Öko-Institut 2008	Adaptation to Scientific and Technical Progress of Annex II Directive 2000/53/EC, final report from January 2008, Öko-Institut e. V., Fraunhofer IZM; download from http://circa.europa.eu/Public/irc/env/elv/library?l=/stakeholder_consultation/evaluation_procedure/reports/final_report/report_revision/_EN_1.0_&a=d
Pinsker 2009a	Martin Pinsker, BMW; Document "Summary of products tested.xls", sent to Otmar Deubzer via e-mail on 2 June 2009
Pinsker 2009b	Pinsker, Martin on behalf of ACEA, CLEPA et al.; Stakeholder document "BMW-results and statements.pdf", sent to Otmar Deubzer, Fraunhofer IZM, via e-mail on 5 June 2009
Pinsker 2009c	Pinsker, Martin; Information on composition of Antaya solders, sent to Otmar Deubzer on 9 June 2009 via e-mail
Rakus 2009	Rakus, Hagen, Volkswagen; Document "Präsentation Indium Soldering-VW.pdf"; sent to Otmar Deubzer via e-mail on 26 May 2009 as Microsoft Powerpoint document; converted to Adobe PDF-document by Otmar Deubzer, Fraunhofer IZM

4.18 Exemption no. 10

"Electrical components which contain lead in a glass or ceramic matrix compound except glass in bulbs and glaze of spark plugs"

4.18.2 Terms and definitions

Curie temperature	temperature at which ferromagnetic materials become paramagnetic

4.18.3 Background

This exemption was reviewed in 2007/8 during the review of Annex II of the ELV Directive (Gensch et al. 2008). The corresponding exemption in the Annex of the RoHS Directive was reviewed in 2008/09 (see final report of the previous review of RoHS Annex (exemption 7c) (Gensch et al. 2009).

During the review of exemption 7c of the RoHS Directive, it was found that lead can be replaced in the dielectric ceramic materials of low voltage capacitors. To adapt the exemptions for lead in ceramics to scientific and technical progress, and in line with the Commission's approach to make exemptions as application-specific as possible, the consultants had recommended to limit the use of lead in dielectric ceramics to high voltage applications of capacitors (Gensch et al. 2009). Yet, there were remaining questions about whether the proposed recommendation would sufficiently specify all relevant applications, or whether other applications of lead in glass and ceramics of components could have been identified.

In the current review of Annex II of the ELV Directive, it must be checked whether and how far the findings during the review of the Annex in the RoHS Directive also apply for the respective exemption 10 of the ELV Directive. The technical background for the exemptions for lead in glass and ceramics of components is identical in both Directives. Technical and scientific alignment of these exemptions and their wording between the two Directives is thus desirable, as far as specific conditions for the use of such components in vehicles compared to non-automotive applications do not justify differences.

4.18.4 Description of exemption

The exemption and its technical background were described in detail in the final report of the previous review of Annex II of the ELV Directive on page 65 ff (Gensch et al. 2008), as well as in the final report of the review of the RoHS Annex (exemption 7c) (Gensch et al. 2009).

Glass, ceramics, and mixes of glass and ceramics with or without lead are used in multifold applications in electrical and electronic components:

- Electrical and electronic components may contain different types of ceramics with different properties. In some of these ceramics, the use of lead still is unavoidable. Figure 56 shows a classification of ceramic materials and their main uses.

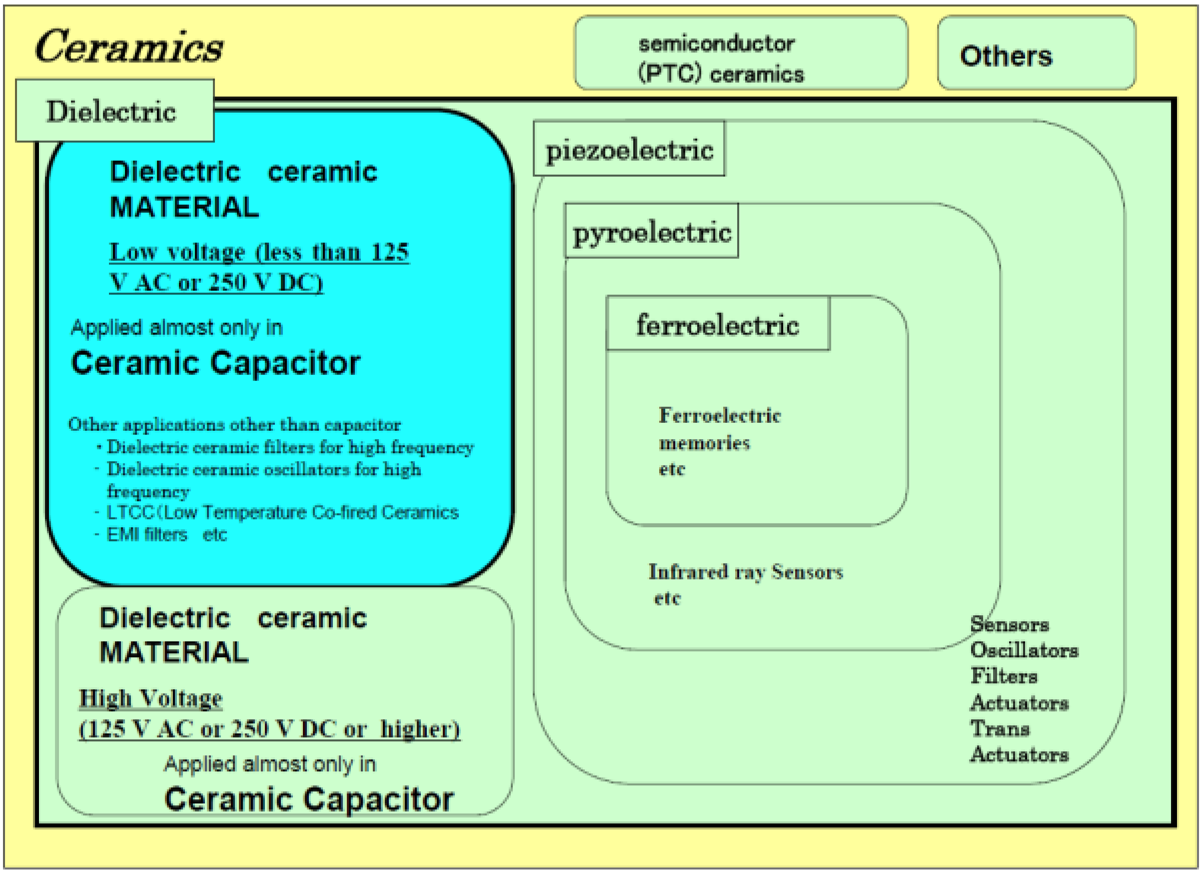

Figure 56 Classification of ceramic materials and their main uses (JEITA et al. 2009)

Figure 76 on page 258 in the annex gives a more detailed overview on these different applications.

- Glass and glass-ceramic materials, as well as glass and glass-ceramic matrix compounds are used in components for specific electrical and mechanical functions. Why in the applications in Figure 56 ceramics can be clearly identified as ceramics, in many other applications, this is not always clearly possible. There are overlaps, so that the exemption covers the use of glass and glass-ceramic materials and matrix compounds. In some applications, the use of lead is still unavoidable. Figure 76 on page 258 and Figure 78 in the Annex give a detailed overview on the uses of such materials in components.

