RoHS Implementation Challenges

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Abstract
Implementation of the RoHS presents special challenges for small and medium sized companies. Limited staff and dependence on outsourced services creates cost burdens for smaller OEMs.

The first major challenge is conversion of existing product Bills of Materials. Conversion is usually much more involved than just re-specifying RoHS compliant parts on the AVL. For some components, it may be difficult to eliminate the offending RoHS element (Cd, Pb, etc.) and still have the product function successfully. Major corporations have been active in proposing and receiving special exemptions from the TAC committee but further additions seem less likely without substantial data.

A second major challenge is the "due diligence" process of collecting, compiling and evaluating supplier certificates of compliance and materials declarations for the multiple suppliers of hundreds of components. New database systems must be added, populated and sustained. Since most "due diligence" protocols advocate random component testing, arrangements must be made to screen and chemically test sample lots from most suppliers. Testing at the assembly level for extremely low levels of the six RoHS elements at the homogenous constituent layer level is problematic for many tiny electronic components. In some cases, it may take 5-10 components to make up the minimum quantity required for chemical testing. Yet, Pb is exempt in some layers while forbidden in other layers of the same component.

A third major challenge is assessing the reliability impact of conversion to RoHS. Thankfully, national and international consortia have addressed many of the major technical issues but each company must still address the impact of tin whisker mitigation strategies, SAC alloy fatigue behavior and higher reflow temperatures on their specific products. In most cases, converted products must be completely re-qualified to assess the impact of these changes on reliability.

Introduction
Most large, multinational corporations began RoHS compliance programs well before the publication of European Directive 2002/95/EC (RoHS) in January 2003. However, many small and medium sized companies have only recently begun to tackle the vast amount of work required to ensure their organizations are in compliance with RoHS/WEEE.[1] There are a number of practical reasons cited for waiting ranging from the hope that legislation will be delayed to the financial need to have others do the basic materials science research required for conversion. Since at past companies, the authors have participated in the early stages of several small companies, we felt it beneficial to present the issues involved in RoHS implementation from the perspective a small to medium sized company.

A number of workshops and conferences[1-6] have provided a general outline of the work that must be done to bring products into compliance with the Directive. Websites such as the one sponsored by The British Ministry of Trade and Industry[7] have provided valuable guidance. As evidence by this 12th International Lead Free Conference, IPC, JEDEC, NEMI and other organizations around the world have been actively engaged in addressing the many process and reliability issues associated with eliminating lead from solder joints. IEC working groups are working on chemical analysis methods for detecting the substances banned by RoHS.

Among the key points that can be gleaned from these presentations is the need to do, at minimum, at least the following to achieve compliance:

- Product Conversion including establishing Design for RoHS compliance guidelines and a review of each existing product Bill of Materials (BOM) for RoHS compliance
- Establish and validate lead free assembly and inventory management processes.
- Gather, compile and store "Due Diligence" documentation in a data management system
- Set up an audit program to screen and chemically test incoming components
- Contemplate individual product reliability issues that can occur from materials and process changes.

This paper will explore some of the details and issues associated with accomplishing this "things to do" list and speculate what the typical costs might be to accomplish RoHS compliance in a small to medium sized company.

Product Conversion

RoHS Compliance presents many product management and design decisions such as whether to bring an existing product into compliance or obsolete it, whether to make use of the currently granted exemptions or attempt to design products completely free of the six RoHS elements, and whether to incorporate other impending environmental initiatives such as halogen-free flame retardants. All of these choices significantly impact product cost, market timing and reliability.

