Impact of the ROHS directive on high-performance electronic systems

Part I: need for lead utilization in exempt systems

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Abstract The European Union enacted legislation, the ROHS Directive, that bans the use of lead (Pb) and several other substances in electronic products commencing July 1, 2006. The legislation recognized that in some situations no viable alternative Pb-free substitute materials are known at this time, and so provided exemptions for those cases. It was also recognized that certain electronic products, specifically servers, storage and storage array systems, network infrastructure equipment and network management for telecommunication equipment referred to as high-performance electronic products, perform tasks so important to modern society that their operational integrity had to be maintained. The introduction of new and unproven materials posed a significant potential reliability risk. Accordingly, the European Commission (EC) granted an exemption permitting the continued use of Pb in solders, independent of concentration, for high-performance (H-P) equipment applications. This exemption was primarily aimed at assuring that the reliability of solder joints, particularly flip-chip solder joints is preserved. Flip-chip solder joints experience the most severe operating conditions in comparison to other applications that utilize Pb in electronic equipment. This paper briefly describes the solder-exempted H-P electronic products, their capabilities, and some typical tasks they perform. Also discussed are the major attributes that differentiate H-P electronic equipment from consumer electronics, particularly in relation to their operational and reliability requirements. Interestingly, other than the special solder exemption accorded to H-P electronic equipment, these products must meet all the other requirements for ROHS compliancy. The EC was aware that issues would surface after the legislation was enacted, so it created the Technical Advisory Committee (TAC) to review industry-generated requests for exemptions. The paper discusses three exemption requests granted by the EC that are particularly relevant to H-P electronic products. The exemptions allow the continued use of lead-bearing solder materials.

1 Introduction

The toxic effect of lead (Pb) is well documented and widely reported to be related to numerous health risks. Therefore, in the US the use of lead (Pb) has been banned in such products as paint, solder for plumbing, and as an additive in gasoline among others for sometime. But its continued use in electronic assemblies has led to a global movement seeking to establish a lead-free environment. In particular, it has been noted that so-called electronic waste, consisting mostly of consumer electronic products, is primarily disposed of in landfills where it poses a serious potential health risk. The concern is related to the possibility that rainwater will leach lead (Pb) from the solder on printed circuit boards (PCBs) and other parts containing Pb, and that the leachate will seep into the groundwater system and contaminate municipal water

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supplies. Based on these concerns the European Parliament and the Council of the European Union (EU) passed legislation, ‘‘Restriction of the Use of Certain Hazardous Substances (ROHS) in Electrical and Electronic Equipment,’’ Directive 2002/05/EC effective July 1, 2006. The ROHS Directive defines the requirements that each EU Member State must embody in separate laws enacted and enforced by each member country. Among these requirements is that a maximum defined concentration of four metals (mercury, lead, cadmium, and hexavalent chromium) and two organic-based fire retardant substances not be exceeded for certain products. This paper contains references to ‘‘lead-free’’ solder alloys, which has become an industry-standard term meaning the solder alloy should contain less than the ROHS Directive limit of 0.1 wt% (1,000 ppm) lead. It does not mean the solder alloy will necessarily contain no lead at all. The scope of the legislation essentially covers all electrical and electronic equipment including consumer electronics, information technology equipment (e.g. laptop, desktop computers), electric light bulbs, etc. There are some product categories that are outside the scope of the legislation: medical devices, military products and monitoring/control devices (under review). Also, the ROHS Directive does not apply to spare parts for the repair of electrical and electronic equipment (EEE) placed on the market before July 1, 2006; or the reuse of EEE placed on the market before that date. Lead is pervasively used in electronic products of all types. Among the allowable usages of lead (Pb) are: glass in monitors, brass and aluminum hardware, free-machining steel members, certain electronic components (e.g. capacitors, piezo electric devices), lead-acid batteries for operation or backup, cable sheathing and solder for components and assembly to PCBs. The quest to replace Pb-bearing solders is a daunting task and is the largest and most costly effort the electronics industry has ever undertaken. Lead (Pb)-based solders have been utilized to assemble circuit boards in electrical products for more then 50 years. The conversion to Pb-free technology has raised some serious reliability concerns within the industry. The European Commission (EC) recognized that the introduction of a new material set in electronic products posed risks, particularly as it relates to reliability. Accordingly, some exemptions were granted because Pb was used in some applications for which there are no known suitable substitutes. For example, the EC allowed the use of Pb in the glass screens of cathode ray tube monitors to provide protection from X-rays. An exemption was also granted for the use of Pb in solder materials, but it only applied to high-performance systems (servers, storage, network infrastructure/telecommunication systems). These electronic products are markedly different from consumer products in almost every way. This paper briefly describes those products that received the special solder exemption and their capabilities because they perform mission-critical operations, a necessary element of modern society. Reliability is the single most important attribute that distinguishes so-called high-performance (H-P) electrical equipment from consumer products. It is imperative that H-P electronic equipment possess the capability to operate successfully and uninterrupted for years on end to perform their important tasks, as contrasted with the occasional use of consumer electronics that provide entertainment and convenience.

The European Commission (EC) further recognized that issues would arise during the lead (Pb)-free implementation process. Therefore, the EC created the Technical Advisory Committee (TAC) to review industry requests for exemptions (i.e. allow the use of Pb) for specific applications. The requests were to cover applications where there currently is no suitable replacement for lead (Pb), or where the replacement substance(s) posed a greater potential risk to human health or the environment than lead. Several important exemption requests were granted by the EC that have particular relevance to high-performance products. The exemptions allow the use of mixed solder joints to attach chips; and the use of Pb for compliant pins, and part of a thermal-dissipation subsystem. These exemptions are all discussed in detail.

2 High-performance electronic systems

The European Union’s ROHS legislation expressly grants an exemption for the use of lead (Pb) in solders, regardless of composition in high-performance, high-reliability systems specifically, ‘‘servers, storage and storage array systems, network infrastructure equipment for switching, signaling, transmission as well as network management for telecommunications’’ [1]. But the intention is to phase out the exemption, and conduct progress reviews every few years with the initial review scheduled for 2008. These products have several characteristics and requirements in common that differentiate them from consumer-electronic products. The most important characteristic is that they all require a very-high degree of reliability since they are relied upon to carry out mission-critical operations and must virtually perform flawlessly over their operational lifetime. Equipment failures could have severe societal or human life consequences. A brief description of the high-performance systems granted a special solder exemption and their reliability requirements follows.

