4.13 Exemption no. 8 a – stakeholder proposal part C (iv)

“Lead in solder for large power semiconductor assemblies”

4.13.2 Description of exemption

ACEA at el. (2009g) apply for an exemption for “Lead in solder for large (> $1cm^2$) power semiconductor assemblies”. According to the stakeholders, no technical solution is at hand. ACEA et al. (2009g) hence do not propose an expiry date, but just a review of the exemption after 2015.

The lead-containing solder is used for the soldering of Silicon chips (Si chips) of 1 cm^2 and more of surface area to lead frames, as shown in Figure 28.

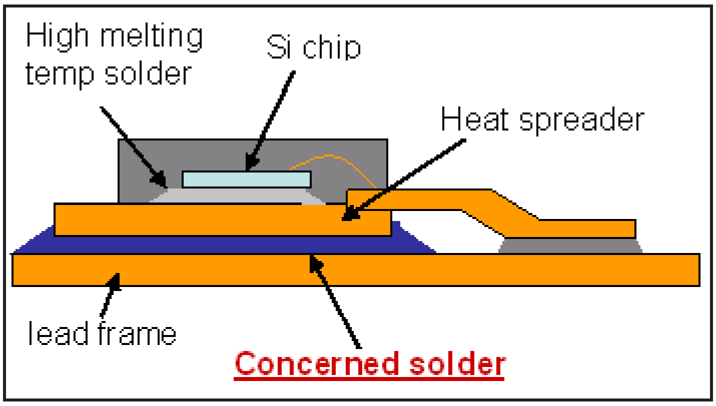

Figure 28 Example describing the requested exemption (ACEA et al. 2009g)

The design can involve an intermediate heat spreader, as illustrated in Figure 28.

The solder joints have to suffice the following requirements (ACEA et al. 2009g):

- The thermal conductivity of all components must be as high as possible and uniform over the complete chip surface, to ensure the fast flow of thermal energy from the chip to the lead frame.
- No appearance of cracks within the soldering phase
- The bond must be stable against cyclic loads

The stakeholders request that the exemption should apply to any soldering of large size power semiconductor assemblies as used in inverters (= power control units to convert AC / DC and DC / AC) (ACEA et al. 2009n). An example of such components are Insulated Gate Bipolar Transistors (IGBT). ACEA et al. (2009g) say that IGBT are silicone (Si) semiconductor chips; they are the main active component in power modules for Hybrid Electric

Vehicles (HEV) and Electric Vehicles (EV). The semiconductor chips are converters that control the electric voltage and current between battery and the electric drive motor / alternator of a vehicle.

ACEA et al. (2009n) say that inverters are used in many stationary applications, and in trains. The here described power modules are automotive–specific development with the exclusive use in HEV and EV. The stakeholders do not know any other uses of these specific units inside or outside the automotive industry.

The power modules are a new development including the specific transistor chip (e.g. IGBT) and including the way of assembly. The development focuses on operational energy efficiency, which implies to concentrate the controlled current as dense as possible in as little volume as possible (ACEA et al. 2009n).

The amounts of SnPb solder used under the requested exemption can be calculated using the example of a of current HEV power module (ACEA et al. 2009g):

- The SnPb solder contains around 50% of lead (w/w, SnPb50),
- each silicon chip requires about 0,64 g of solder, equalling to 23,2 g of SnPb solder per power module (36 chips per module, one module per car),
- each HEV or EV car thus contains around 11,6 g of pure lead,
- assuming sales of 10,000 HEV and EV cars would result in around 120 kg of lead per year.

4.13.3 Justification for exemption

ACEA et al. (2009g) claim that no lead-free substitutes are available that are technically sufficiently reliable. The stakeholders following sections describe the stakeholders' justification.

Soldering process and performance of the solder joint (ACEA et al. 2009g)

The solder between the heat spreader and the lead frame must melt at a temperature lower than the melting temperature of the solder used for the Si chip soldering (around 300°C).

Cracks and voids have a detrimental influence on the bond reliability and the heat dissipation of the soldered transistor chips. These chips, Insulated Gate Bipolar Transistor (IGBT) type components, are subjected to high currents during the operation, which result in high thermal loads. As the application, high-density power modules for HEV and EV, are newly developed, there is yet no practical experience available on the amount and magnitude of real-life load cycles, and no experience on the fatigue behaviour of the solder and the soldered components. To allow an assessment of the long-term solder stability, and conduction capacity, specific temperature cycle and power cycle tests have been designed, to determine a minimum needed resistance against high cyclic loads.