At minimum, conversion of existing designs involves reviewing the Bill of Materials (BOM). For supplier designed purchased parts, the Approved Vendor List (AVL) must be reviewed and in many cases changed to reflect new RoHS compliant manufacturer's part numbers. This is not a trivial task given the vast number of individual part numbers and suppliers used by even a small electronics OEM. Some example cost estimates may put this into perspective. A reasonable estimate of component engineering time for one part might be 1.0 to 1.5 hours in order to review the AVL, investigate supplier's websites for RoHS compatible components, and then make changes in the document control and enterprise management systems. Given that a typical BOM might have between 50 and 100 supplier designed electronic components and that even a small company probably has at least 20 to 30 individual products, typical economics might resemble:

1.0 to 1.5 Hrs per PN x $75/Hr = $93/PN
50-100 PNs per BOM = $7000
20-30 Products x $7000 = $175,000

Similar costs might be expected for work contracted to outside agencies. Many smaller companies deal with part shortage and cost reduction issues by maintaining a large approved vendor list for off the shelf electronic components. This permits Purchasing to have a high degree of flexibility concerning supply shortages and pricing. Such strategies can be quite costly from a "due diligence" documentation and auditing standpoint. With each additional supplier added to the AVL, the costs of collecting documentation and chemical auditing increase. For this reason, some companies are making a concerted effort to reduce their supply base. This is something that is easier said than done at smaller companies since they lack the purchasing power with distributors and producers to demand "first in line" treatment when parts on in short supply.

In addition to the off the shelf electronic components, each mechanical part drawing must be reviewed and, in some cases, changed to eliminate non-RoHS compliant materials. Consideration should be given to adding "Must be RoHS Compliant" callouts in drawings in addition to reviewing the materials of construction. Besides its role in solder and tin platings, lead (Pb) is frequently used as an alloying element in metals to impart free machining or other desirable characteristics. Lead (Pb) has also found frequent usage in glass and ceramic chemistries to lower glass melting temperatures and improves other key properties. Fortunately, the issuance of exemptions has eased the engineering burden somewhat by allowing continued use of lead, cadmium and mercury in cases where no reliable technology yet exists to replace these elements. But the exemptions represent a reprieve not a pardon and they may only be valid until someone demonstrates the feasibility of a technology free of the banned substance. So each OEM must decide whether to change the product design or make use of the exemption in the hopes they will become semi-permanent.

If the product requires large, high layer count multilayer printed circuit boards and heavy thermal mass parts such as heat sinks or large area array components, the high peak reflow temperatures required for lead free solders will probably force a change to higher temperature printed circuit board laminate materials. Given the nature of many high frequency / high speed electronics, impedance differences may lead to the need for alteration of the printed circuit board designs as well. Differences between the mechanical properties of lead free solders can also have a significant design impact on the longevity of leadless and flip chip designs.

Once again to put things in perspective, a reasonable example of the costs to do such redesign activity might be:

10 Hrs per PN x $100/Hr =$1000 / PN
5 Mechanical PNs per BOM requiring redesign =$5000 / BOM
20-30 Products x $5000 = $125,000

This would bring the total costs for BOM Conversions of existing products to $175,000 + $125,000 = $300,000. This cost figure does not include the case where no suitable substitute exists for one of the RoHS substances in the product and no exemption currently exists to ease the transition. In such a case, the company may be faced with a major research effort to find a replacement and/or a major effort to generate the technical case and lobby for an exemption. Discovering that the removal of Pb, Cd, etc. is not possible at this late date could prove quite dire with less than six months to go before the July, 2006 deadline.

In addition to these product conversation activities, the prudent organization would also develop "Design for Environment" guideline documentation and a training program to assist designers in future product creation and avoid re-introduction of non-RoHS compliant parts during Engineering Changes Orders.

Assembly Process Conversion
Fortunately, much of the fundamental assembly process research required to produce RoHS compliant assemblies has already been done and reported in books[12, 13, 14], workshops[3] and forums such as the IPC/JEDEC lead free conferences[4, 5, 6]. Despite this, there are still plenty of decisions for each company to make based on their individual product requirements. These include whether to go with a mainstream SAC alloy (Sn / Ag 3% / Cu 0.5%) or use a more specialty solder alloy for temperature or mechanicals reasons. Suitable methods must be adopted for keeping RoHS compliant and non-RoHS compliant inventories separated and accommodating both lead free and lead containing rework and field returns. An assessment must be done of the company's current contract manufacturer (CM) to determine if the CM has adequate equipment and experience with lead free processes and inventory handling. Given that all these preliminaries are in place, there is still the task of doing pilot run evaluations on each converted product to establish reflow profiles, detect any product specific problems and generate functioning samples for product qualification and reliability testing.