2.1 Solder-exempted systems and their functions

2.1.1 Server systems

Servers are often classified into three categories. (a) Entry-level (Fig. 1 b, d) systems, which possess a very significant processing capability and are utilized for a variety of applications: management and integration of small-to-large business operations, and optimized to integrate network and distributed computing. They are also used for specialized applications such as patient monitors; and for (control) equipment in hospitals, industry, etc. In some cases sophisticated desk-top personal computer (PC) systems may possess similar capabilities, but even so-called entry-level servers are designed and tested to provide a very high level of reliability not characteristic of PCs. (b) There are several types of mid-range systems, some are architected to provide optimum management and integration of business operations (Fig. 1f); while others are designed to maximize computing power for business, government, and scientific applications with the ability to model complex systems, perform detailed data mining, etc. by reliably performing massive scalar-integration operations (Fig. 1e). (c) High-end server systems, often referred to as mainframe or enterprise systems (Fig. 1c) are configured to provide unmatched computing performance, data integrity, security, scalability, and interconnection capability. Because of these unique attributes they are used to provide massive, reliable computing power for such applications as insurance, international banking, and airline reservations in the business arena; are the basis of national security systems; perform operations at all levels of government and military; research; development; etc. [2].

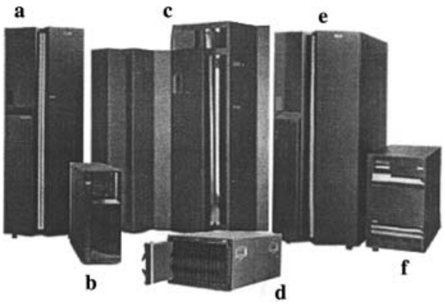


Fig. 1 The photograph depicts a range of IBM server systems. (**a**) pSeries, intermediate high-end. (**b**) iSeries, low-end. (**c**) zSeries, high-end. (**d**) xSeries, configurable blade server. (**e**) pSeries, high-end server. (**f**) iSeries, mid-range server (courtesy of M. Hoffmeyer, IBM Corporation)

2.1.2 Storage Systems

The storage function is an integral part of complex and sophisticated information systems that store, provide, and direct the flow of information to server systems. Disk libraries (Fig. 2a) are large stand-alone systems used to access frequently needed information. These systems are faster than tape systems and typically consist of more than 125 drives, where each drive provides storage of more than 70 giga bits (GB) of information. Tape systems (Fig. 2b) are also stand-alone units with a capacity of about 6,000 tape cartridges, and with tape drives that can read and write tape media. They provide long-term storage and access libraries. Storage Area Network (SAN, Fig. 2c)

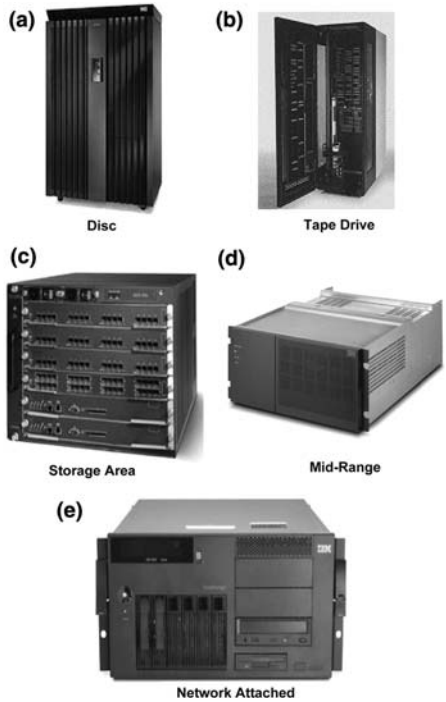


Fig. 2 The photograph depicts a range of storage systems. (**a**) Disc library. (**b**) Tape drive system. (**c**) Storage Area Network (SAN). (**d**) Mid-range system. (**e**) Network Attached Storage (NAS) (after Ref [2]) (courtesy of IBM Corporation)

systems serve as a switch or a director of information among servers and/or storage units. These units are capable of very rapid data rates, e.g. 10 GB/s or more. Mid-range Systems (Fig. 2d), so-called because they are often utilized to support mid-sized businesses, are rack-mounted units. They consist of a small number (15 or so) of disc drives that provide a continuous flow of data across storage networks. Network Attached Storage (NAS, Fig. 2e) systems are also rack-mounted units that contain a small number of disc drives and configured to serve as an interface between a LAN and SAN [2, 3].

2.1.3 Network infrastructure and telecommunications equipment

The solder exemption granted for network infrastructure equipment specifically relates to routing, switching, signaling, transmission, network management or security and telecommunications. Network infrastructure equipment consists of integral and complex elements of information systems that provide mission-critical support for communication networks.

2.2 High-performance systems vs. consumer electronics

The requirements and characteristics of high-performance electronic products are very different from consumer electronics (Table 1). The PCBs are very complex compared to consumer products and typically consist of a large number and high mix of attached components, with thousands of solder joints (Fig. 3). High-end equipment is expensive, low volume, and usually owned by corporations. The equipment is sophisticated, requiring long development cycles to assure the demanding functional and reliability requirements are met. These products experience continuous utilization over their operational life time, with virtually no allowed down time. In some applications such as satellite systems there is no opportunity for repair; while others must operate under harsh environmental conditions, experiencing temperature extremes between – 40 and 70°C [4]. The successful operation of high-performance systems is absolutely necessary, given their potential societal and life/death consequences in the event of failure, compared to annoyances of consumer-product failures. Changes that have the potential of compromising reliability such as the introduction of Pb-free solder joints cannot be incorporated into high-performance systems until they are demonstrated to pose a very low risk.

Table 1 Typical characteristics and requirements of high-performance systems vs. Consumer electronics

Characteristic/ Requirement	High-performance systems	Consumer electronics
Complexity	High to very high	Low
Development time	2–5 years	1–3 mos.
Owners	Corporations	Individual end users
Product life	Servers/Storage: 5–15 years Network Infra. Equip: 15–20 years Telecommunications: up to 25 years	1–5 years
Utilization	24 h/day, 7 days/week over product life time	Intermittent over life time
Volumes	Very low	Very high

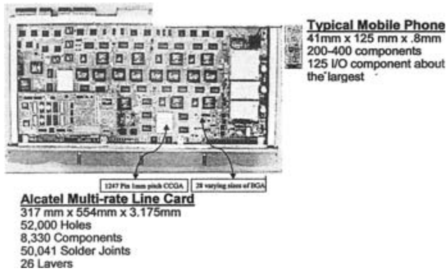


Fig. 3 Photographs that illustrate the difference in complexity between a telecommunications infrastructure product (high-performance) PCB and a mobile phone PCB (consumer product). The photographs are approximately to scale (after Ref. [4]) (courtesy of Alcatel)

2.3 Reliability and operational requirements

The reliability and operational requirements of the high-performance systems granted a solder exemption, far exceed those of any other electronic equipment in use today. For example, these systems are expected to be capable of continuous operation 24 h per day, 7 days per week, for at least 10 years in most cases [2, 3] and up to 25 years for some telecommunications equipment. The allowed "downtime" for high-performance systems varies from an average of 5.3 min per year for network infrastructure equipment [5] to essentially no allowable failures for mainframe computer systems (Table 2) and the storage systems that support them. For example, based on an average of 100 installed units, a mainframe computer typically only experiences one incident repair action (IRA) in over 10 years of operation. However, the system is still fully or partially functional so repairs can be made at the

Table 2 Typical mainframe computer operational and reliability capabilities

Feature/Aspect	Capability
Typical field life	90,000–100,000 h
Lifetime operating percentage	99.9954%
Average total lifetime downtime	Less than 4 h
Frequency of an Incident Repair Action (IRA)*	> 10 years
Frequency of an Unscheduled Incident Repair Action (UIRA)*	> 30 years

*Average based per 100 installed units in the field (after Ref. [3])

user's convenience. Sometimes no failures are involved, but modifications made to update the system such as installing a microcode patch, change a channel card, etc. An actual system crash or so-called unscheduled incident repair action (UIRA) typically only occurs about once every 30 years or more, also an average based on every 100 systems installed in the field. The requirements for high-performance systems far exceed those of consumer electronics, which are only used occasionally and whose operational lifetime is normally 1–5 years. Also, there are no particular reliability norms associated with consumer-electronic products.