ACEA et al. (2009g) claim that the currently available lead free soldering materials, SnAgCu solder, and SnPb solder, have different physical characteristics, which are displayed in Table 16. Cracks and voids will more likely occur in the soldering phase of lead-free solders. The risk of a detriment of the in-vehicle reliability is increased. Therefore the substitution is technically yet impracticable, according to the stakeholders (2009g).

Table 16 Comparison of material parameters of eutectic SnPb and SnAg3Cu0.5 solder (ACEA et al. 2009g)

	SnPb	SnAgCu	
Young’s modulus (E)	22	31	GPa
Elongation	38	23	%
Hardness	13	15	HV
Melting Point	183	218	deg.
Solder spread (240°C)	87	75	%

ACEA et al. (2009q) explain that the higher elongation and the lower E-modulus indicate the higher ductility of SnPb solder. It has better surface wetting properties due to the higher solder spread value. The operational conditions are characterized by sharp heat gradients, and high currents. The material properties of the SnPb solder make it more appropriate for the use in very demanding applications, where the good connection of both soldered surfaces must remain under the conditions of use (ACEA et al. 2009q). The higher ductility can better compensate the differences in thermal expansion between the bonded materials, which occur under operation conditions with sharp heat gradients.

Crack expansion investigation

According to the stakeholders the research for lead-free alternatives has just started. The most important criterion for failure / non-failure is the tendency of a solder to withstand crack propagation under thermal stresses. Thermal stresses, with steep variations of the amplitude, result from the power cycles occurring during the normal in-duty use of the modules (ACEA et al. 2009g).

The stakeholders explain that, if cracks occur, the shape of cracks is usually sharp and straight (ACEA et al. 2009g). Greatest matter of concern is the progression of the crack under cyclic load. Figure 29 shows a solder joint being cracked due to the cyclic thermal loads. Solder material is SnAgCu solder.

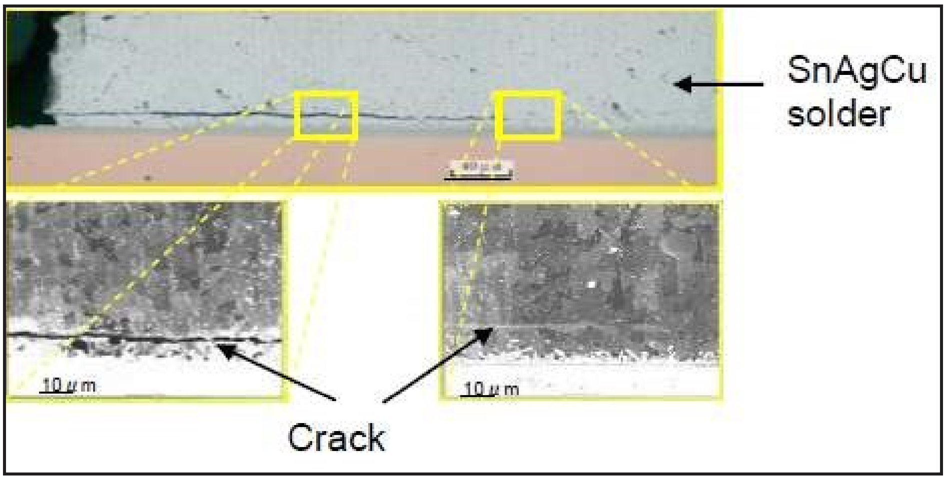

Figure 29 Crack in SnAgCu solder (ACEA et al. 2009g)

The straight crack is progressing from the outer side towards the inside. ACEA et al. (2009g) explain that the SnAgCu solder's phase structure does not prevent the expansion of the crack.

Figure 30 shows the structure an SnPb solder joint consisting two phases, Pb and Sn, and the structure of a SnAgCu solder joint (with crack).