For the purposes of cost estimation, suppose that SMT and 2nd OP tooling, line setup and operation cost $5000 per pilot run. Also assume that it will probably take about 100 assemblies for qualification samples and to get the SMT reflow / 2nd OP processes dialed in for each product assembly. Further assume that the raw component costs are $100/assembly. Example costs for accomplishing the assembly process conversion and generating samples for product qualification and reliability testing might be:

SMT & 2nd OPs tooling, setup & operation = $5000/ Pilot run
$100 /assembly x 100 assemblies = $10,000 / Pilot Run
20-30 Products: 25 x $15,000 / Product Pilot Run = **$375,000**

This cost estimate assumes that the Contract Manufacturer already has considerable general experience with lead free assembly processes and handling RoHS compliant materials. It also does not account for increases in inspection and rework costs as a result of non optimized lead free SMT, wave and hand solder operations. Nor does it account for scrap that may be generated when lead (Pb) containing parts are accidentally loaded on lead free assemblies and subsequently are discovered during at final audit with XRF equipment.

Due Diligence Documentation

Most RoHS compliance advisors[1, 2, 3,6,7] advocate the collection, evaluation and storage of extensive "due diligence" documentation from all component suppliers. This documentation typically should consist of a Certificate of Conformance to the RoHS Directive (CoC), a Materials Declaration that lists the percent composition, layer by layer, of all the substances in the component, and, if possible, chemical laboratory test data, which validates all the documentation. Some contend that a Certificate of Conformance should to be enough but European legal experts[2, 3] advise that a CoC alone would not be treated as having done adequate "due diligence" should the product be challenged entering the E.U. The British DTI RoHS website[7] provides useful guidance concerning due diligence, advising that there be a rational basis for determining whether a particular supplier's certification is trustworthy. In short, there is no one size fits all prescription but it is clear that merely accepting a CoC from a supplier is probably not enough and that some combination of supplier evaluations, Materials Declarations, test data and the OEM's own auditing of this data is appropriate. Besides the purpose of supplier evaluation, the Materials Declaration turns out to be very helpful if XRF or chemical analysis is to be done since sample preparation schemes and instrument calibration can be a strong function of the non-RoHS materials in the sample.

While it is possible to extract some or all of this documentation from suppliers during the component conversion process mentioned previously, it requires considerably more effort than just discovering the suppliers RoHS or "Green" part number and placing that number in the AVL. Although some suppliers have readily offered all this information on their websites, in many cases, several emails or phone calls are required to convince suppliers to provide the Materials Declaration or analysis data. There are a significant number who have yet to prepare Materials Declarations for their components. As mentioned previously, the data collection problems are compounded by the use of a large number of suppliers for a given part number. From a due diligence standpoint, data must be collected from each of the multiple suppliers listed for a given part number.

Ready access to this information will become necessary if product is challenged upon entry into the EU. Based on the Self Declaration approach, a company may have less than 28 days to produce evidence that the components within their product comply with the RoHS Directive[8]. Some smaller companies have, to date, avoided the costs of professional data management software by making maximum use of spreadsheets and other home made database products for Engineering data management. Given that even a small company may have several thousand component part numbers, each with as many as five suppliers, RoHS compliance begins to necessitate the organization of this information into a professional document control database. Such systems cost, at minimum, $150,000 for the basic system and $40,000 or more additional expense for RoHS/WEEE data collection modules with the additional expense of personnel to input the data and manage the system. It is not unreasonable to expect the implementation of this type of a system to cost in excess of $200,000.