2.4 Use of lead in high-performance electronic systems

High-performance electronic systems typically are complex. For example, a large-scale electronic processor consists of 10,000 or more individual parts that are combined into subassemblies that are themselves combined into functional assemblies or systems, e.g. power, memory, logic, cooling, etc. Many of these contain lead (Pb). Individual parts, subassemblies, and assemblies are categorized into subclasses to efficiently manage parts purchasing, the vendor supply line, and production. Although there are no industry standards, some typical subclass categories that utilize lead and common to many high-performance products are listed in Table 3. Lead (Pb) is an ingredient in a variety of materials utilized in electronic products including cathode ray tubes, (CRTs) for shielding radiation, in cables as a PVC stabilizer, in certain ceramic components (e.g. capacitors, piezo electric devices), but predominantly in solders. It is estimated that over 200,000 electronic components contain lead-bearing solders. Solders are literally the "glue" that hold electronic products together and also possess the necessary electrical, mechanical and thermal properties. Solder is utilized as a coating material on the traces (i.e. copper circuitry) of PCBs and component lead frames. Solder is used for flip-chip solder bumps, and solder-ball terminated components (BGAs, CSPs). It is also used to attach all the circuit elements to PCBs (components, connectors, passives, etc.), to form hermetic seals for some components, etc. Eutectic (63Sn–37Pb) solder has been universally used for the assembly of cards and boards, but both low-Pb solders (85Sn–15Pb) and high-Pb solders (97Pb–3Sn) are utilized in electronic products as well [6].

Table 3 Some lead (Pb) containing hardware categories common to many high-performance electronic products

Part/Assembly category	Lead (Pb) utilization
Electronic functions	Card/component lead finishes Solder joints
Memory functions	Component lead finishes
Logic functions	Component lead finishes
Storage finishes	Component leads/card Solder joints
Power supply	Components/solder/card/finishes
Voltage Reg. Modules	Components/solder/card/finishes
I/O & system cards	Surface finishes
Actives/Optics/Passives	Lead finishes
Cables/Connectors	Thermal stabilizer in cables Connector finishes
Mechanical parts	Metal joining (solder)
Black/Grey boxes	Hard drives Monitors Power supplies

3 Exemptions important for high-performance electrical systems

The ROHS legislation notes a variety of applications (Table 4) where the use of lead (Pb) is permitted regardless of the electronic product category since no viable alternative materials are known. It is also stated

Table 4 ROHS Lead (Pb) exemptions for any electronic product

Exemptions
Non-solder related
Piezo electric devices
All glass products
Cathode ray tubes, fluorescent tubes, filter glass
Lead utilized as an alloy with certain metals
0.35% in steel
0.4% in aluminum
4.0% in copper
Electronic ceramic components
Lead-acid storage batteries
Solder related
High-lead content solders, > 85% Pb
Two-element solders, > 80% Pb, but < 85% Pb

in the Annex of the ROHS legislation that the use of lead in solders is permitted (i.e. with no concentration limitations) in servers, storage systems, and network infrastructure/telecommunications equipment. It should be noted however, that the use of lead in these high-performance systems is also banned, except for solder materials. The European Commission (EC) never issued any guidance documents that defined the term ‘‘solder’’, which has caused some controversy and confusion in the industry. For many applications there is broad agreement, while in others it is not clear if the exemption applies. In any event, the general solder exemption (> 85% Pb), and the solder exemption for high-performance systems were granted to assure the reliability of solder joints, which will be discussed in detail later in this paper.

The EC realized that as the electronics industry pushed forward in implementing Pb-free technology new issues were likely to arise. Accordingly, a procedure was put in place whereby the EC’s Technical Advisory Committee (TAC) reviews industry-generated exemption requests. Three exemption requests granted by the EC that are of particular importance to high-performance systems are: flip-chip mixed solder joints, the use of Pb for compliant-pins, and for a C-ring utilized in a cooling system.

4 Lead (Pb) use in solder exemptions for microelectronic packages applications

4.1 Components with wirebonded chips

The ROHS Directive makes it necessary to eliminate lead (Pb) (i.e. < 1,000 ppm level) in microelectronic components utilized in electronic products that do not qualify for an exemption such as personal computers (PCs), personal data assistants (PDAs), camcorders, digital cameras, and other consumer electronics products. Although lead (Pb) is used internally for some microelectronic components, it is most often used for component terminations (i.e. lead-frame finish, or solder ball/bump) and the solder paste to reflow attach components to the next level of assembly, typically a printed circuit board (PCB). The use of Pb for some major microelectronic package types is illustrated in Fig. 4. A quad flat pack (QFP) consists of a chip that is adhesively back-bonded to the chip carrier. Thin gold or aluminum wires are bonded to pads located around the periphery of the chip that provide the electrical path between the chip and plastic chip carrier. Lead–tin coated metal fingers, called leads, extend beyond the molded plastic body and are used to attach the package to the PCB. A Pb-free lead finish (e.g. pure Sn) is used to render these components ROHS compliant. This is also true for solder-plated pads on quad flat non-leaded (QFN) and bumped chip carrier (BCC) packages. They also utilize adhesively-mounted wirebonded chips (Fig. 4b, c). Plastic ball grid array (PBGA) components and their enhanced versions EPBGA or HPBGA with wirebonded chips (Fig. 4d, e) consist of an array of solder balls on the under side of the plastic chip carrier, used for attachment to a PCB. The standard solder ball composition is typically eutectic Sn–Pb or eutectic Sn–Pb with 2% Ag to help reduce leaching Cu from terminal pads during reflow operations. Both compositions are compatible for assembly with Sn–Pb solder paste. ROHS-compliant versions are created by utilizing Pb-free solder balls, usually a Sn–Ag–Cu (SAC) solder alloy.