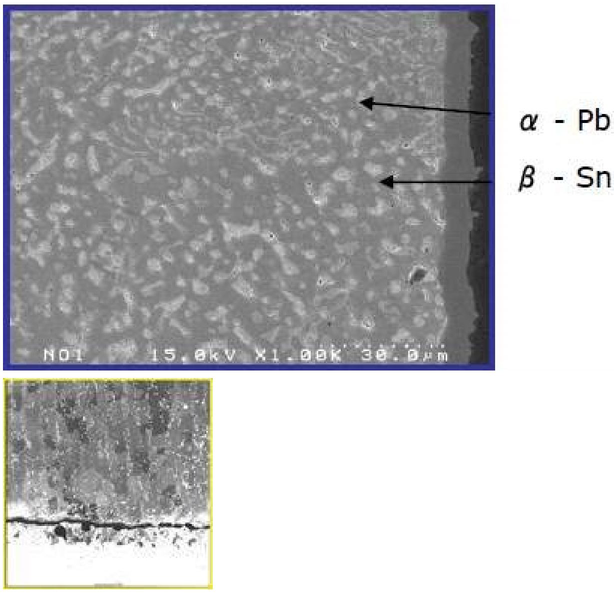

Figure 30 Phase appearance in SnPb solder (above) (ACEA et al. 2009g) and in SnAgCu solder (with crack) (ACEA et al. 2009n)

According to ACEA et al. (2009g) the SnPb solder phase structure shows more ductile properties than the one of the SnAgCu, especially considering creep fatigue. The Sn and the Pb phase coexist. The shapes of the phase boundary lines are round, like balls or globulites.

This appearance indicates a ductile behavior. The borders do not end abruptly, as in the case of SnAgCu solder Figure 29 on page 126 (ACEA et al. 2009n).

A numerical simulation of the temperature cycling test confirms the above findings. The simulations were carried out using a CAD model as shown in Figure 31. (ACEA et al. 2009g).

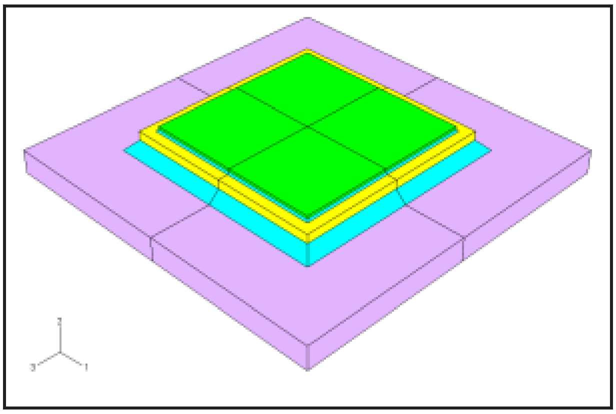

Figure 31 Model for simulation of loads in thermal cycling (ACEA et al. 2009g)

The load is assumed to be thermally induced stresses following the conditions shown in Figure 32. The cyclic load simulates the condition of high stress fatigue with long holding times (ACEA et al. 2009g).

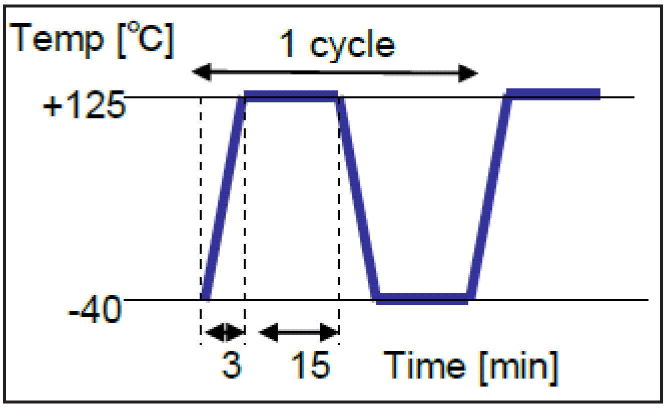

Figure 32 Temperature profile used in thermal cycling simulation (ACEA et al. 2009g). Amplitude of temperature: -40 to +125; Holding time: 15 min; Cycle time: 36 min

Failure criterion is the (simulated) crack length, the failure condition the amount of thermal cycles (ACEA et al. 2009g). Figure 33 shows the result of the numerical simulation.