The stakeholders indicate the amounts of lead used in ceramics and in glass in vehicles covered by the ELV-Directive as shown in Table 22.

Table 22 Estimated amounts of lead in glass and ceramics of electrical and electronic components in vehicles (CLEPA et al. 2009b)

Area of lead use	Amount
Pb in glass	27 t
Pb in ceramic (piezo)	250 t
Pb in other ceramics	100 t
Total	~ 380 t

The above numbers do not comprise 100% of lead used in these applications, but just a good estimate of the main applications, according to the stakeholders (CLEPA et al. 2009b). The detailed uses of lead in different applications is listed in Figure 77 in the annex. Summing up the amounts of lead uses indicated in this table results in a total amount of around 550 t of lead used under exemption 10 in vehicles. It is not clear how much other than the main uses of these materials actual contribute to the total amount of lead used.

4.18.5 Justification for exemption

Basic information on ceramic capacitors

Dielectric ceramics

If electrodes are set on both sides of a substance which does not conduct electricity (insulator), and if they are connected to positive/negative power sources respectively, "electric polarization" is generated within the insulator. Ceramics generating such electric polarizations are "dielectric ceramics". The major characteristics of dielectric materials are to store electricity, not to conduct electrical currents (JEITA et al. 2009a).

Dielectric ceramics are mainly made of titanium dioxide (rutile), calcium titanate, strontium titanate, magnesium titanate and barium titanate. To obtain the intended electrical properties, these materials are used individually or in multiple combinations, sometimes with additional dopants like for example lead.

Crucial performance requirements of capacitors

The main characteristics of capacitors are (JEITA et al. 2009a):

- high capacity to accumulate electricity (high dielectric constant, high relative permittivity) for both low and high voltage uses;
- small dielectric losses when electricity is accumulated, important in particular for high voltage uses;
- high breakdown voltage (capacity to withstand high voltage), important in particular for high voltage;
- high frequency characteristics (capacity to be used with high frequencies), important for both low and high voltage.

High and low voltage uses of ceramic capacitors are a crucial distinction criteria with respect to lead use and substitution.

Shapes and manufacturing technologies of capacitors

Ceramic capacitors can be found as disk-type and as multilayer ceramic capacitors (MLCC).

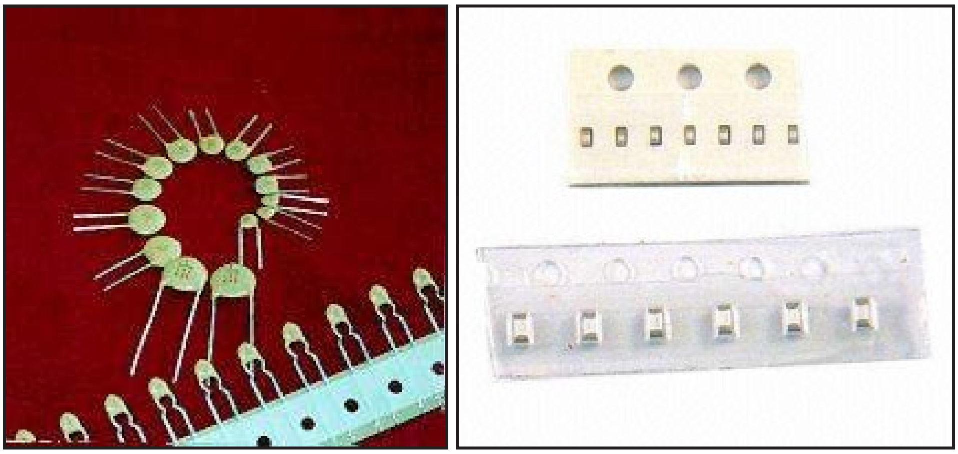

Figure 57 Disk (left) and MLCC type capacitors (source: www.allproducts.com)

A crosscut view of an MLCC capacitor is shown in Figure 60 on page 191.

Besides their shape, ceramic capacitors can be differentiated by their electrodes into noble metal electrode (NME) capacitors and base metal electrode (BME) capacitors (ACEA et al. 2009). The use of noble metal electrodes characterizes a manufacturing technology of ceramic capacitors. The inner electrodes are formed by noble metals (silver and palladium), which are sintered together with the dielectric ceramic, which contains lead. The NME technology was used from the very beginning to produce ceramic capacitors. The first ceramics needed high sintering temperatures of more than 1 000°C, and the noble metals forming the electrode are needed to withstand these high temperatures without being oxidized (Murata 2009).

The demand for ceramic capacitors grew rapidly in the past. The base metal electrode (BME) technology was therefore developed in the 1980s. A main driver were the high material prices of the noble metals in the NME capacitors, especially of palladium. In this BME technology, "base metals" like nickel or copper form the inner electrodes. Nickel and copper electrodes, however, cannot withstand high temperatures and therefore need ceramics with lower sintering temperatures. They must be sintered in ovens with nitrogen atmosphere. In consequence, the BME technology needs special low temperature ceramic systems and high investments for the manufacturing technology. These ceramics can be lead-free for capacitors in low voltage applications, as explained in the subsequent sections of this report (Murata 2009).

Due to the high investments, BME technology capacitors can be used only in high volume productions, whereas capacitors with special characteristics and/or in lower quantities may have to be produced in NME technology also in the future. BME capacitors cannot be used in small scale productions (Murata 2009).

Currently, high voltage capacitors in applications with high quantities and lower performances are produced with BME technology, whereas capacitors for higher performance and lower quantities have to be produced in NME technology also in future (Murata 2009).

Use of lead in dielectric ceramic materials of low voltage capacitors

Lead as dopant in the dielectric ceramic of capacitors

The high sintering temperature ceramics used in NME technology as explained in the previous chapter still are used in applications, which need high performance and stable electrical features. In the low voltage area, these types of ceramics need lead as dopant. Dopants are added to a base material ceramic to achieve the specific electrical and/or mechanical properties needed in the capacitor (Murata 2009). For low voltage NME capacitors, barium-titanate ceramics are doped with lead, so that the lead content is around ~1% in the ceramic lattice (ACEA et al. 2009).

Possibilities and limits of lead-free ceramic capacitor use

Generally, capacitors with a rated voltage of less than 125 V AC or 250 V DC do not use lead-containing dielectric ceramics. In remaining low voltage applications, (BME) capacitors with lead-free dielectric ceramics in principle can replace the (NME) capacitors with leaded ceramics in most cases. The substitution requires, however, a redesign of the whole electrical module or unit. BME-types are suitable and even better performing substitutes in nearly all cases except where good mechanical stability and/or high ESD (electrostatic discharge) robustness are required (ACEA et al. 2009, Murata 2009).

The stakeholders say (ACEA et al. 2009) that there were ongoing efforts to replace NME type by lead-free BME type capacitors. BME capacitors, according to the stakeholders (Murata 2009), cannot fully replace the NME capacitors due to the performance differences of the ceramic materials. For those applications new exemption requests will have to be issued (Murata 2009).

The majority of automotive applications operate at voltages below 125 V AC or 250 V DC. Most ceramic capacitors used in automotive electronics thus can be lead-free. Lead-containing NME type capacitors are, however, used in vehicles to prevent damages in case of high voltage impulses from the electrical system or from electrostatic discharges (ESD).