4.2 Components with flip-chips

4.2.1 *Attributes of flip-chips*

Flip-chips provide for large numbers (several thousand) of tiny (about twice the diameter of a human

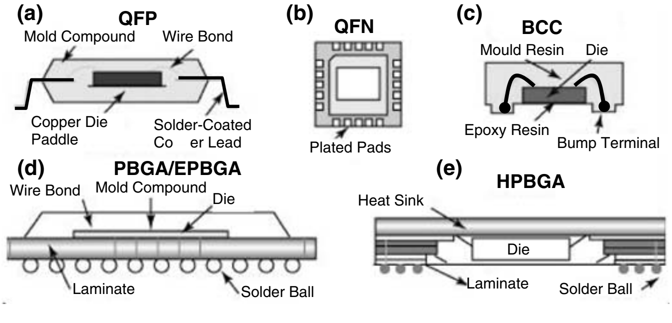


Fig. 4 Illustration depicting several microelectronic package types: (**a**) Quad flat pack (QFP). (**b**) Quad flat non-leaded (QFN). (**c**) Bumped chip carrier (BCC). (**d**) Plastic ball grid array (PBGA)/enhanced plastic ball grid array (EPBGA). (**e**) High-performance ball grid array (HPBGA) (after Ref. [7])

hair), densely-spaced solder bumps spread over the entire active surface of the device. The solder bumps are located below the chip allowing close chip-to-chip spacings (typically referred to as brickwalling). Close chip proximity is important since it allows for the efficient use of chip-carrier real estate, but even more important, it reduces the chip-to-chip distance, thereby significantly increasing the circuit speed, i.e. performance. Flip-chip interconnections also provide superior electrical performance (i.e. low inductance and resistance) since they are very short, large-diameter conductors compared to the wire interconnections utilized for wirebonded chips. Flip-chip solder joints have demonstrated a very high degree of reliability in the field, the highest of any chip interconnection technology. Their very-high interconnection density capability, excellent electrical characteristics (even for high frequency and multiple simultaneous switching conditions), and high reliability are some of the major reasons that flip-chips are so widely used in high-performance, high-reliability electrical equipment. It is also thought to be the reason the EC provided a general exemption for solders with > 85% Pb, i.e. to assure the integrity and desirable mechanical properties of solder joints, and those of flip-chips in particular.

4.2.2 Flip-chip solder joint requirements

Flip-chip solder joints serve several important purposes: they provide both an electrical and thermal path between the chip and next level of assembly, as well as a mechanical attachment. Wirebonding only provides an electrical path. Flip-chip solder joints must, therefore, maintain adequate mechanical properties, particularly the ability to withstand thermal fatigue. Thermal fatigue is the result of a mismatch in the coefficient of thermal expansion (CTE) between the materials attached to the opposite ends of the solder joint (i.e. the silicon chip and next level of assembly material). Solder joints experience shear stresses when exposed to temperature cycles that result from electrical equipment being turned ''on'' and ''off''. Lead (Pb) is almost unique in its ability to withstand failure upon being bent back and forth during the course of up to several thousand thermal cycles. That is, high-Pb solders have the ability to relieve stress through plastic deformation, in contrast to high-Sn solders where the ability to undergo plastic deformation is considerably more difficult. The ability to undergo plastic deformation (i.e. be ductile) without undergoing failure is an important characteristic for flip-chip solder joints. High-Pb solder joints accommodate shear stresses internal to the solder joint instead of ''passing'' the stress on to the fragile, stiff and brittle silicon chip.

Finally, high-Pb, high-melting solders such as 97Pb–Sn (MP = 322°C) often used for flip-chip solder bumps, have the ability to withstand high current densities over long periods without undergoing a degradation process referred to as electromigration, discussed in Part II.

4.2.3 Flip-chips mounted in BGA packages

Converting BGA microelectronic packages with wirebonded chips to ROHS-compliant (i.e. Pb-free) versions requires changing the solder balls to a Pb-free solder. But the situation is more complicated in the case of packages with flip-chip mounted semiconductor devices. Consider for example a flip-chip with 97Pb–Sn solder bumps reflow attached to a ceramic BGA chip carrier, (Fig. 5a). Although the BGA solder balls are 90Pb–10Sn (Fig. 5b), the attached component may or may not be ROHS compliant. The composition of the flip-chip solder bumps are compliant. But the composition of the BGA solder joints may not be compliant depending on the fraction of eutectic solder volume comprising the joints. The component consists of eutectic Sn–Pb solder fillets that attach the 90Pb–10Sn solder balls to the CBGA. Depending on the eutectic

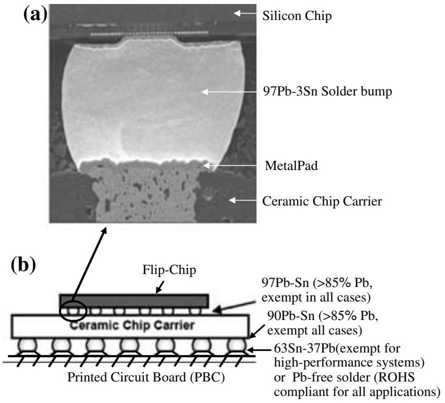


Fig. 5 A flip-chip with high-Pb (97Pb–3Sn) solder bumps is attached to a ceramic chip carrier that has high-Pb (90Pb–10Sn) solder balls. (**a**) Photomicrograph of a vertical cross section of a flip-chip solder bump directly reflow-attached to a metallized pad on the ceramic chip carrier (after Ref. [8], courtesy of IBM Corporation). (**b**) Sketch depicting two ways the ceramic BGA can be attached to the PCB: with eutectic Sn–Pb (exempt for high-performance systems) or Pb-free solder, which is ROHS compliant but creates a mixed solder joint that is not forward compatible

Sn–Pb solder volume utilized to surface-mount attach the component to the board determines if the lead content in the CBGA solder joints are > 85% in order to be ROHS compliant. That is, if the amount of eutectic Sn–Pb solder paste used to SMT-attach the CBGA component is too great, the resulting lead (Pb) concentration in the CBGA solder joints will be < 85%; and therefore not ROHS compliant. Exempted high-performance equipment (i.e. servers, storage and storage array systems, etc.) are not affected by the eutectic Sn–Pb solder volume issue since they can utilize any solder independent of Pb content. Note that if the BGA component with 90Pb–Sn solder balls is attached to the PCB with a Pb-free solder, a mixed solder-joint condition is created. Although ROHS compliant, it is considered a reliability risk (i.e. not forward compatible) as discussed in Part II.

