
7	N2	5	100	2 med	VOC Free	on	265	0.135
8	N2	6	110	3 high	Alcohol	on	275	0.062
9	N2	6	130	1 low	WS	off	255	0.094
10	Air	3	90	3 high	WS	off	265	0.062
11	Air	3	115	1 low	VOC Free	on	275	0.094
12	Air	2	130	2 med	Alcohol	on	255	0.135
13	Air	4.5	90	2 med	WS	on	275	0.094
14	Air	3.5	115	3 high	VOC Free	off	255	0.135
15	Air	4.5	130	1 low	Alcohol	on	265	0.062
16	Air	6	90	3 high	Alcohol	on	255	0.094
17	Air	5	110	1 low	WS	on	265	0.135
18	Air	6	130	2 med	VOC Free	off	275	0.062

Table 1 – Design of Experiments Parameters for Wave Solder Process Characterization

High Reliability Electronics

Many iNEMI members are designing & manufacturing high reliability electronics. Many of these firms are taking advantage of Pb exemptions offered under the RoHS directive and therefore expect to continue to use SnPb assembly for some time (at least for the short term). Over the longer term, however, most of these same companies are planning for Pb-free conversion. Due to the supply chain conversion to Pb-free, this posture is creating a number of challenges/risks:

- The vast majority of component suppliers are converting to Tin finishes for I/O terminals. Tin whiskers remain a concern for high reliability applications.
- Most Pb-free BGAs are not compatible with Sn-Pb assembly processes.
  - Either need to have ongoing availability of Sn-Pb compatible BGAs, or
  - Need to develop a robust process for Mixed Assembly.

Many high reliability applications make use of large, complex PWBs. Once this segment does convert to Pb-free, a number of issues are identified:

- High complexity Boards stress materials and process for Pb-free assembly (e.g. laminates).
- Component survivability due to higher processing temperatures (especially for wave).
- Greater temperature variability over these complex assemblies.
- Robust repair processes do not currently exist.

In order to address these issues, iNEMI has formed a High Reliability Task Group to work with the supply base to insure that High Rel product needs are met. The group has now completed two position papers as one means of communication. The first paper covers the following:

- Addresses availability of SnPb compatible BGAs for High Rel segment.
- Communicates clear requirements for Tin Whisker mitigation and testing practices.

This position paper is available at:
http://thor.inemi.org/webdownload/projects/ese/High-Rel_RoHS_recommends.pdf

The group recently completed a second document to cover manufacturing issues with thermally complex assemblies. This document is available at:
http://thor.inemi.org/webdownload/projects/ese/High-Reliability_RoHS/High_Rel_position_021606.pdf

ENERGY AND THE ENVIRONMENT

In the 2004 iNEMI ECE roadmap, more emphasis is placed on sustainability, the impact of European legislation on the electronics industry, and the R&D needs to support environmentally conscious design. This reflects a more forward-looking posture for the industry as it relates to developing sounder scientific basis for environmental considerations. Specific findings/needs of the roadmap include:

- Development and implementation of good scientific methodologies to assess true environmental impacts of materials and potential trade-offs of alternatives.
- Development of cost-effective, energy efficient power supplies.
- Development of a common, meaningful, straightforward definition of sustainability that is relevant to the electronic industry and its supply chain, can be applied quantitatively at the business level, can be easily communicated to stakeholders, can be used to set targets, and that encourages an integrated, lifecycle sustainability strategy.

Halogen-Free Electronics

In epoxy resin circuit boards, TBBPA (Tetrabromo bisphenol A) covalently reacts with the epoxy resin backbone and ceases to exist as a chemical entity. Approximately 96% of printed wiring boards utilize TBBPA.

A series of studies has been conducted on unreacted TBBPA. In 1995, the World Health Organization (WHO IPCS) undertook a full scientific assessment of the environmental and human health impacts of TBBPA. Key findings from this study indicated that:

1) TBBPA has little potential for bioaccumulation.
2) Environmental detection is limited to very few sediment/soil samples.
3) The human health risks associated with TBBPA for the general population are considered to be insignificant.