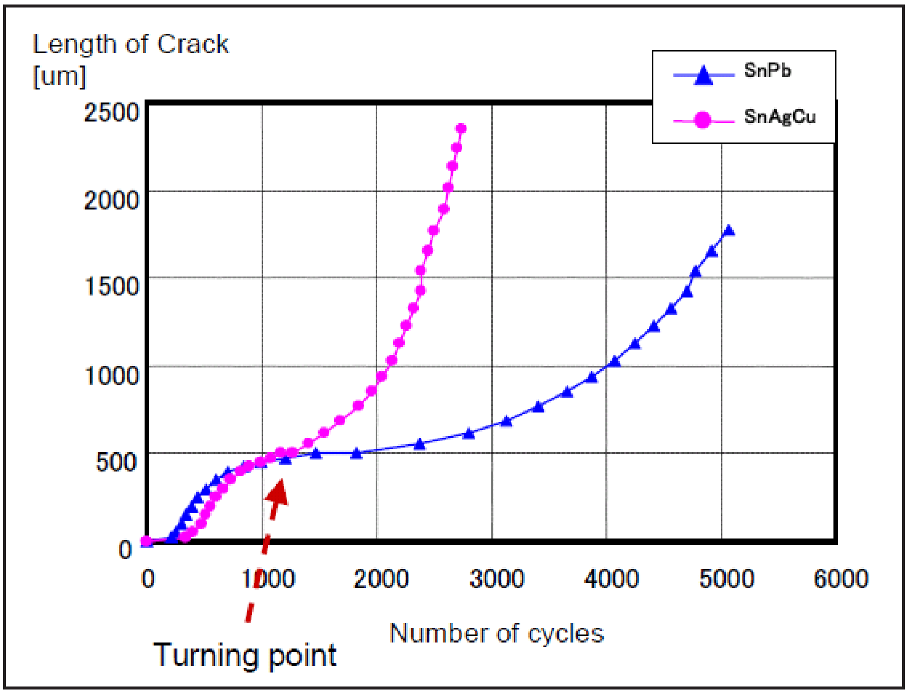

Figure 33 Result of the simulated thermal cycling test (ACEA et al. 2009g)

The result confirms the findings that the crack propagation is faster in lead-free solders.

Voiding

ACEA et al. (2009g) explain that the vaporization of contained materials, such as the flux, cause formation of voids. The gases cause void inclusions, if they can not evaporate from the liquid solder. The higher the liquidity of the solder material during the process, the easier the gases can be released out of the solder. The liquidity of SnPb solder at a given temperature is better than those one of the lead free SnAgCu solder. Figure 34 shows solder samples processed in a reflow oven under similar conditions (ACEA et al. 2009g).

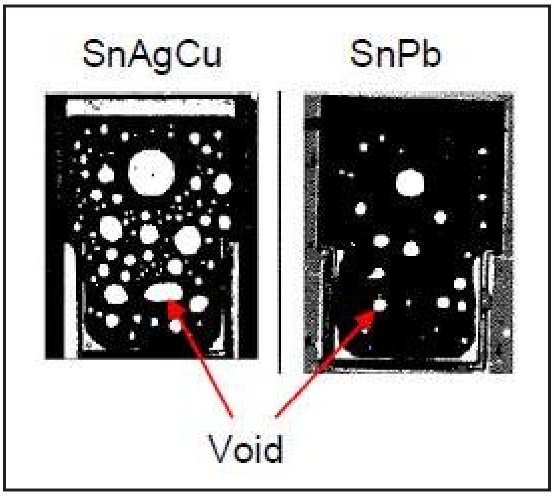

Figure 34 Forming of voids in lead-free and non-lead-free solder joints (ACEA et al. 2009g)

The picture shows more voids in the lead-free soldered solder joint.

Voiding and failure mechanisms

A soldered connection was exposed to a thermocycling test (TCT) of over 4 000 cycles, after which following photos were taken by Scanning Acoustic Tomography. Voids on the crack surface of lead free and lead containing solder is documented (ACEA et al. 2009g).