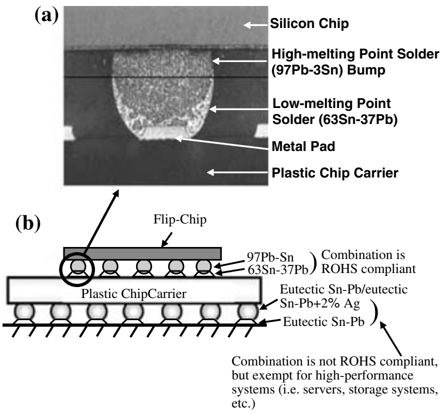


Fig. 6 A flip chip with a high-Pb (97Pb–3Sn) solder bumps is attached to a plastic chip carrier that has low-melt solder balls (eutectic Sn–Pb). (**a**) Photomicrograph of a vertical cross section of a flip-chip solder bump attached to a metallized pad on the plastic carrier with a low-melting point solder, eutectic Sn–Pb (after Ref. [8]) (courtesy of IBM Corporation). (**b**) Sketch depicting the attachment of the plastic chip carrier with eutectic Sn–Pb solder paste forming an all-eutectic Sn–Pb solder joint that is not ROHS compliant, but exempt for high-performance systems

The use of plastic BGA chip carriers has become widespread owing to their reduced weight and lower cost compared to ceramic BGAs. The flip-chip solder bumps of some BGA part numbers may only be available with high-Pb solders (i.e. 97Pb–Sn) that require a 340°C or higher reflow temperature which is much higher than plastic chip-carrier materials can withstand. The chips are therefore attached with a low-melting-point solder, usually eutectic Sn–Pb to circumvent the problem. The use of a low-melt solder to attach flip chips with high-melt solder bumps (Fig. 6a) has recently been approved by the European Commission. Although this combination consists of two different solder compositions, they are both of the same Pb–Sn solder family. The degree of high-Pb solder dissolution into the low-melting eutectic Sn–Pb solder is normally quite limited under standard assembly reflow conditions. This solder combination typically results in high-reliability solder joints because most of the solder joint is high-Pb which characteristically provides superior fatigue resistance. Flip-chips with eutectic Sn–Pb solder bumps can be directly reflowed to plastic chip carriers without the concern of thermally degrading the carriers. These solder joints are ROHS-compliant even though the Pb content is less than 85%. The inherent thermal-fatigue resistance of all-eutectic Sn–Pb flip-chip solder joints is less than their dual-solder counterparts, i.e. 97Pb–3Sn solder bumps mounted to a PBGA component with eutectic Sn–Pb solder paste. However, the thermal fatigue resistance of all-eutectic flip-chips with an underfill mounted on PBGA chip carriers is equal to or exceeds the fatigue resistance of dual-solder flip-chips. The use of an underfill material becomes an issue in situations where chip replacement (i.e. rework) may be necessary, such as multichip modules, where it may become necessary to replace one or more chips. Replacing chips with underfills is time consuming, and a reliability concern. It is not a recommended procedure for H-P equipment. Plastic BGA components normally have eutectic Sn–Pb (some contain 2% Ag) solder balls (Fig. 6b) and are attached to the PCB with eutectic Sn–Pb solder paste. This lead-containing BGA solder joint is not ROHS compliant but is exempted (i.e. allowed) for high-performance systems. It was the standard surface-mount (SM) assembly process in use prior to the ROHS legislation going into force.

5 Exemption for the use of Sn–Pb coated compliant pin (push pin) connectors

Compliant-pin refers to an interconnection technology that mechanically and electrically joins a connector to a printed circuit board (PCB) without the use of a solder process [9]. This technology has been widely utilized in applications requiring high reliability such as the telecommunications and defense industry for more than 20 years [10, 11]. The most common designs are illustrated in Fig. 7. Initially, solid pressed-fit pins were utilized where the pin diameter was slightly greater than the plated-through-hole (PTH) diameter, requiring some deformation of the pin and hole material

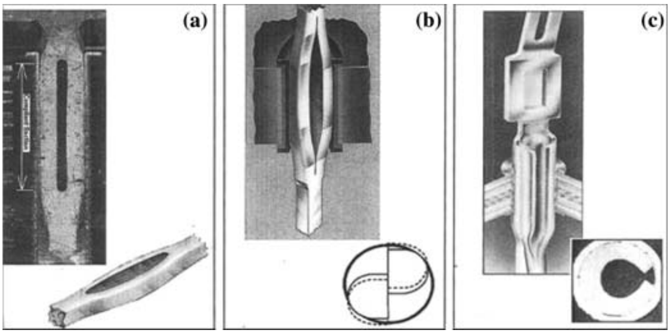


Fig. 7 Illustration depicting several compliant-pin designs. (**a**) Eye of the needle. (**b**) Tyco Electronics patented "Actin Pin". (**c**) Winchester Electronics patented "C-Press" (after Ref. [12])

when the pin was inserted into the hole. Very tight tolerances of both pins and PTHs were required to avoid damage upon pin insertion or extraction. Since compliant pins compress, the allowed tolerances of both pin and hole diameters is much greater than for solid pins, and the insertion and extraction forces much less compared to solid pins [13]. Compliant-pin connections are widely used in high-performance systems because they allow for very high-density and high reliability designs (Fig. 8).

5.1 Advantages of compliant pins over soldered connections

Compliant-pin connections have several important advantages over soldered connections. In high-performance systems it is often necessary to locate active components on both sides of a PCB, thus installing wave-soldered, through-hole components becomes problematic since many active components cannot withstand wave soldering temperatures. The situation becomes even more aggravated in the case of high-melting point Pb-free solders. Compliant-pin connections allow the attachment of large, high-thermal-mass components, connectors or daughter cards to backplanes without the complications inherent to solder processes. Additionally, compliant-pin connections provide the capability for very-high packaging density due to the ability for connectors to share the same contacts and stagger components or connectors on the top and bottom of a PCB (Fig. 7a, b). Since there are no minimum space limitations, as there are for soldering processes, smaller plated-through-holes (PTHs) can be utilized with compliant-pin systems which allows for a higher signal line density between PTHs. Signal integrity is also better in compliant-pin systems

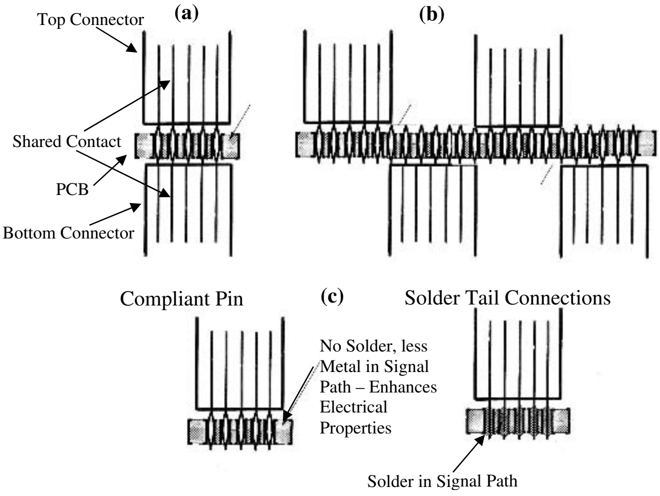


Fig. 8 Illustration depicting several advantages of compliant-pin connections over soldered connections. (**a**), (**b**) higher packaging density, thus enhanced electrical performance. (**c**) Enhanced signal integrity due to interconnection features (after Ref. [14], (courtesy of P. Isaacs, IBM Corp.)

compared to the configuration of soldered PTHs (Fig. 7c). All of these factors contribute to provide a superior electrical performance capability. Accordingly, compliant-pin terminations have become the predominant method of attachment for backplane systems; providing reliable connections with high-performance capability, i.e. signal integrity at multi-megabit transmission rates [15, 16]. High-density, compliant-pin connections are becoming even more important because of greatly increased network bandwidth and speed requirements. It is now a key consideration given the ever increasing data-transfer rates between a mother board and daughter cards in high-performance systems [17].