The breaking strength of BME type capacitors is lower (~100 MPa as the order of magnitude) The stakeholders (ACEA et al. 2009) list typical applications in automotive areas that rely on good mechanical stability and/or high ESD robustness, like (ACEA et al. 2009):

- battery line applications;
- engine control units;
- airbag control units;
- air conditioning;
- antiblocking system (ABS) control units.

ACEA et al. (ACEA et al. 2009) explain that for the same ESD robustness, a 10 nF (nano-Farad, unit for the capacity) lead-containing NME type multilayer ceramic capacitor (MLCC) has to be replaced by a BME type capacitor with a higher capacity. The submitted results of an ESD stress test shall support this statement (ACEA et al. 2009).

Case	Cap.	Char.	Voltage rating (V)	designation
0603 NME w. Pb	10 nF	X7R/NME	50	„10nF ESD“
0603 BME w/o Pb	10 nF	X7R/BME	50	„10nF std“

Figure 58 NME and BME capacitor used in ESD testing (ACEA et al. 2009)

The above capacitors of equal capacity were used in an ESD test. Figure 59 shows the test result.

	AEC-Q200	contact discharge		air discharge	
10 nF NME w. Pb	18kV	18kV	8kV	18kV	8kV
10 nF BME w/o Pb	8kV	6kV	4kV	6kV	4kV

Figure 59 Result of ESD testing (green: passed; red: failed) (ACEA et al. 2009)

The lead-free BME capacitor has a clearly higher failure rate.

Figure 60 shows an ESD damage in a BME MLCC capacitor.

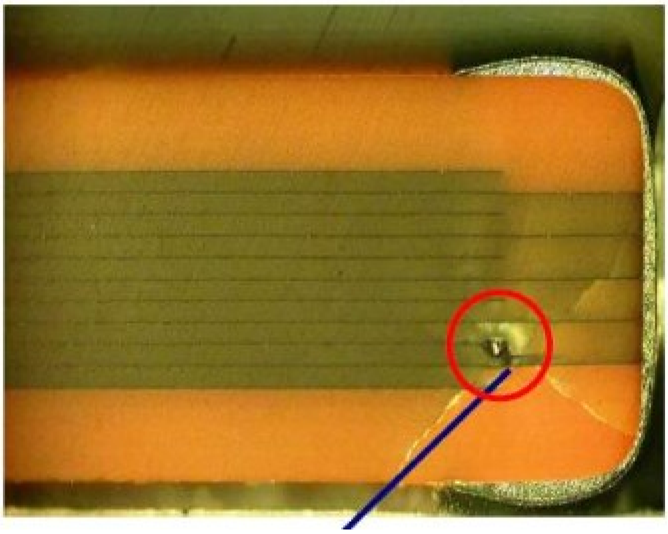

Figure 60 Failure produced with 25kV air discharge in a BME-type capacitor (ACEA et al. 2009)

ACEA et al. (2009) explain that for the same ESD robustness, a lead-containing NME MLCC of 10 nF capacity has to be replaced by a 47 nF BME capacitor, which deteriorates the system function. Other solutions are being developed, but are currently not validated at system level. The conflicts apparently are not resolved yet on system level (ACEA et al. 2009).

BME capacitors thus can replace NME capacitors in the low voltage area, which, however, requires a redesign and requalification of the electronic circuit and the printed wiring board. Lead containing NME type capacitors currently are still needed for reliability and safety reasons (ACEA et al. 2009).

Lead in dielectric ceramic materials of high voltage capacitors

The stakeholders point out (CLEPA et al. 2009a) that higher voltages above 125 V AC or 250 V DC may occur in specific automotive applications such as

- in electric and in hybrid electric vehicles (HEV);
- mechatronics;
- head lights;
- VFD/LCD displays.

Function of lead in ceramics of high voltage capacitors

JEITA et al. (2009a) explain that high operational voltages and high capacities require dielectric ceramics with small dielectric losses.

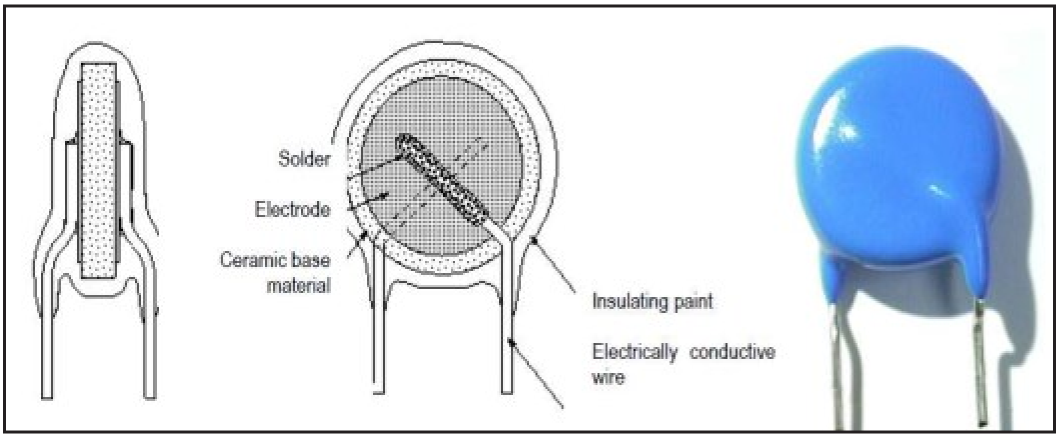

Figure 61 High-voltage disk type ceramic capacitor (JEITA et al. 2009a)

Strontium titanate ceramics are used for high voltage capacitors. Without lead, however, strontium titanate has a very low relative permittivity (capacity) at room temperature. It is less than 10% of the leaded strontium-titanate ceramic materials. In order to obtain the same capacity, a very large shape would be necessary, which in most uses technically is not acceptable (JEITA et al. 2009a).

Lead-oxide is therefore added to increase the relative permittivity (capacity). Different to lead containing ceramics in the low voltage area, lead here is not used as a dopant, but the ceramic system itself is based on lead and other heavy metals (Murata 2009). Leaded strontium-titanate ceramics are the current standard material for high voltage capacitors. (JEITA et al. 2009a, Murata 2009) These lead based ceramics in the high voltage area are used both with NME and BME technology (Murata 2009).

In the voltage range above 125 V DC and 250 V AC, lead containing ceramics hence are needed to achieve sufficient performance. Key parameter is the dielectric loss at high electrical field strength. (Murata 2009) During polarization and de-polarization of a dielectric material, its molecules and atoms are aligned according to the electrical field. This alignment results in dielectrical losses, which heat up the dielectric ceramic.

Lead-free barium titanate (BaTi) ceramics have a high relative permittivity, as can be seen in Figure 62. This lead-free ceramic thus can be used in low voltage applications. However, under high voltage, the dielectric loss is around one magnitude higher compared to lead containing capacitors.

	Relative permittivity	Dielectric loss (%)	DC breakdown voltage (kV/mm)	AC breakdown voltage (kV/mm)	Impulse breakdown voltage (kV/mm)
Current lead-based materials	2700	0.04	15.3	8.0	8.0
Barium titanate-based materials	3000	0.80	11.8	6.7	6.0
Strontium titanate	200				
Notes	Bigger is better	Smaller is better	Bigger is better	Bigger is better	Bigger is better

Figure 62 Comparison of materials for high-voltage capacitors (JEITA et al. 2009a)

Due to the high dielectrical loss, the lead-free BaTi capacitor heats up much more than the lead-strontium-titanate one (current lead-based material), as shown in Figure 63 (JEITA et al. 2009a).