Product and Supply Chain Auditing

Auditing the supply chain through chemical testing is advised in Annex D of The British DTI Guidance Document (November 2005)[9] as part of a company's "due diligence" efforts. It is also advisable to prevent non-compliant components from being accidentally built into product. There are several current supply chain issues that make screening components prudent. Some component suppliers have not changed part numbers but merely converted to RoHS compliant parts after a particular date. The only way to prevent mixing their non compliant parts with compliant parts is by Date Code verification. Shortages of RoHS compliant parts in the coming months will likely force smaller companies to consider the component "gray market" where the pedigree of the parts is unknown. In addition, there is confusion particularly among some suppliers about what constitutes a RoHS compliant component.

A typical chemical audit strategy might incorporate the use of X-ray Fluorescence (XRF) equipment to screen components followed by further testing of suspected components using a variety of wet chemical instrument methods (ICP-AES, FTIR/GCMS, UV-VIS). Both the $300,000 plus price tag for purchasing all this equipment and the trained chemists to operate it, lead most small companies to seek outside laboratory services to do this work. To continue with the previous economic scenario, a typical company might have an average of 50-100 parts per BOM and 20-30 BOMs, it is reasonable to have an average component count of 2000 unique part numbers. Now suppose that by careful analysis of package style commonality and trustworthiness of suppliers, you can narrow the list of audit candidates down to 10% of the 2000 part numbers or around 100 components to audit for RoHS compliance. If we assume an average cost per sample of analysis of $500, our costs for chemical auditing would be $100,000 to establish at this point in time that all the company's parts were RoHS compliant. Regrettably, due to the inevitable changes that occur in the supply base over time, this exercise might have to be repeated, at minimum, on an annual or semi-annual basis. If, in order to reduce the need for continually sending samples out for chemical testing, the company decides to purchase a tabletop or handheld XRF unit and appropriate standards for screening, these initial RoHS conversion costs would increase by perhaps another $50,000. This would bring the grand total for initial audit testing to around $150,000**.**

XRF is commonly cited as the best means to quickly screen components. A number of desktop and handheld units are available. Casual use of tabletop or handheld XRFs can be useful in detecting gross amounts of RoHS substances in components such as the presence of bromine in plastics, high cadmium or lead levels in plastics. But it is the authors' experience that accurate analysis of Pb and Hg at the 0.1% levels in most materials requires extensive calibration. Accurate detection of low levels of cadmium (around the 0.01%) is very difficult. In this case, calibration usually involves using standards that contain trace Pb, Cd, Hg, etc in the precise type of material matrix to be tested. For example, to accurately detect 120 ppm Cd in a tin-silver-copper solder, it may be necessary to calibrate the XRF machine with a minimum of 3 NIST traceable standards that have 200 ppm Cd, 100 ppm Cd and 50 ppm Cd, respectively. Because of this, it is dangerous to assume that just because the XRF has not detected an element that the sample is RoHS compliant. XRF units can also give false positives as well. Figure 1 shows an analysis of a cable with an XRF. The automated XRF program has detected high bromine, cadmium and mercury levels. Figure 2 shows that the automated XRF program has mistaken antimony (Sb) for cadmium (Cd). One of the antimony peaks occurs at the same spectral energy that the program was using to look for cadmium. In Figure 3, the XRF may have mistaken thallium (Tl) for mercury (Hg). Since the energy peaks from both elements are coincidental in many places, it may take wet chemical analysis to determine which is present. Many of these problems can be solved by adjusting and calibrating the automated program but it demonstrates the need for excellent software and extensive calibration with materials similar to those being inspected.

XRF Inspection of Cable Insulation

Item	Pb[ppm]	Hg[ppm]	Cd[ppm]	Cr[ppm]	Br[ppm]
Wire Insulation	73.3	3936	973.9	0	70020
Calibration					
XRF Value	45.1	96.0	77.3	96.4	928.4
Std Value	107.8	25.3	114.6	------	808

Figure 1. XRF inspection of the plastic insulation on a wiring harness. High mercury, cadmium and bromine levels were identified by the automated inspection program.