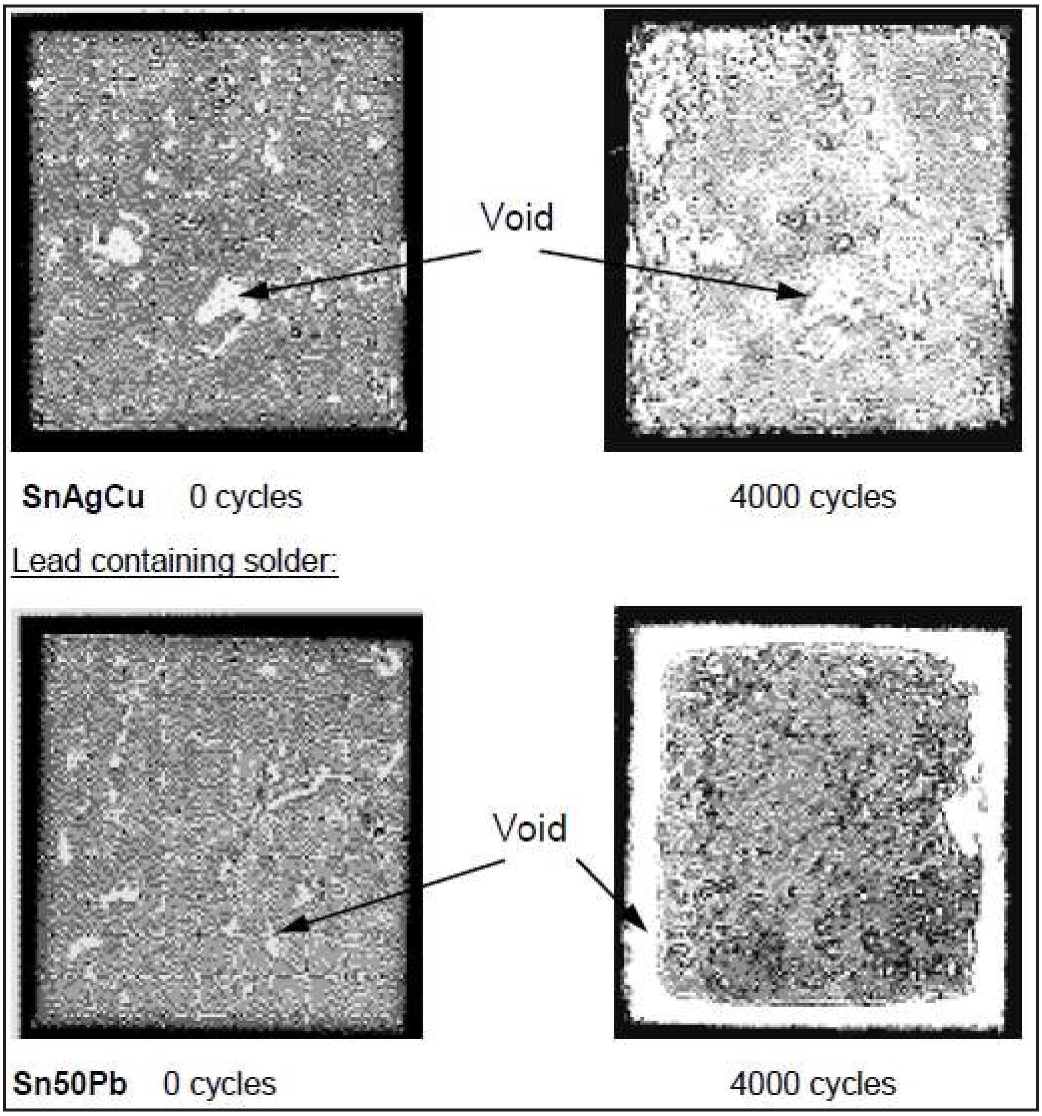

Figure 35 Voids on crack surface (ACEA et al. 2009g)

According to the ACEA et al. (2009g), the pictures show that the occurrence of cracks in SnAgCu solder and in SnPb solder is following different rules. Crack expansion in SnPb is initiated from outside the chip, which is the expected mode under thermal induced bending, where the points of highest stress are at the boundaries of the soldered areas. In the SnAgCu solder, the formation of cracks starts at the place of existing voids, which is not according to the expectations (ACEA et al. 2009n).

The stakeholders draw the conclusion that in the case of lead free solder the forming of cracks happens in an unexpected and unpredicted way. The failure mechanism is not known (ACEA et al. 2009n). Any material, solder or other, should only be introduced in mass production when the failure mode is known; with the underlying goal to calculate and avoid any damage that would cause a failure (ACEA et al. 2009n).