5.2 Role of Sn–Pb solder coating

Compliant-pin connector systems depend on a very thin (1.27–1.78 μm thick) tin–lead, solder-plated coating with the lead content ranging from 3 to 10%. The lead (Pb) acts as a lubricant to reduce the force necessary for inserting components into a PCB. This lubrication effect ensures that the PTHs in the PCB are not damaged when inserting or removing high-pin-count components. A typical insertion force ranges between 4 and 10 lbs. per pin [18]. The Sn–Pb coating aids in removal as well. However, the retention force must be sufficient to maintain the integrity of the connection [18]. Typical compliant-pin retention forces vary between 2 and 10 lbs. per pin. The need for a sufficient lead (Pb) content in the Sn–Pb solder coating is illustrated in Fig. 9. In the case of high-pin count, high-density boards utilized in mainframe computers, a nominal 90Sn–10Pb composition is utilized (50–70 μ thick), with a minimum of 3% Pb as noted earlier. If the Pb concentration is too low (approximately 2% or less) the PTHs are observed to become damaged when inserting or extracting components (Fig. 9b). When the insertion and removal forces are excessive the plating and hole shape of PTHs is damaged and so distorted that reliable connections cannot be made [11]. Lead–tin coatings also possess the necessary contact point wiping characteristics. Surface oxides and other debris are wiped away at both the pin and PTH surfaces when the pin is inserted. The clean, fresh surfaces make physical contact with each other, and provide the optimum conditions to create an air-tight electrical connection (Fig. 10).

5.3 Search for Pb-free solder coatings

Several studies were conducted investigating the effect of various combinations of Pb-free solders utilized (Table 5) with PTHs and eye-of-the-needle design compliant pins [19–21]. It was determined that all compliant pin and PTH combinations tested created less than the maximum allowable hole distortion, and left more than the minimum allowable plated thickness remaining in the PTHs. Also, no cracks were observed in the plating of the through-holes as required by IEC 60352–5 specifications [22] in an initial study [19]. A subsequent re-evaluation [20] confirmed that all the test combinations also conformed with a more stringent PTH deformation requirement as set forth in R4–10 of the Network Equipment Building System (NEBS) Telcordia Specification, GR-78-CORE. Another test was conducted [21] with Au over Ni-coated pins in addition to the Pb-free combinations listed in Table 5 evaluated in the earlier tests. Based on the combined results of these studies the effect of the

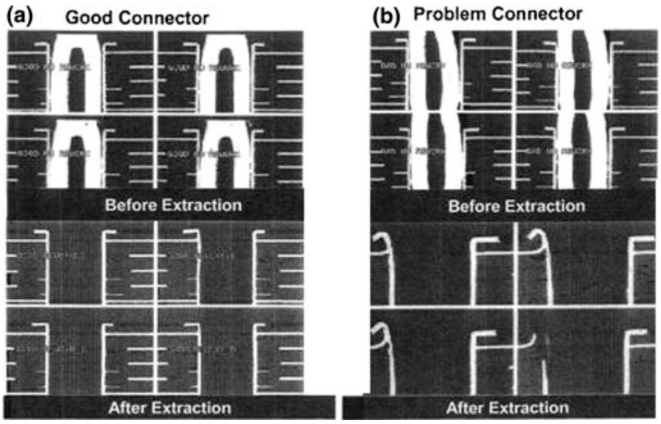


Fig. 9 Cross section of a board (**a**) with a compliant-pin connector that met the solder-coating requirements, therefore there is no damage to the plated through hole both during pin insertion (top) and after extraction (bottom). (**b**) A compliant-pin connector whose Pb concentration in the Sn–Pb coating was below requirements resulted in damage to some PTHs after the compliant-pin connector was removed (courtesy of IBM and Molex Corporations)

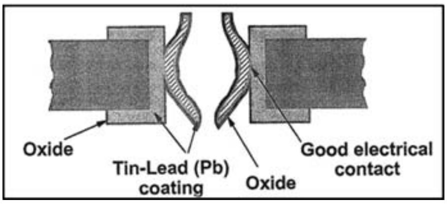


Fig. 10 Illustration depicting a compliant-pin with debris and oxide wiped from the pin and PTH surfaces that are in contact forming an optimum air-tight electrical connection (after Ref. [12])

Table 5 Potential Lead-free alternatives evaluated

Compliant-pin coating	Printed Circuit Board Material (i.e. PTH)
Sn–Pb (benchmark)	Electroplated Ni/Au
Pure Sn, matte	Copper/OSP
Pure Sn, bright	Immersion Tin (Sn)
	Immersion Ni/Au
	Immersion Ag

various pin coatings on insertion force are ranked as: matte Sn > gold > bright Sn–Pb > bright Sn. In general, the use of Pb-free compliant-pin finishes causes the insertion force to increase by approximately 15% compared to a Sn–Pb coating [23]. For high-pin-count components, connectors, etc., this translates to a significant increase in the total force applied to a card or board. The impact of this increase must be well-understood before Pb-free solders and coatings can be utilized for compliant pins in high-performance, high-reliability systems. Similarly the retention forces for the pin finishes are ranked as: matte Sn > bright Sn–Pb > bright Sn > gold. To determine the effect of environmental factors the various Pb-free pin and PIH combinations were exposed to three conditions: room ambient (23°C, 30–50% RH/5,000 h), heat/humidity (60°C/93% RH/5,000, 6,000 h), and thermal cycling (– 40 to 85°C/air-to-air, 10 min dwell/2,500 cycles) [21]. Tin whiskers were observed to nucleate and grow on all three pin coatings even though a Ni undercoat was used to mitigate their formation (Table 6). The temperature/humidity condition had the greatest effect in accelerating Sn-whisker formation and growth. Based on the Sn-whisker sizes observed, both the matte and bright-Sn pin coatings met the Class 2 acceptance criterion of the iNEMI Sn-whisker test, i.e. < 40-μm size whiskers. The level of risk introduced by whiskers of this size may be reasonable for some applications, but not high-performance equipment without a thorough investigation including extensive qualification testing. This also includes the use of gold finishes for compliant pins. Although Au finishes eliminate the Sn-whisker issue, they nevertheless result in unacceptably high insertion forces, low retention forces, and a very significant increase in cost. The trade-off of adverse mechanical performance for the elimination of Sn whiskers is also not acceptable. The EC granted an exemption to allow the use of Pb for compliant-pins, and in consideration of the issues noted, for good reason. However, studies are continuing in an effort to resolve the outstanding concerns.

Table 6 Tin-whisker growth observed during testing

Compliant-pin finish	Sn-Whisker formation, Size (μm)
Ni/bright Sn–Pb	Yes, 20–30
Ni/matte Sn	Yes, 20–37
Ni/bright Sn	Yes, ~20

6 Use of Lead (Pb)-coated C-rings: an important test case

6.1 Single-user exemption request

All the exemptions granted when the ROHS legislation was enacted (Feb 13, 2002) pertained to practices in common usage across the electronics industry. Exemption requests were generally made through an industry association and carried the unanimous consensus of the association's membership. The matter of an exemption request that only affected the product(s) of a single company first surfaced with an IBM request for the use of lead rather than a lead (Pb)-free solder for an application specific to IBM mainframe computers.