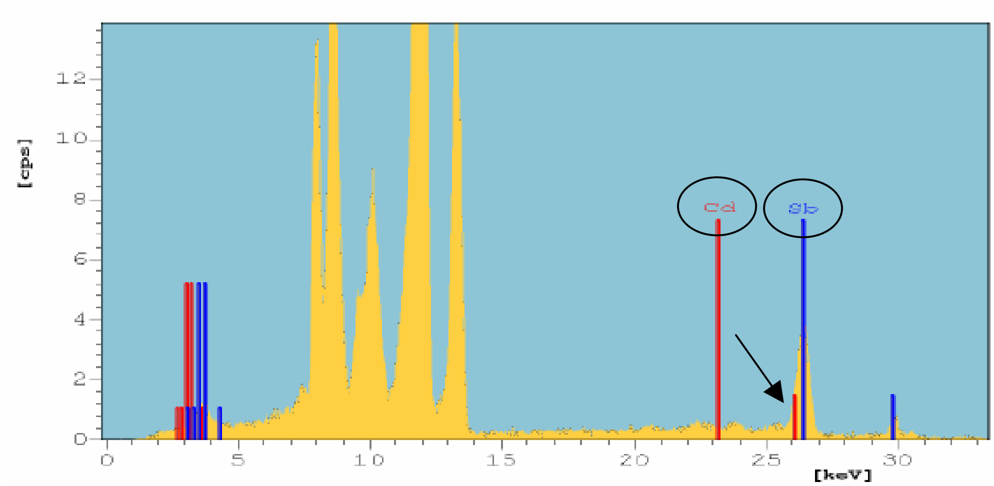

Figure 2 The XRF program has mis-identified Antimony (Sb) for Cadmium (Cd)

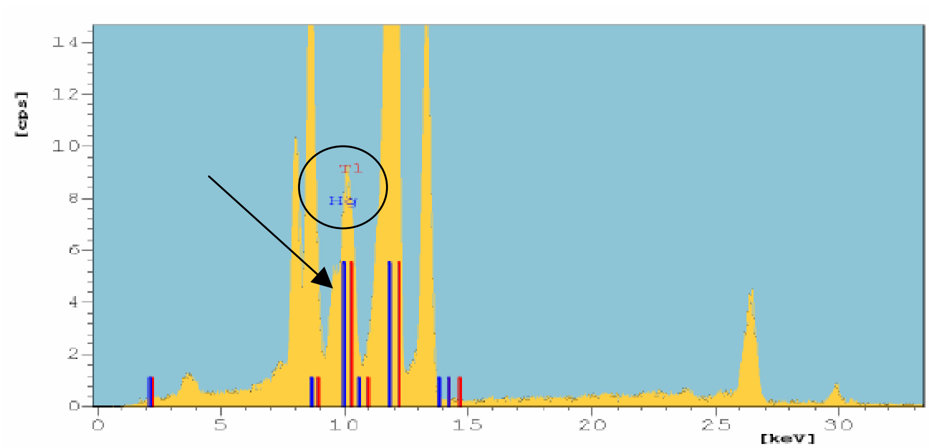

Figure 3 The peaks for Thallium (Tl) and Mercury (Hg) are close together leading to an ambiguous answer

The British DTI Guidance Document (November 2005)[9] explains in Sections 27-33 that the RoHS concentration limits apply to each "homogeneous constituent layer." It further explains that "homogeneous" means any layer that can be "mechanically disjointed" by "unscrewing, cutting, grinding, crushing and abrasive processes." In

Section 33, it further lists a semiconductor package as an example of a component that contains many homogeneous constituent layers. To the author's knowledge, there is, as yet, no size or weight exemption pertaining to this homogeneous constituent procedure. There are, however, practical limits to the size/weight of homogenous constituent layers that can be analyzed based on the known chemical and spectroscopic analysis methods.