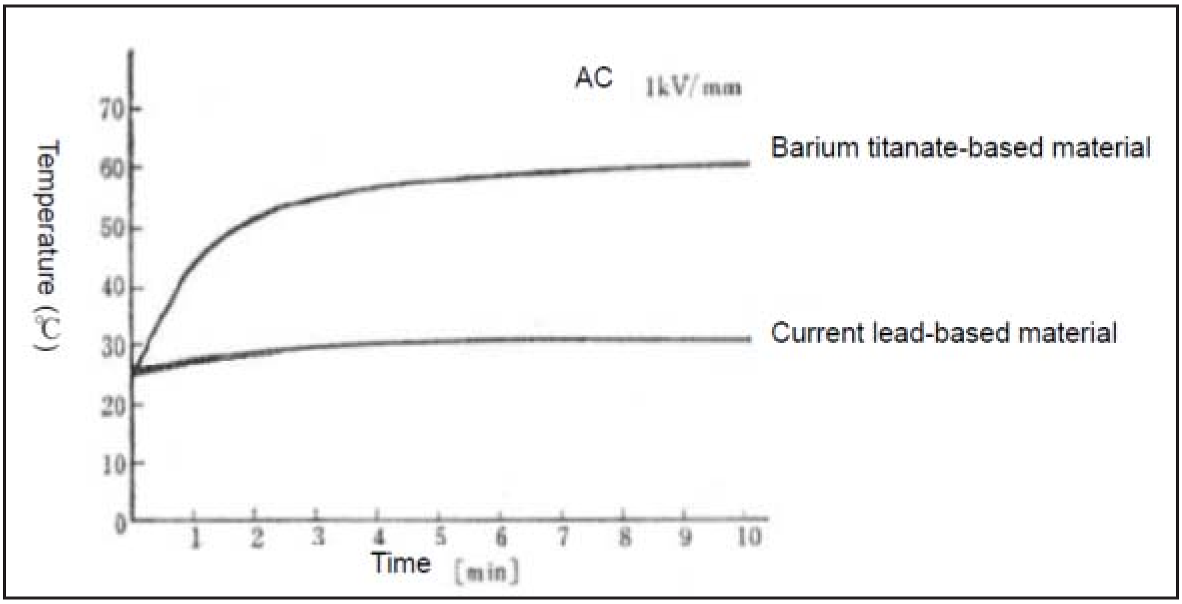

Figure 63 Temperature increase of capacitors under high voltage load (JEITA et al. 2009a)

The hot BaTi capacitor may become unstable. Additionally, barium titanate easily warps when high electric voltage is applied, which may reduce the mechanical stability even further (JEITA et al. 2009a).

Presently, according to the stakeholders (JEITA et al. 2009a), lead-strontium-titanate ceramics are the only possibility offering high relative permittivity and low dielectrical losses and at the same time sufficing all other requirements of high voltage capacitors (cf. Figure 76). NME and BME metal capacitors in high voltage uses.

Alternatives to ceramic capacitors

Capacitors using dielectric materials other than ceramics have problems concerning frequency characteristics and breakdown voltages. JEITA et al. (2009a) claim that there is no perspective for substitution since the high voltage capacitor characteristics cannot be obtained.

Conclusion

The stakeholders conclude (JEITA et al. 2009a) that non lead-based materials are not practical for capacitors used with high voltage voltages. Other than ceramic capacitors cannot replace ceramic capacitors in such applications. The use of lead thus is unavoidable.

Lead in the ceramic of piezoelectric components

In 2008, the use of lead in the ceramics of piezoelectric and PTC components was explained in detail in the review of the Annex of the RoHS Directive (exemption 7c) (Gensch et al. 2009), as well as in the last review of Annex II of the ELV Directive (Gensch et al. 2008). The stakeholders had shown that viable substitutes at an industrial level are not yet available and are not foreseeable in the near future. There is neither evidence nor hints that this situation has changed since these last reviews.

PZT based dielectric ceramic materials of capacitors in integrated circuits (ICs)

Specific material properties and uses

The stakeholders (NXP 2009) explain that besides the piezoelectric properties, lead-zirconium-titanate (PZT) shows also ferroelectric properties: They are polarized, and the polarization can be reversed by an external electromagnetic field. PZT ceramic thus has the ability to switch polarisation in the electrical field. It has the highest known dielectric constant (k = 1000 – 1200) (ESIA 2006), and a high electrical breakdown voltage of 100 V and more. PZT ceramics therefore are the most effective technical ceramic material to ensure best filter and electrostatic discharge (ESD) performance as required in automotive applications. The PZT based materials in combination with NME (noble metal electrode) only (MIM) meet the ESD performance required in integrated circuits (ICs) or discrete semiconductors. There are no alternative technologies/materials, which can provide the same performance (NXP 2009, ESIA 2006).

The lead content of the PZT based material is typically between 58% and 68% by weight, depending on the proportion of Zr and Ti, with the PZT layers being very thin (ACEA et al. 2009).

Lead is required to achieve the high dielectric constant of the PZT based applications in semiconductors. The PZT layer is encapsulated by layers of silicon nitrides and oxides, electrode metals and polymer layers. Therefore, the PZT is not exposed to the environment (NXP 2009).

Ferroelectric thin films based on PZT are currently used on silicon chips for (NXP 2009):

- FRAM (ferroelectric random access memories, non-volatile memories;
- low voltage high-density (MIM) capacitors ("high-k") with a breakdown voltage of more than 100 V;
- research activities worldwide also consider PZT for use in microactuators ("piezo-MEMS" (micro-electromechanical systems).

Capacitors store electrical energy in dielectric materials. Two electrodes are used to conduct the energy to and from the capacitor. Figure 64 illustrates the two common capacitor types for integrated capacitors. The silicon substrate can be used as electrode (MIS or MOS). In this case, all capacitors share the substrate as ground electrode. MIM capacitors can be used in any configuration (NXP 2009).

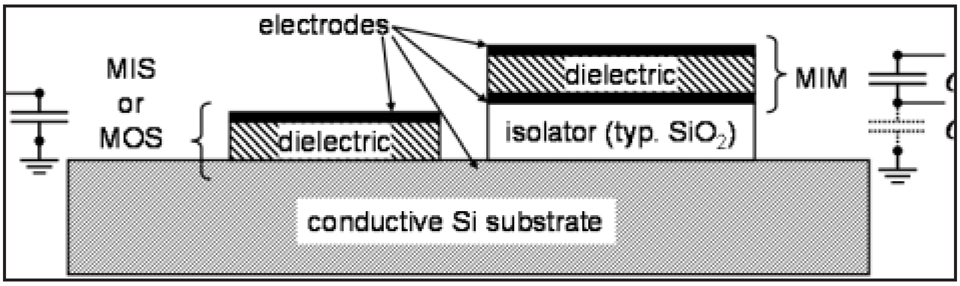

Figure 64 Typical thin-film capacitor configurations: MIM and MIS or MOS (NXP 2009)

MIM *metal insulator metal*

MIS *metal insulator semiconductor*

MOS *metal oxide silicon*

Only thin film ceramics based on PZT offer the combination of high breakdown voltages, high permittivity and temperature stability to realize silicon integrated capacitors and the ferroelectric advantageous properties of FRAMs. These devices are highly reliable and are easy to manufacture (Ramtron 2009).