6.2 Cooling requirements

All server products are designed to perform massive computing tasks. Significant quantities of heat are generated due to a high degree of integration for numerous high-power devices. Each server has its own unique heat-removal requirements. Even servers manufactured by the same company, like IBM, often utilize different hardware design concepts to achieve the desired performance and reliability objectives through custom designs that efficiently remove heat from a particular platform. The architecture of IBM's very-high performance mainframe computers (i.e. zSeries), results in the generation of significant quantities of heat, the source of which is a unique processor module referred to as a thermal conduction module (TCM). This technology allows a large number of chips to be placed in close proximity to each other on a single ceramic chip carrier, which greatly enhances both performance and reliability, but also localizes the heat that the chips generate. IBM introduced the TCM technology in its mainframe systems starting with the 3081 Processors (1981). At that time a combination of 118 closely-spaced logic and memory devices were mounted on a 90-mm multilayer ceramic (MCM) chip carrier. The TCM assembly was designed to maintain the chip-junction temperature below 81°C with a maximum thermal load of 4 watts per chip, and a cooling capacity of up to 300 watts. Cooling was achieved by a separate spring-loaded piston contacting the back side of each chip (Fig. 11). The array of pistons was contained in a housing that in turn contacted a water-cooled cold plate that removed the heat. A key aspect of the TCM's design in meeting its heat-removal requirements was charging the assembly with helium gas to a pressure of 0.16 MPa (1.6 atm.) to minimize the thermal resistances at the chip-to-piston and piston-to-housing interfaces [25]. But the TCM assembly's ability to meet its functional cooling requirements over its operating lifetime depends on maintaining the integrity of a seal created by a C-ring (Fig. 12).

The C-ring is clamped between the cooling housing and a flange brazed to the ceramic chip carrier. Since the computing power of mainframe computers has steadily increased, correspondingly the TCM's heat-removal requirements dramatically increased as well. By 1991, TCMs utilized in the IBM Enterprise System 9000$^{\text{TM}}$ family of processors had a heat dissipation capability of 600 watts [26]. The number of chips (typically about 16) mounted on TCMs utilized in IBM's current mainframe systems (i.e. eServer z990) is much reduced due to very large scale integration (VLSI) technology. However, these very complex chips each possesses 10K or more I/O solder bumps and dissipates 180–200 watts. Currently TCMs are required to dissipate between 800 and 1,200 watts depending on the particular system. The current, more compact and simplified TCM design (Fig. 13) utilizes a thermal interface material (TIM) to provide a more direct heat-removal path between a chip and the hat to which an air-cooled heat sink is attached. Helium is also charged into these TCM assemblies to provide a benign internal atmosphere. The C-ring must prevent oxygen or other gaseous species from entering the TCM and degrading the TIM or chemically attack the flip-chip solder joints.

6.3 C-Ring requirements

The C-ring core material is Inconel 718, 0.38µm thick and has a 2.5µm non-compressed height. It is electroplated with pure Pb, 63–115 microns thick, resulting in a deposited average weight of 3.1 g. The lead (Pb) is overcoated with a very thin coat of a multi-component, blended wax [27] (Fig. 14). The Pb coating exhibits excellent sealing characteristics to both ceramic and metal surfaces, to maintain near hermetic conditions (i.e. a helium leak rate of 10^{-8} atm-cc/sec) over the anticipated 10-year life of a TCM. The seal experiences 500 lbs. of force per inch of the seal. The Pb seal also

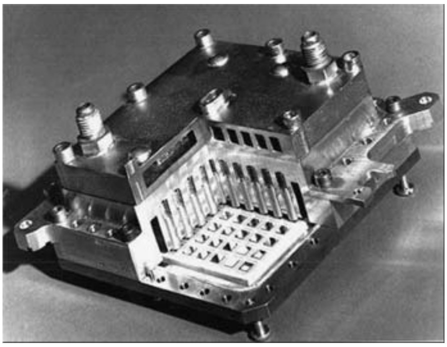


Fig. 11 Oblique-view photograph of the TCM assembly utilized in IBM 3081 processors, with a cut-out section to make some pistons and mounted chips visible (after Ref. [24])

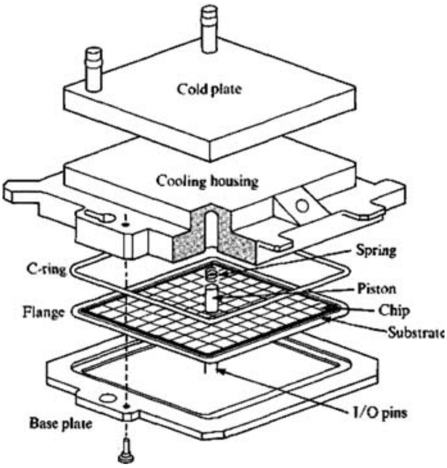
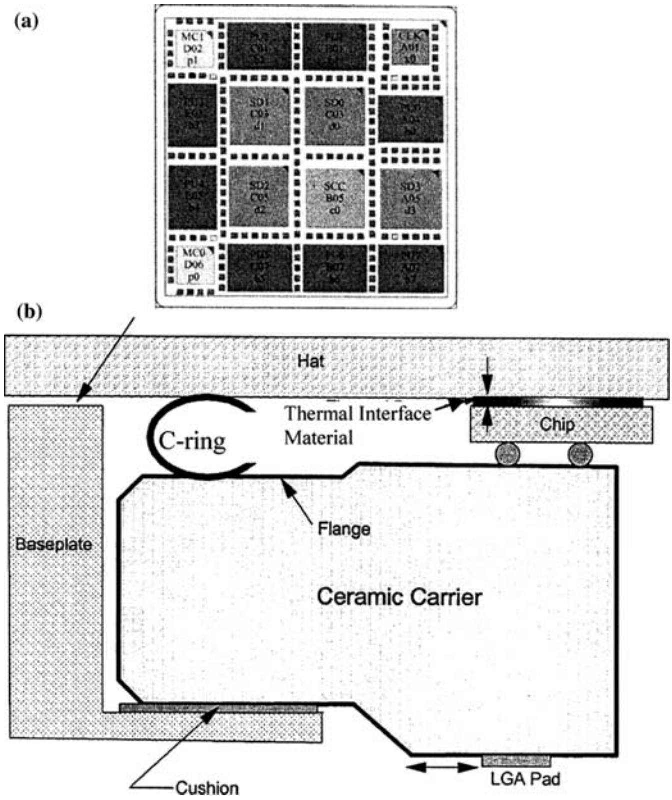


Fig. 12 Illustration depicting the major elements comprising a TCM assembly used in IBM 3081 processors (after Ref [25])

Fig. 13 Major elements comprising TCMs utilized in IBM eServer z990 mainframe computers. (**a**) Typical top surface floor plan of chips and decoupling capacitors mounted on a 93 mm × 93 mm ceramic chip carrier. (**b**) Side-view schematic depicting a TCM assembly (after Ref. [27])



provides excellent wear characteristics when exposed to accelerated thermal cycle (ATC) stress testing, eliminating the effect of C-ring motion resulting from the coefficient of thermal expansion (CTE) mismatches between the C-ring and the materials it is in contact with [27].