A practical example of this issue has arisen with suppliers of small passive components. Some suppliers have submitted tin lead plated components for chemical analysis and when they found that the total lead (Pb) concentration of the component was below 1000 ppm, advertised the components as RoHS compliant. By the DTI Guidance document definition, these parts are not RoHS compliant since the lead (Pb) level in the termination plating (one "homogeneous constituent" layer) was 15% not 1000ppm. This was easily verified by targeting the termination area with a Scanning Electron Microscopy Energy Dispersive X-rays (SEM-EDX) beam. Over 40 percent of the "RoHS Compliant" components the authors used in their first pilot runs were found to have this problem. These parts were compliant if the entire component is ground up, dissolved and then analyzed; the parts are not compliant if individual homogeneous constituent layers are examined by more expensive micro spectroscopy techniques.

As this example points out, while the limits for the six RoHS substances have been set at levels that are within the capabilities of well-calibrated analysis equipment, there are many challenges remaining with sampling practices particularly with attempting to analyze individual homogeneous layers of component. There remain many difficulties in converting extremely heterogeneous solid electronic components into a liquid that can be injected into chemical analysis equipment. Many electronic components are smaller than the minimum sample size for wet chemical methods so multiple components must be used to make up one sample for analysis. Adding to these difficulties is the requirement that each "homogeneous constituent" layer (plating layers, sub component constructions, etc) of a component must meet the RoHS substance maximum limits. In many cases, economical means have not been found to analyze individual layers of tiny electronic components.

Figures 4 through 6 show examples of electronic components that have been cross-sectioned and the homogeneous constituent layers have been identified.

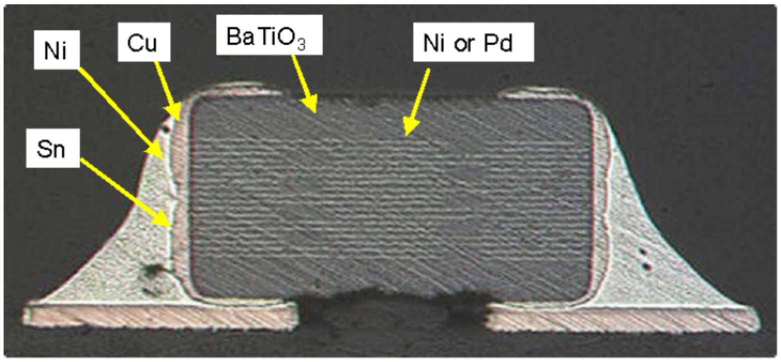

Figure 4 – Example of the homogeneous constituent layers found in an 0402 capacitor (Component weight is .0013 grams)

For the parts shown in Figures 4-6, it may take as many as 1500 of these 0402 components to make up constitute the 2 grams required for standard ICP-AES chemical analysis for lead, cadmium, mercury. There are methods such as Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICP-MS) that will permit parts per million chemical analysis of the individual layers of one component such as those shown in Figures 4-6 but these methods can cost as much as $550 per layer or several thousand dollars per component. Clearly the environmental impact of RoHS elements in some of these components does not justify such costs and it is also hoped that future enforcement actions will not require it either.

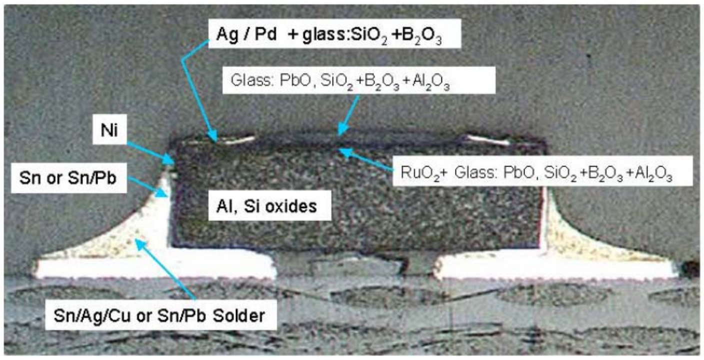

Figure 5 – Example of the homogeneous constituent layers found in an 0402 resistor