The stakeholders say (Ramtron 2009) that for automotive FRAM applications, in particular the long term memory retention cannot be achieved with potential substitute materials. Such FRAMs are used in anti-lock brake systems and airbag controllers. They are thus safety-relevant and at the current state of science and technology cannot be replaced (Ramtron 2009).

According to the stakeholders (NXP 2009), PZT based ferroelectric memories have unique properties for mainstream flash and EEPROM chips (NXP 2009):

- low voltage
- low power consumption
- fast write
- high endurance over a broad temperature range

The FRAMS and integrated capacitors based on PZT outperform existing technologies. For both the PZT based integrated capacitors as well as for the FRAMS, market introduction is fairly new. Mass production only started around 2000 (NXP 2009).

Physical background

The capacitance density is a measure for how much capacitance "C" can be achieved at a given plate area "A" of a capacitor. With the progressing miniaturization in microelectronics, the available space becomes smaller. It is therefore crucial to achieve high capacitances on small available spaces (areas), which requires high capacitance densities.

The stakeholders explain (NXP 2009) that the capacitance density (capacitance C per area A) of a plate capacitor depends on the relative permittivity k and the thickness d of the dielectric layer. The vacuum permittivity ε0 is constant, while k depends on the dielectric material:

$$\frac{C}{A} = \frac{\varepsilon_0 k}{d}$$

Equation 1: Density of capacitance (NXP 2009)

The thickness of the capacitor depends on the desired breakdown voltage V_b and the breakdown field E_b.

$$d = \frac{V_b}{E_b}$$

Equation 2: Thickness of capacitors (NXP 2009, modified)

Replacing “d” in Equation 1 by Equation 2 results in the following equation for the density of the capacitance:

$$\frac{C}{A} = \frac{\varepsilon_0 k E_b}{V_b}$$

Equation 3: Thickness of capacitors (NXP 2009)

The capacitance density increases for a desired breakdown voltage V_b with the relative permittivity k of the dielectric material used in a capacitor and the breakdown field. These two parameters, however, are not independent from each other. Empirical investigations show for low and medium permittivity k that the breakdown field decreases with increased permittivity (NXP 2009) (see Figure 65 on page 198):

$$E_b \propto 1/\sqrt{k}$$

Equation 4: Proportionality of breakdown field and permittivity

For the capacitance density this means that a higher permittivity k leads to an increased capacitance density for a given breakdown voltage specification:

$$\frac{C}{A} \propto \sqrt{k}$$

Equation 5: Proportionality of capacitance density and relative permittivity

According to the stakeholder (NXP 2009) recent results for PZT exceed the empirical trend so that the capacitance density is even higher than expected from the extrapolation from low permittivities. Thus, the PZT-based ceramics offer the unique combination of high relative permittivity k at a high breakdown field and high breakdown voltage.

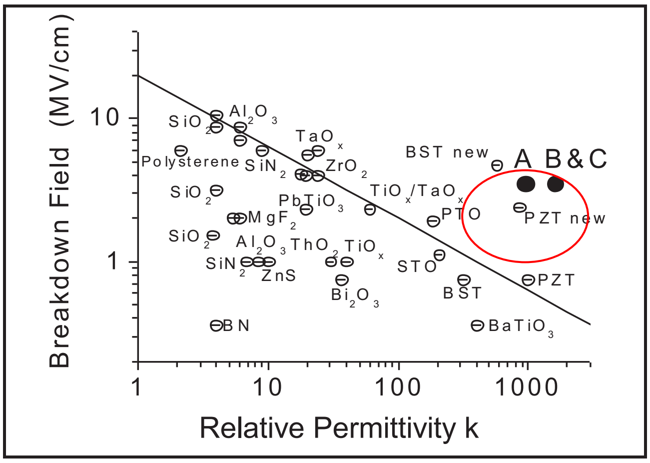

Figure 65 Breakdown field as function of the dielectric permittivity k for various thin film dielectrics (NXP 2009)

According to the stakeholder (NXP 2009), no alternative to PZT is currently known for thin films that achieve the same high permittivity, the same high breakdown field and at the same time meet stability specifications of 20% for temperatures between -25 to +85°C.

Substitute materials

ESIA states (ESIA 2006) that its member companies are committed to finding alternatives to the use of lead in semiconductor devices, e. g. through participation in EU funded projects, such as MAXCAPS or FOXPAD, searching for alternative materials (NXP 2009). So far, non of the examined alternative materials like SBT, BST, ZnO, and others works as well as PZT.

BST (Barium strontium titanate) has proven sufficient permittivity and temperature behavior. The permittivity of BST is only half the permittivity of PZT (NXP 2009, ESIA 2006). This would result in much larger devices, which won't meet the size dimensions of current and future applications in semiconductors. Barium titanates have also the disadvantage of a worse matching of the thermal expansion coefficient to the silicon substrate. They thus increase the thermal mismatch, which over time may result in failures. Performance characteristics with alternatives are severely degraded (ESIA 2006).

NXP and ESIA claim (NXP 2009; ESIA 2006; Ramtron 2009) that only thin films ceramics based on PZT offer breakdown voltages, permittivity and temperature stability to realize silicon integrated capacitors.

Substitute technologies

Trench (MOS) capacitors could be a potential alternative to high-density silicon integrated capacitors.

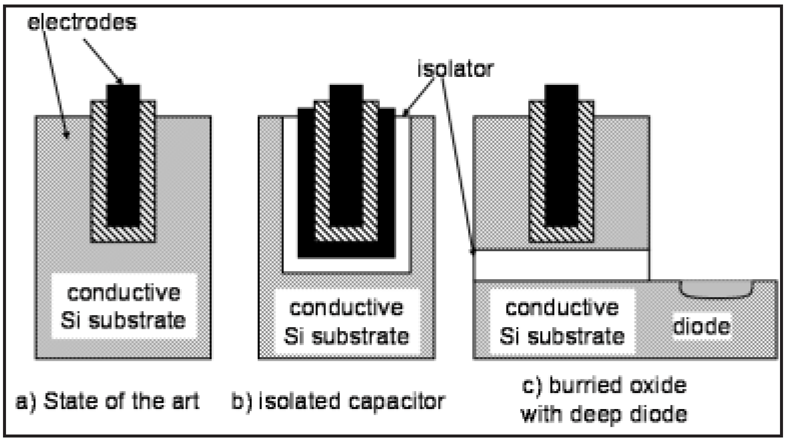

Figure 66 MOS trench capacitors (NXP 2009)

According to the stakeholders (NXP 2009, ESIA 2006), however, trench capacitors have

- much lower capacitance density and
- significantly lower breakdown voltage only (30 V, compared to 100 V for PZT-based materials (ESIA 2006)

compared to PZT based capacitors.

The disadvantage of a the lower capacitance density can partially be compensated by using the 3rd dimension making the capacitors larger. However, the stakeholder claims (NXP 2009) that the breakdown voltage of PZT based capacitors cannot be reached and that the MOS trench capacitors thus are not a viable substitute for the PZT based capacitors containing lead. MIM-type high k capacitors cannot be verified without PZT ceramics.