6.4 Lead-free alternatives

A number of solutions were evaluated, among them: elastomer and metal O-rings; elastomer, metal, and composite gaskets; and plated elastomers. Other plated coatings were evaluated on the Inconel core in place of Pb, among them: Au, Ag, Pb–Sn, and In. All those potential solutions failed to meet the requirements. Among the reasons were: high gas permeation rate, high wear rate causing an unacceptable loss of normal force, and poor ATC test performance [27]. Lead (Pb) was the only material found suitable to meet the performance requirements. In early 2004 the European Commission (EC) granted an exemption for this application.

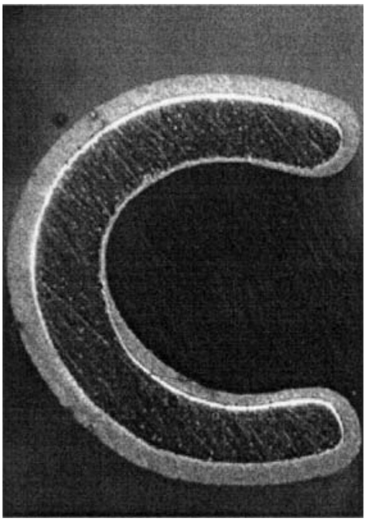


Fig. 14 Photomicrograph of a C-ring in cross-section, consisting of a 0.015-in. thick Inconel core, electroplated with 0.002–0.004 in. of lead (Pb) (after Ref. [28])

This request served as an important test case. If viable solutions exist to implement Pb-free technology, it is generally understood that the EC requires that those solutions be adopted, with cost only a minor consideration from an EC perspective. However, this case involves an important principal. Other mainframe manufacturers have solutions that do not involve the TCM approach, but have completely different architectures and methods of cooling. What is at issue here is the impact that forcing ROHS compliance could have on innovation, product competitiveness, and the pursuit for optimum product quality and performance. That is, IBM and its competitors each adopted a system architecture and design in the belief it provided the best approach to be competitive and provide the highest performance products over time. These are typically long-term strategies, as shown in IBM's case. If the EC had insisted that IBM abandon its TCM-based approach, and acted similarly with other entities in instances requiring a major design departure from their products, these actions among other things would only serve to have a serious adverse impact on technical innovation and progress, clearly not objectives of the ROHS legislation. This unintended negative impact was avoided by the granting of IBM's exemption request.

7 Summary/Conclusions

This paper has discussed the most important differences between consumer electronic products and those high-performance products that the EC permitted the continued use of lead (Pb) in its solder exemption. In addition, the paper discussed three specific industry exemption requests that have a particular importance and relevance to high-performance equipment applications. It was concluded that:

(1) High-performance equipment differed markedly from consumer electronics in several important respects.

   (a) High performance equipment is relatively expensive and low volume. It has a 10-to-25-year operational life, is often refurbished, and those portions that are ultimately discarded only represent a very small fraction of the electronic waste in landfills.

   (b) The complexity of high-performance equipment is often orders of magnitude greater than that of consumer electronics. Introduction of new Pb-free assembly materials makes the product assembly task more difficult and that increased difficulty directly translates into the creation of defects and a corresponding reduction in reliability.

   (c) The most important factors that differentiate high-performance from consumer electronic equipment are a demanding set of reliability requirements. Among these are the ability to operate continuously for 10–25 years with virtually no downtime due to failures. Some telecommunication equipment must meet these requirements in harsh outdoor environments or satellite systems in space environments with little or no opportunity for repair.

(2) Lead is an ingredient in a variety of materials utilized in electronic products including batteries, glass in monitors, cable sheathing, some ceramic components, and in solders. Solders are used as a coating material for PCBs, component lead frames and solder bump/ball terminations; and are universally utilized to attach components, connectors, and other circuit elements to printed circuit boards (PCBs). A main board in a high-performance electronic product may have 10,000 or more attachments, resulting in the need to create thousands of sound and reliable solder joints.

(3) A variety of leaded chip and component termination combinations have been exempted (i.e. allowed to be used) by the EC for high-performance systems. It is permitted to attach a flip-chip with high-Pb solder bumps to the next level of assembly ($>$ 85% Pb) with eutectic Sn–Pb solder ($<$ 85% Pb). These high-Pb flip chip/eutectic tin–lead solder joints typically exhibit good fatigue properties since both solders are of the same solder family (Pb–Sn), and also because most of the high-Pb bumps remain undissolved in the eutectic Sn–Pb solder. This was an important exemption since the use of plastic over ceramic for BGAs is increasing rapidly. A eutectic Sn–Pb attachment provides a sufficiently low-reflow temperature to preserve the integrity of plastic chip carriers. Being ROHS compliant does not necessarily qualify a solder joint for high-performance applications. For example, BGA components with high-Pb solder balls ($>$ 85% Pb) reflow-attached to PCBs with Pb-free solder paste, creating a joint consisting of a solder mixture.

(4) A close proximity of components is necessary in high-performance systems to reduce the delay

time in transmitting information point-to-point. Densification therefore plays a large part in enhancing performance. The use of compliant-pins is the preferred method of interconnection in high-performance systems because they provide a much higher level of densification than possible with soldered pin-in-hole (PIH) connectors. It also avoids the processing problems introduced by locally heating large and complex assemblies. A Pb–Sn coating, with 3–10% Pb has been the only known material that provides the requisite combination of characteristics (i.e. contact wipe, low insertion forces, and sufficient retention force). All Pb-free materials, including gold, were found not to be adequate for high-performance systems. Very recent work utilizing tin over a nickel underlay on top of a copper substrate appears to provide an acceptable combination of properties and is being implemented by many of the major compliant-pin manufacturers.

(5) IBM was granted a request to use lead (Pb) as a coating for a C-ring that creates a seal that prevents the oxidation of flip-chip solder joints. It also prevents the degradation of a material that provides the heat-removal path for chips contained in an assembly central to the performance of IBM's mainframe computers. Lead (Pb) is the only known metal that satisfies all the requirements, although many others have been investigated. Aside from the fact that the request involved a significant percentage of the world's mainframe computing capacity, the request served as an important test case. By granting the request, the EC indicated it would consider the needs of even individual manufacturers, particularly in cases where forced compliance clearly would result in impeding progress and innovation.

In summary, it was absolutely necessary for the EC to recognize that the integrity and reliability of high-performance systems had to be preserved. Granting a solder exemption was an important step in helping to assure the reliability of H-P systems. But since even high-performance systems are required to be ROHS compliant, so it is likely that unanticipated issues will continue to surface during the implementation process and into the future. Three already have, as discussed in this paper and the EC is already considering others.

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