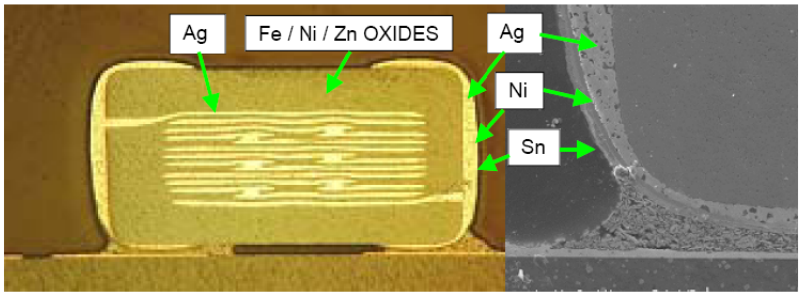

Figure 6 – Example of the homogeneous constituent layers found in a 0402 inductor

To proceed with the more accepted method of ICP-AES analysis, it would be necessary to somehow dissolve these components into a liquid that can be injected into the instrument. Figure 7 demonstrates how this would most likely be done:

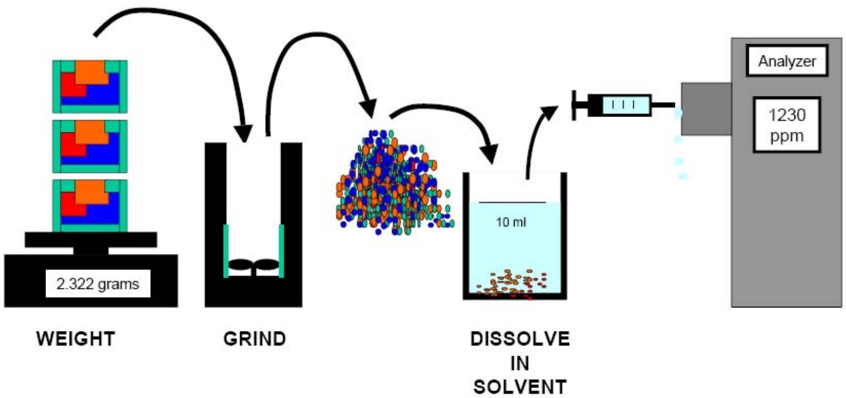

Figure 7. Sample preparation for chemical analysis of an electronic component

The parts should first be ground up to speed up the dissolution process. A typical problem that can occur during grinding is the smearing and adherence of sample material to the walls of the grinding vessel. If one component of the sample preferentially sticks to the vessel walls, this could lead to concentration changes in the sample. In the case of plastics, it may be necessary to use a cryogenic grinding method to turn the soft plastic into powder. Another question is whether the grinding device itself is contributing metal or abrasive particles to the sample. In the case of passive components, the ceramics in the components can be quite abrasive to grinding equipment. Causing extraction of vessel wall material into the sample. After grinding, the next task is to dissolve the powder in a suitable solvent. A dilemma arises if it is discovered that part of the sample remains in the bottom of the dissolving container and will not go into solution. Does the precipitate that will not dissolve contain Pb, Cd, Hg? If the chemist is successful with all these sample preparation steps, the ICP-AES will give a highly accurate answer in parts per million for the entire sample. But, for many tiny electronic components it does not tell the levels for each “homogeneous constituent layer”.

In the case of common chip resistors as shown in Figure 5, there is another interesting issue. Suppose a 1200 ppm lead (Pb) level is detected from a wet chemical analysis as shown in Figure 7. Is the lead due to the lead-oxide passivation glass on the surface, which is exempt per the Annex 5, or is it due to lead in the terminations which is not exempt? SEM-EDX or microXRF could be used to detect lead (Pb) levels above 1% on the terminations but such systems are usually not accurate down to the RoHS limits. There are similar challenges in sampling and measuring hexavalent chromium and flame retardant materials[10]. The IEC TC-111 WG-3 committee is working to address some of these issues but there are many challenges to overcome prior to July, 2006.