Conclusion

The stakeholder concludes (NXP 2009) that technically there are no alternatives for integrated MIM like PZT capacitors. PZT is the only material to integrate highest capacitance density with high breakdown voltages on silicon to ensure best filter- and ESD-performance at low leakage current levels. Trench- and BST-capacitors cannot fulfil the requirements.

Lead in PZT ceramic passivation layers of multilayer ceramic varistors

Multilayer ceramic varistors (MLVs) are used in electronic circuits to protect the circuitry from overly high voltage (e. g. from ESD, electrostatic discharge) or from electromagnetic interferences (EMI). The ceramic material used in MLVs is hexagonal zinc oxide (ZnO), doped with Bismuth, Cobalt, Manganese and Antimony oxides. Lead is contained in a ~20 µm thick passivation layer in the form of a lead-zirconate-titanate (PZT) ceramic. The lead content within these materials is up to 0,5% by weight (ACEA et al. 2009).

The PZT layer together with bismuth serves as sintering aid for liquid phase sintering. Without lead, the phase equilibrium between palladium (Pd, the inner electrode is Ag/Pd 75%/25%), and bismuth is distorted so that reliability and function parameters decline (ACEA et al. 2009).

The stakeholders claim (ACEA et al. 2009) that at the current state of science and technology, there is no reliable alternative to the use of the lead-containing PZT passivation layers. The use of glass coatings instead of a ceramic PZT coating resulted in high failure rates in most automotive applications compared to the lead-containing coating. As safety functions are involved (e. g. airbag, ABS, gear control) the research has to be continued until all failure rates have been dropped to required levels (ACEA et al. 2009).

Lead in the ceramic of PTC components

Function and ceramic materials used

Positive temperature coefficient ceramics (PTC ceramics) increase their electrical resistance with increasing temperature. Examples of material compositions are barium-strontium-lead-titanate, barium-titanate and lead-zirconate-titanate with dopants. The basic PTC material barium-strontium-lead-titanate undergoes a phase transition (from ferro- to paraelectric) at a certain temperature (Curie temperature, material dependent). If properly processed and slightly donor doped (< 1 mol %), such materials are “PTCR active”, meaning that they become semiconductive at low temperatures and quite highly resistive at temperatures above the Curie temperature (ACEA et al. 2009).

PTC components and their use

PTC ceramics are used in components called thermistors as overheating detector (temperature sensor) and for over-current protection in all engine section parts and all car electronic circuits. PTC materials as self regulated heaters are in use also for cabin heating, fuel and fuel filter preheating, and nozzle heating (e.g. washer and crankcase ventilation) (ACEA et al. 2009, JEITA et al. 2009a).

Function of lead

The lead content of these materials is up to 50% by weight. Lead is used in the solid solution of barium titanate and lead titanate. Substituting the barium atoms of barium titanate by lead atoms increases the Curie temperature and creates a PTC ceramic for high-temperature operation.

In automotive applications with its high operating temperatures, only material with a Curie temperature of at least 120°C is suitable for automotive applications. Lead is also indispensable for these ceramics to achieve the required resistance-voltage characteristics and distribution of the resistance value. Typical Curie temperatures for PTC cabin heaters, for example, are in the range of 140–190°C (ACEA et al. 2009). PTC ceramics with lower temperatures cannot achieve the necessary heating power (ACEA et al. 2009).

To achieve Curie-temperatures of 120°C and more, lead in the PTC ceramic cannot be replaced. Adding lead to the Barium titanate matrix of the PTC ceramic is the only possibility to raise the Curie temperature of the basic Barium titanate to the required levels (ACEA et al. 2009).

Substitution of lead

The alternative material for lead in PTCR's, bismuth (Bi), can be used in very rare cases only. Its solubility in barium titanate is low compared to lead. There are reports that Bi can raise the Curie temperature by approx. 18 K, which is insufficient. At the same time, it is known that Bi can improve the volume resistivity of PTC resistors. $Bi_2Sn_3O_9$ in small amounts improves the resistivity above the Curie point. Higher amounts of Bi will form bismuth-titanate phases, which are not ferroelectric and thus do not contribute to the PCTR performance. Bi thus cannot be considered a replacement for lead. In fact, there is no other material than lead containing material available to shift the Curie temperature as necessary for PTC applications (ACEA et al. 2009).

Besides the Curie temperature effect, lead in PTC ceramics is crucial for switching applications and over current protection, where it enables high switching reliability and high voltage strength. Lead free alternatives are only available for operation temperatures far below 120°C, which is too low for most automotive applications. Lead-free PTCs are less reliable and have less voltage strength. Furthermore, higher Curie-temperatures are often needed to obtain equal permissible currents with miniaturized parts (ACEA et al. 2009).

For PTC components, which are used for temperatures below 120°C, lead-free alternatives might become available in the next three years (JEITA et al. 2009e). According to the stakeholders, automotive applications require components that can withstand at least 120°C.

Lead in the ceramic of compensation capacitors in ultrasonic sonars

Functional principle of ultrasonic sonars

Ultrasonic sensors in vehicles are used as sonars to detect obstacles e. g. when driving backwards and for parking assistance systems. They measure the distance between the car and an obstacle and warn the driver to avoid accidents and damages.

The ultrasonic ceramic is a piezoceramic and works as sender and receiver. It is therefore called sensor. An alternating current electrical impulse (drive signal) into the piezoelectric ceramic makes the piezoceramic vibrate and generates an ultrasonic signal, which is transmitted, as illustrated in Figure 67.

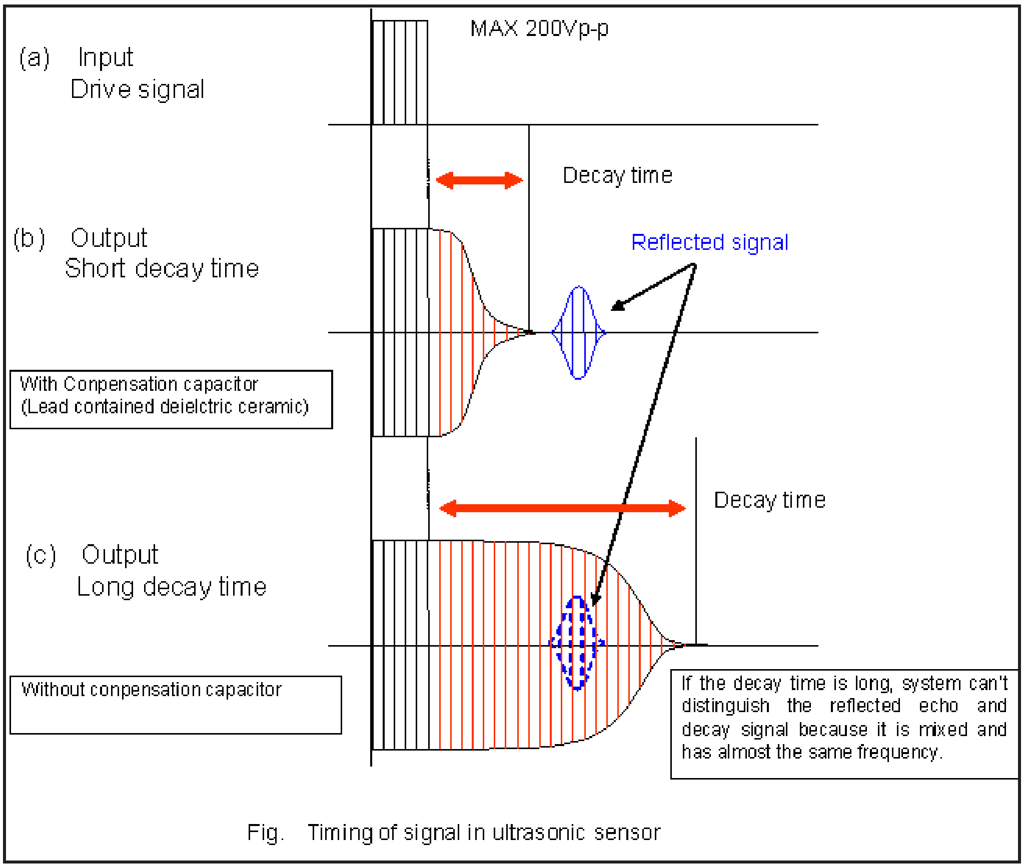

Figure 67 Functional principle of an ultrasonic sonar (JEITA et al. 2009c)