Six independent studies from 1990-1997 concluded that TBBPA is not found to be a significant source of potential human dioxin exposure upon proper incineration (IPC, 2003).

In spite of these findings, a number of iNEMI firms are looking to eliminate these substances from their products. The rationale for this is as follows:

1. Emerging consideration of “progressive” public, institutional, and corporate procurement groups in Sweden, Norway, Denmark, Netherlands, Germany, UK, France, and Japan. Companies without halogen-free product offerings have begun to lose bids in these regions, especially in the mobile phone space.
2. Very limited consumer electronics and information technology on halogen-free product offerings are available.
3. Supply chain capability and capacity is not established. Standards and generic technology need development.
4. NGOs like Greenpeace are targeting actions against companies that use TBBPA.
5. Lack of legislation results in “material-of-the month” behavior driven by multiple environmental groups – we need a coordinated effort driven by a major industry influence.

These members have established a new project on Halogen-Free Electronics. The focus of this project is on printed wiring boards (PWBs). The objectives of the project are to:

- Build on industry knowledge and capability.
- Consider unique market segment requirements.
- Identify technology readiness and gaps.
- Stimulate supply capability.
- Recommend standards development opportunities.

The steps of this new project will be to:

- Define electrical requirements based on market segment application.
- Validate electrical and mechanical properties.

- Loss tangent and Dk modeling over required range of signal speed.
- Mechanical performance validation for Pb-free assembly.
- Validate material supplier and PWB manufacturer infrastructure capability.
- Estimate costs – volume market leader for new material may not achieve cost parity with best-in-class FR4.

THE 2007 iNEMI ROADMAP

Work is already well underway for the next roadmap cycle. While our schedule for release is essentially the same as past cycles, we have decided to add a year to the title to reflect the availability date to the public (iNEMI members will get access to the next roadmap during Q4 of 2006 – same as 2004 cycle). For this edition we are working to increase international participation (with focus on Asia and Europe). The first European iNEMI roadmap meeting was held in conjunction with Productronica in November of 2005. Other sessions are planned for both Europe and Asia including a workshop to be held in conjunction with HDP '06 conference in Shanghai (week of June 26-30, 2006). In addition to the cooperation we already enjoy with a number of industry groups, we are pleased to say that the board assembly roadmap will be developed in cooperation with SMTA.

CONCLUSION

The foundation of iNEMI's methodology is based on the biennial creation of technology roadmaps. Those who participate in the Roadmap creation get a broad view of the supply chain landscape from customers, competitors, and suppliers. Roadmaps can become "self-fulfilling prophecies" as many within industry focus on the identified challenges and benchmark their company against the user needs. The iNEMI roadmap process enables participants to understand and exploit new business opportunities within the manufacturing supply chain, improve the probability of providing the "right solution at the right time," and improve return on investment based on providing timely and needed solution. The roadmapping process can be a valuable tool for building industry consensus on the priorities for the greening of electronics.

iNEMI forms projects to address technology and infrastructure gaps identified through the consortium's roadmapping and gap analysis activities. iNEMI identifies areas: (1) that are not being addressed by other industry efforts, and (2) where members can collectively have an impact. Projects aim to eliminate gaps through:

- Accelerated deployment of new technology
- Development of industry infrastructure
- Dissemination of efficient business practices
- Stimulation of standards

The four Phases of iNEMI ECE projects to develop alternatives to the use of lead in electronics and to establish an infrastructure to meet the requirements of the European Union's RoHS directive are excellent examples of the achievements of the iNEMI process and its impact in strengthening the global electronics industry. iNEMI encourages increased international participation in this process.

Acknowledgements

The authors wish to thank the many individuals who have participated in the iNEMI roadmapping process and the iNEMI members who have conducted the projects that we have summarized – especially the project leaders identified in Figure 1.