The above discussion points to the fact that it is not necessarily a simple matter of sending audit samples off to the lab for chemical analysis. Interpreting the results when they come back may be perplexing if not completely misleading. As with many of the tasks associated with RoHS, the entire project of auditing can be assigned to contractors. It is, however, the OEM who is ultimately responsible for the outcome, if not on legal grounds, then through the simple fact that his product may be sequestered indefinitely while misunderstandings about chemical analysis are explored by the authorities. While this is a challenging burden for the chemists of larger companies, smaller electronic companies may find the task of sorting through these issues daunting.

Product Reliability

One last area to consider is product reliability verification. As with lead free assembly engineering, considerable research work has been done and summarized in several excellent books[12, 13,14]. While many companies would typically conduct qualification testing after any major process change, several features of lead free soldering makes this an imperative. The SAC alloys used to replace tin-lead alloys have different solder fatigue properties and while most types of SMT solder joints appear at least as reliable with lead free alloys, this is not the case for all types. In addition, the higher reflow temperatures required by SAC alloy subject all the materials in the assembly to increasing thermal stresses making issues of moisture sensitivity worse. Many component packages have been redesigned to accommodate these higher temperatures. Standard FR4 printed circuit boards are no longer suitable for many designs because of the higher reflow temperatures. All of these factors make extensive product requalification a necessary part of converting products for RoHS compliance. Typical product qualification testing for many industrial electronics products entails a regime of 500 hour of thermal cycle, 1000 hours of humidity testing at 85^{o}C/85% RH, 100 cycles of thermal shock and several thousand hours of burn-in testing. Typical industry costs per product can range from $100,000 to $180,000 for environmental oven time, testing and personnel expenses. Assuming that by careful examination, the 20-30 products in the previous sections could be reduced to testing perhaps 10 representative family types, the product requalification tests would conservatively cost: $100,000 X 10 = $1,000,000. These costs would not include any Finite Element Modeling or thermal-cycle-to-failure testing to qualify new types of package solder joints; only normal product qualification tests.

The replacement of tin-lead platings with 100% matte tin have given rise to grave concerns in the electronics industry concerning the risk of tin whisker formation. Tests have been developed and published[15] for investigating the reliability of various tin platings but the tests are quite costly and time consuming. The tests involve multiple, optical or SEM inspections of representative plating samples after exposure to thermal cycling for 1000 hours and 30^{o}C / 60%RH and 60^{o}C / 87% RH for 3000 hours. The tests are probably best done by individual component manufacturers rather than after assembly. Many major OEMs are requiring that this testing be done to validate the platings used on individual components. Producers of peripheral products sold to these OEMs must either be able to collect this data from each component supplier or do the testing themselves. Given the number of inspections and environmental chamber time, these tests could cost between $20,000 and $30,000 per test. Assuming that the company must conduct this testing to compensate for the absence of data from critical parts suppliers, tin whisker testing could easily add $100,000 to the product conversion costs.

Conclusions

Neither the RoHS Directive nor government guidance documents address precisely what a company must do to ensure RoHS compliance other than be sure that the levels of the six RoHS elements are below the prescribed limits. Most believe that simply obtaining Certificates of Compliance from suppliers is probably not adequate but there is considerable flexibility in what constitutes “due diligence” beyond this. This paper has presented what might be viewed by many to be the typical “due diligence” activities a small to medium sized company might need to do to ensure RoHS compliance.

This action list is lengthy and there are many gray issues yet to be resolved. Most companies have found that conversion takes several years from the time management decides to respond until the final qualification testing is complete. This poses serious problems for any company who is just now beginning the conversion process and may be insurmountable for some smaller companies. Perhaps the most serious challenge facing smaller and medium sized companies are the costs of doing a minimum job of “due diligence.” The total estimated costs of this conversion are presented in Table 1:

Table 1.

Activity	Cost
Purchase Part Conversion	$175.000
Mechanical Components	$125,000
Pilot SMT & 2nd Op Runs	$375,000
Data Management Software	$200,000
Screening & Chemical Test Auditing	$150,000
Qualification & Tin Whisker Testing	$1,100,000
Total	**$2,125,000**

Some I have talked with believe these costs are very conservative. Two million dollars of non-revenue enhancing expense is a considerable burden for many small electronics companies.

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