Design changes facilitating the use of lead-free solders

The stakeholders explain that the described design of power modules containing die bonded Si chips (IBGT) are a major innovative component in hybrid electric vehicles (HEV) and in electric vehicles (EV) (ACEA et al. 2009g). In those vehicles, a fast and energy-efficient control of voltage and current must be assured, with fast and abrupt changes of the current direction (to / from the battery). These vehicles must function in similar environment and with similar robustness as any other vehicle that is on the market.

ACEA et al. (2009g) say that a design change could possibly reduce or make obsolete the need for using SnPb solder. However, the described design is now just about to show its functionality in practice. Any design change should be linked to the development of a second generation of the power modules. Therefore, the change of the design is at that moment impracticable (ACEA et al. 2009g).

Environmental arguments

ACEA et al. (2009g) claim that HEV have the potential to realize saving of fuel compared to similar vehicles with a combustion engine only. EVs are widely recognised as the most environment friendly and future relevant means of personal road transport, as any local emission of exhaust gases becomes obsolete (ACEA et al. 2009g).

Stakeholders’ conclusions

ACEA et al. (2009g) sum up that the solder must offer a good balance of hardness and elongation, to withstand cyclic thermal stresses. Not enough experience is yet available regarding the estimation of the life time of lead free soldered joints. The development of a suitable new solder, and the development of process condition for the production and production facilities is ongoing. The evaluations are being continued, but results are not yet promising enough to initiate a change towards lead-free solders and appropriate designs (ACEA et al. 2009g).

4.13.4 Critical review of data and information

Efforts to achieve legal compliance

ACEA et al. (2009g) state that a design change could possibly allow the replacement of lead in this application. The stakeholders were asked to provide a roadmap when these design change will be implemented. ACEA et al. (2009q) regret to not be able to provide a well developed roadmap. The stakeholders target 2015 for these design changes, but confine that upcoming difficulties during development would postpone this date (ACEA et al. 2009q).

ACEA et al. explain that that these power devices are newly developed. The stakeholders hence were asked to justify why these power modules were developed for the use of lead-containing solders and not for lead-free soldering knowing that lead has been banned in the ELV Directive.

The stakeholders explain that the power modules with semiconductors of large size (> 1cm^2) have been developed since 1999, with prototypes being built since 2003 (ACEA et al. 2009l).

The specialty in this design is the large size of the transistor chips, and the high density of currents. The controlled electric current is about 100 A per chip, corresponding to almost 1 A per mm^2 or higher. The high energy density increases the efficiency of the unit, and decreases its size and weight (ACEA et al. 2009l). The stakeholders further on put forward that SnPb solders of special composition (SnPb50) were used in the designs because of the challenges the energy density poses to the solder quality and the soldering process (ACEA et al. 2009l). The use of lead solders reduces the number of novelties in the design at the early phase. The risk of failure is therefore less than in the case of development of a new soldering process at the same time. As a result, the units will be available earlier on the market, where they will lead to positive effects on fuel consumption, according to the stakeholders (ACEA et al. 2009l). Moreover, the stakeholders explain that earlier developed modules are soldered with high melting temperature solders containing above 80% of lead. The current designs hence are already an improvement. The first attempts for lead free soldering, according to the stakeholders, were done in 2007, and are ongoing since then (ACEA et al. 2009l).

The stakeholders’ approach to restrict the number of unknown factors at the beginning of the development using well-known lead solders is understandable. In the context with the fact that the development already started in 1999, it is also acceptable that lead-free solders at that time were not taken into account as highest initial development priority, the more as the lead content was reduced in later development stages from around 80% of lead down to around 50% according to the stakeholders.

In the later phase, although the ban of lead is in place since 2003, the attempts for lead-free soldering started in 2007 only. The stakeholders argue that the ELV Directive and its Annex II always have provided an unlimited exemption for solder in electronic circuit boards and other electric applications from the ban of lead (ACEA et al. 2009q). It was only from 01. August 2008, the Commission Decision 2008/689/EC introduced an expiry date (ACEA et al. 2009q). In addition, the stakeholders mention that the power semiconductor market is not necessarily depending from the automotive industry, but vice versa the activities for E-driven systems and hybrid vehicles largely depend on the availability of suitable power semiconductors and systems (ACEA et al. 2009q). If the automotive industry cannot rely on the availability of components with proven components and processes, the very successful and efficient introduced, CO_2 reducing, efficiency measures which were developed under the required and unlimited exemption for lead in electronics are endangered.