An obstacle would reflect the ultrasonic sound wave (echo). The reflected signal hits the piezoelectric ceramic and makes it vibrate, which generates an electronic signal. The signal processor calculates the distance of the vehicle to the obstacle via the time difference between the transmission and reception (JEITA et al. 2009c).

Use of lead-containing compensating capacitors

The stakeholders explain (JEITA et al. 2009c) that the ultrasonic sensor is based on lead-containing ceramics. The sensor's precision of distance measurement depends on the capacitance of the sensor ceramic, which, however, changes with the outside temperature to which the car – and the sensor – is exposed to. The capacitance increases for more than 0,5% per degree Celsius of temperature increase. Exact distance measurements over a wider outside temperature range thus are impossible.

To compensate the temperature-related shift of capacitance in the ultrasonic ceramic, a compensating ceramic capacitor is used. The capacitance of this capacitor also changes with the temperature, but inverse to the capacitance of the ultrasonic sensor. The capacitance of this compensating capacitor decreases for more than 0,4% per degree of temperature increase. The capacitance changes in the ultrasonic sensor ceramic and in the ceramic compensating capacitor thus are working in opposite directions and thus almost compensate each other. Figure 68 illustrates these effects.

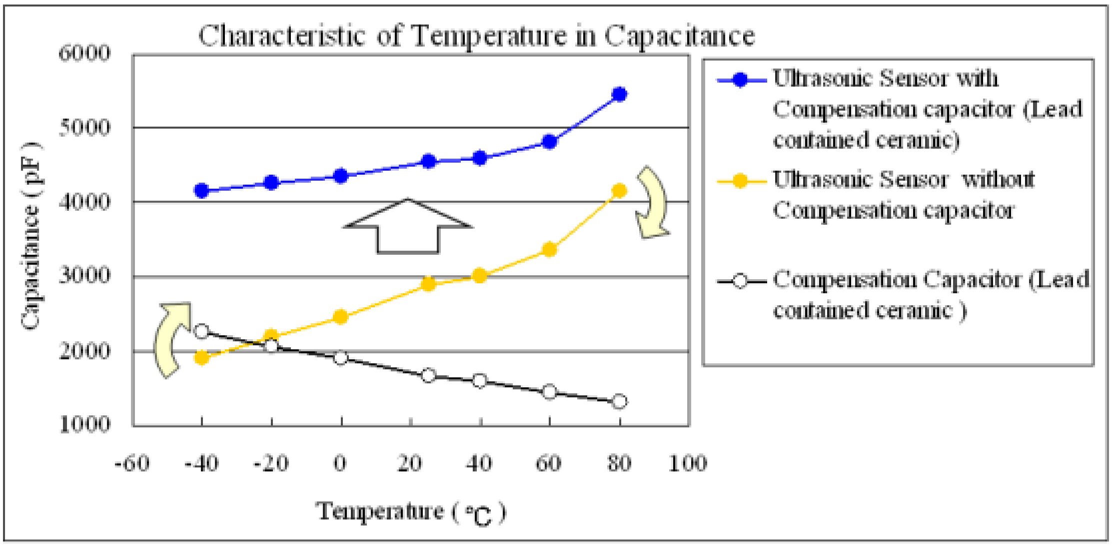

Figure 68 Temperature characteristics of capacitance in sensor and temperature compensating capacitor (JEITA et al. 2009c)

Lead-free dielectric ceramic capacitors have a temperature coefficient of only around 0,3% per degree Celsius (JEITA et al. 2009c). The overall compensation thus is not sufficient, according to the stakeholders (JEITA et al. 2009c), to achieve a sufficiently exact distance measurement over a broad temperature range. Without the lead-containing compensation capacitor, the measured distance can deviate up to 50% from the actual deviation, in particular in the low distance range below one meter. As the sensor also is part of the parking assistance system, these deviations are unacceptable and may lead to accidents and damages.

The dielectric ceramic of the compensating capacitor contains less than 1 mg of lead. The stakeholders claim (JEITA et al. 2009c) that the use of these lead-containing capacitors is unavoidable.

As such capacitors in ultrasonic sensors are operated below 125 V DC, the use of such capacitors requires a specific exemption. The proposed exemption “Use of lead in dielectric ceramic materials of capacitors with a rated voltage of less than 125 V DC/250 V AC” does not cover this application.

Lead in glass and glass-ceramic materials

Glass, glass-ceramic and glass or glass-ceramic matrix compounds with lead are used in manifold applications. From the material scientific point of view, a clear differentiation between glass and glass-ceramic materials and matrix compounds is not always possible. It thus does not make sense at the current state of science and technology to further differentiate these materials in their applications and in the exemption wording.

Glass and glass-ceramic materials and matrix compounds with lead are used in (ACEA et al. 2009):

- low melting type glass frit in thick film paste for electronic components, such as hybrid integrated circuits, resistors, capacitors, VFD Displays, etc.;
- low melting type glass frits in glass paste for protection (such as hermetic seals) and bonding applications (such as sensor components);
- glass encapsulations based on low melting type glass tubes such as glass diodes, VFD Displays and thermistors.

The main functional aspects of lead glass and glass-ceramic materials and matrix compounds are (ACEA et al. 2009):

- pre-coating for thick film resistors;
- surface protection coating;
- vacuum (adhesion) assurance;
- resistor binder (adhesion assurance for ceramic base materials);
- electrode binder (adhesion assurance for ceramic base materials);
- hermetic sealing.

Several components contain such glass materials (ACEA et al. 2009):

- varistors;
- chip resistors;
- pressure and strain sensors;
- bridge rectifying devices;
- power transistors;
- power thyristors;
- quartz oscillators;
- diodes;
- thermistors;
- vfd displays.

Figure 78 in the annex gives a detailed overview on the different uses of these materials. This annex also explains the details of the lead uses and the problems with substitution (JEITA et al. 2009b).

The contents of lead in these materials depend on the exact application:

- glass / Surface protection coatings with 45% to 5% (weight) lead concentration;
- glass in electrodes with 1% to 57% (weight) lead concentration;
- glass in resistor binders (adhesion assurance for ceramic base materials) with 3% to 30% (weight) lead concentration;
- glass for bonding pastes with 5% to 80% (weight) of lead concentration;
- frit glass used in VFDs with up to 60% (weight) of lead concentration;
- ruthenium lead oxide for resistors with around 55% to 60% (weight) of lead concentration;
- glass in the thick film layers of components.