Exemptions are always temporary, as they are reviewed periodically. It is the manufacturers' obligation to aspire legal compliance, and to move their suppliers towards development and supply of compliant products wherever technically possible even though an exemption might still be in place. As can be seen in the review of exemption 8b (lead in solders for soldering on glass), exemptions can easily be at disposition, once a stakeholder claims to have a solution. Once a solution is available, the use of lead is no longer unavoidable and the exemption would have to be repealed to suffice the requirements for exemptions in Art. 4 (2) (b) (ii). The previously unlimited exemption for lead in solders thus is no justification for a start of lead-free developments as late as in 2007.

Although the new developments may result in environmental improvements as higher fuel efficiency, this cannot serve as a justification not to aspire compliance with the material bans in the ELV Directive. The manufacturers' legal obligation is to undertake efforts to develop and produce compliant equipment. Only if the use of the banned substances is demonstrably unavoidable, exemptions can be justified.

The stakeholders further on justify the 2007 starting date for lead-free soldering development that they concentrated their lead-free attempts on the components with the highest lead content (ACEA et al. 2009q). Automotive power electronic of the size in question is relatively new and got increased importance in the last years in relation with new fuel saving concepts (e.g. "hybridization", and other novel systems, etc.). Before that, there were single niche applications for power electronics in some vehicles only (ACEA et al. 2009q).

Unless the legislators lift the ban of lead in general or for specific exemptions permanently, the stakeholders will have to prove in the next review round that they have undertaken steps to achieve compliance with the material bans in the ELV Directive.

Melting point of the solder and voiding

The stakeholders justify their exemption request that the solder melting point must be lower than the melting temperature of the solder used for the Si chip soldering (around 300 °C). This, however, can be achieved with lead-free solders as well, as the stakeholder themselves indicate in Table 16 on page 125. The melting point of most lead-free solders is between around 210 and 230°C.

The stakeholders agree that the melting point is not a justification for the exemption, but explain that their exemption request is based on the other described material properties of lead-free solders (ACEA et al. 2009n).

Higher occurrence of voiding in lead-free soldering is a well-known phenomenon which can be tackled with adapted solder profiles like peak temperatures, time at peak, cooling rates, optimization of the flux, etc. The stakeholders, however, put forward in their example in

Figure 34 on page 129, that the soldering conditions were similar. What would be necessary for a viable comparison are soldering conditions optimized for the soldered product and the applied solders. The effect might then at least be reduced.

ACEA et al. (2009n) agree to this, but put forward that under any, and even as optimal as possible conditions, there are always more voids been formed with lead free solder than in eutectic SnPb solder. This comes mainly from the higher viscosity of the former in comparison to the very low viscosity of the latter. The optimal solder stays at low viscosity and high liquidity over a long time during the cooling, so that the gases can escape the solder before being entrapped (ACEA et al. 2009n).

Given the additional constraint that cracks have been observed to form at the voids in the large power semiconductor chips, the stakeholders' explanation is a plausible reason to assume that the voiding in lead-free solders is an additional reliability problem.

Confinement of the exemption

From the information available, and in the absence of contrary information, it is recommended to grant this exemption. The exemption needs further clarification in its scope and wording, however.

The stakeholders propose the following exemption wording:

Lead in solder for large (> 1cm^2) power semiconductor assemblies.

The stakeholders explain that the main reasons for selecting lead-containing solders for this new development was the were the steep profile temperature changes as consequence of the high current densities to be processed, in combination with the large area of the heat spreader to be soldered. The exemption in the currently proposed wording could, however, be used for applications as well, where the high current density criteria does not apply. Further on, the proposed wording scopes power semiconductors, without giving an exact definition of the "power" that makes the semiconductor a power semiconductor in the sense of the exemption. To avoid abuse and uncertainties, the exemption is therefore limited to nominal current densities of 1 A/mm^2. The stakeholders agreed to this confinement (ACEA et al. 2009n).

From the explanation the stakeholders provided for the construction of the power semiconductors, the lead solder is used for soldering the heat spreader carrying the power semiconductor to the lead frame:

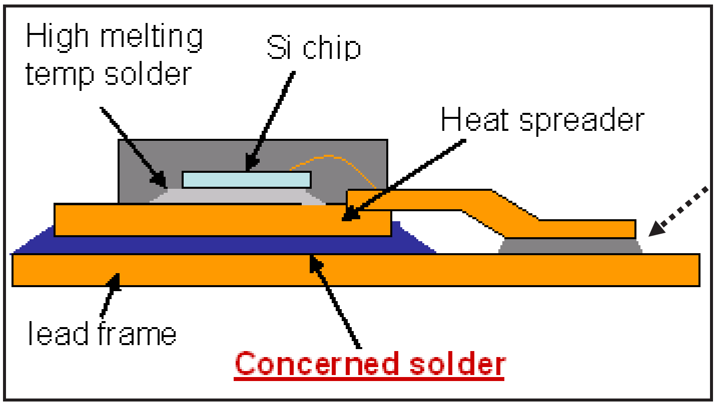

Figure 36 Use of lead solder in requested exemption (ACEA et al. 2009g)

The stakeholders' wording proposal "Lead in solder for large (>1cm²) power semiconductor assemblies" does not take this into account and would, e. g., also allow the use of lead solder in other locations, e. g. the one indicated with the dashed line arrow in Figure 36, or where the high melting point solders with 85% and more of lead content are used in the above figure.

"Lead frame" reference

The "lead frame" in Figure 36 was discussed with the stakeholders, too. "Lead frame" is too specific, as heat spreaders may also be soldered to printed wiring boards, which would be different from soldering to a "lead frame". It was decided that "heat sink" is the better term, as this comprises soldering the heat spreader to a lead frame as well as to a printed wiring board or other substrate materials.

Clarification of size reference

It is further on not clear what the 1 cm^2 in the wording is referring to. According to the stakeholders' submitted exemption request, it should refer to the size of the semiconductor chip (Si chip in Figure 36) (ACEA et al. 2009g). According to other information , the 1 cm^2 area should refer to the solder area size (ACEA et al. 2009n). The solder area, however, is not a clear reference, as this might be the area covered by the solder joint on the lead frame in the above figure or the area on the bottom of the heat spreader. These areas are different, as due to the gravity, the solder joint covers a larger area on the heat spreader than on the semiconductor. *The projection area of the chip is therefore recommended as an unequivocal reference for the size of at least 1 cm².*

Limitation to HEV and EV

The stakeholders had explained that these power semiconductor assemblies were specifically developed for use in hybrid electrical vehicles and in electrical vehicles. It was therefore discussed with the stakeholders whether the exemption could be limited to hybrid electrical and electrical vehicles. The stakeholders say that power semiconductors are essential components also in other vehicles, such as in start-stop systems or power electric peripheral equipment (ACEA et al. 2009q). A restriction of the exemption to specific vehicles thus is not adequate.

Wording of the confined exemption

Other exemptions, like the proposed exemption C (v), describe a similarly complex construction (see section 4.14 on page 137). This exemption is taken over from the RoHS Directive, where other, similarly or even more complex exemptions (e. g. exemption 15 of the RoHS Directive) give detailed guidance on where the exempted lead solder may be used.

Following these examples, the reviewers recommend the following wording:

Lead in solder to attach heat spreaders to the heat sink in power semiconductor assemblies with a chip size of at least 1 cm² of projection area and a nominal current density of at least 1 A/mm^2 of silicon chip area.

4.13.5 Final recommendation exemption 8 C (iv)

It is recommended to grant the exemption. According to the information submitted, there are currently no sufficiently reliable lead-free alternatives available. Art. 4 (2) (b) (ii) thus would justify an exemption. As the stakeholders indicate that lead-free solutions may be available in 2015, it is recommended to review the exemption in 2014 and to adapt it to the scientific and technical progress.

The proposed wording is:

> *Lead in solder to attach heat spreaders to the heat sink in power semiconductor assemblies with a chip size of at least 1 cm² of projection area and a nominal current density of at least 1 A/mm^2 of silicon chip area; review in 2014.*