Figure 78 in the annex lists the amounts of lead used in more details. The total amount of lead used in glass, glass-ceramic and glass- and glass-ceramic matrix compounds is around 30 t per year (CLEPA et al. 2009b).

The stakeholders explain the functions of the lead in glass, glass-ceramic and matrix compounds (ACEA et al. 2009):

- lowering the softening points and the viscosity during processing;
- better alignment of thermal expansion;
- improved electrical insulative properties;
- higher affinity to other materials for binding and bonding materials;
- higher weather resistance.

According to the stakeholders (ACEA et al. 2009), the above specific properties of leaded glass are of importance (ACEA et al. 2009):

Viscosity (ACEA et al. 2009)

Leaded glass is used for bonding of materials. It has a low viscosity needed to flow well during such bonding process. Bad flow potentially causes pin holes and other (surface) imperfections. The glass thus may become sensitive to cracks and other mechanical damage when subjected to mechanical stresses, which will occur during normal operation. Cracks, occurring e. g. in sensors, cause unacceptable sensor drift and potential sensor failure. Lead-free materials' viscosities are lower in the order of 100.

Softening temperature range (ACEA et al. 2009)

Leaded glass has a low softening temperature. The glass is used to bond silicon strain gages with aluminium bond pads on stainless steel diaphragms as well as for ceramic-on-ceramic bonds. The firing temperature – i. e. the temperature at which the silicon is bonded to the stainless steel, normally around 850°C range – must not exceed the (eutectic) melting temperature of the aluminium. Other bonding materials than leaded glass have higher softening temperatures potentially causing junction spiking and other reliability issues in the aluminium on silicon.

Differences in the coefficient of thermal expansion (CTE) (ACEA et al. 2009)

The CTE of the glass should be within a specific window and compatible with the materials, to which it is bonded, such as stainless steel and aluminium. Under temperature changes, low values compared to the bonding partner can cause tensile stress, too high values can generate high compressive stress in the glass. Both may result in glass cracks and, cones-quently, component failure.

Electrical Properties (ACEA et al. 2009)

The insulation properties of leaded glass are acceptable, while alternative glass materials show higher ionic conductivity. The electrical insulation thus may break down affecting reliability and performance of the components.

In principle, lead-free alternatives are (ACEA et al. 2009):

- organic based alternatives have issues with stability, inability to withstand the pro-cessing temperatures, and no protection (ability to create a good vacuum seal).
- other metal oxides than lead oxides

Figure 77 in the annex shows the discussed substitutes and the main obstacles for their use at the current state of science and technology. Currently available lead-free materials cannot satisfy all necessary conditions (JEITA et al. 2009b). When substituting leaded materials by lead-free ones, typically the requirements for one set of attributes leads to unacceptable performance in another attributes, according to the stakeholders (ACEA et al. 2009).

Figure 69 shows examples of properties of some of the alternative glass compositions evaluated. This is not an exhaustive list, but highlights the tradeoffs found in substitute materials (ACEA et al. 2009).

Characteristics	Pb glass	Zn glass	P-Sn glass	Na-Al-P-B
Affinity	Good	Not good	Not good	Good
Low softening point	Yes	No	Yes	Yes
Coefficient to thermal expansion	Good	Good	Good	Not good
Weather resistance	Good	Good	Not Good	Not Good
Electrical Properties	Good	Good	Good	Not Good

Figure 69 Properties of lead and other type glass materials (ACEA et al. 2009)

The stakeholders put forward (ACEA et al. 2009) that, although alternative compositions have been employed partly in consumer electronics products, the much wider temperature ranges, vibration, the combination thereof, and reliability concerns have made substitution within automotive applications unfeasible for most components. Several types of compositions, e.g., have been developed and tested for lead free glass frits. They are, however, inferior in their weather resistance characteristics. For hermetical sealing, bonding & glass encapsulations, lead free glass materials are available in general, but their process temperatures are too high, and the interactions between glass and ceramic during bonding are unpredictable.

The stakeholders maintain (ACEA et al. 2009) that, lead-free glass types are not expected to be applicable in vehicles before 2018 to 2019. They propose to continue the exemption without expiry.

4.18.6 Stakeholders' request to leave exemption 10 unchanged

The stakeholders cooperated in the recast of exemption 10. Nevertheless, they express their preference to leave exemption 10 unchanged (CLEPA et al. 2010) for the reasons explained in the subsequent sections.

Status of lead reduction

The stakeholders put forward that the lead content per vehicle has already been reduced from approx. 2 kg in 2003, when the ELV directive came into force, to approx. 300 g today. The battery is not taken into account in these values, because it has a special position given the possibility of return and recycling (CLEPA et al. 2010).

The stakeholders call for a strategy for further substitution or reduction that takes the following criteria into account (CLEPA et al. 2010):

- cost/benefit analysis;
- social and economic criteria;

- permitted “residual content.

Feasibility

The industry stakeholders claim (CLEPA et al. 2010) that their representatives and the EU Commission consultants had worked closely together to come up with a recast of exemption 8 (a–j) that is acceptable for all parties. However, in practice, comprehensive procedural guidelines are required to describe the complex interrelations that enable a “compliance” decision at project level. Automotive industry claims that such guidelines make enforcement of an exemption unnecessary burdensome compared to the environmental benefit of the relatively small reduction of lead content.

The stakeholders raise the question how the relevant authority could check the compliance of such a complex application-specific exemption, because

- valid or non-valid applications first have to be identified, which is practically impossible in the above-mentioned case for laymen – and sometimes even for material laboratories.
- In most cases, the parts are very small and are therefore practically impossible to identify as an element of the component.

The stakeholders fear that a comparable situation will result if exemption 10 is broken down to detailed applications (CLEPA et al. 2010).

Hampering innovation

The stakeholders claim (CLEPA et al. 2010) that an application-specific exemption list means in essence a limited list and no longer an informative description of what is meant. Furthermore, such a listing is based on today’s knowledge, i.e. would block innovation since future technological developments are not yet known. For example, in case of completely new applications giving technical solutions to future (societal) questions (safety, aging population, environment), it would be necessary to apply for an exemption to be added to the list. The stakeholders are not certain that such an exemption request would be granted based on today’s evaluation criteria (CLEPA et al. 2010).

Particularly in the case of exemption 10, where the amount of lead is in the (milli)gram range (excluding PZT application injectors, which use more lead (see Table 22 on page 187), the stakeholders believe that it would be justified for reviews to take a broader scope rather than just examining the possibility of avoiding use (i.e. use criteria going beyond Article 5(1)(b)) (CLEPA et al. 2010).

Alternative proposal

On the basis of the above arguments, CLEPA et al. (2010) take the following stance to the consultants' proposal for providing a greater level of detail for exemption 10:

- A list of the applications known today as containing lead in glass or ceramics was drawn up in the documents provided by CLEPA et al. during the stakeholder consultation. Details and explanations have been added during the evaluation.
- Industry represented by members of the relevant EU and U.S. automotive industry (AI) supplier associations and JEITA from Japan provided input, thus ensuring a representtative and international cross-section of views.
- Only one application was identified for which an expiry date could be defined, which is NME capacitors. Estimated overall amount of lead caused by the use of such capacitors is not more than 25 milligrams.
- There is no suitable substitute for any other applications known today, which is why no expiry date can be defined for them.
- Altogether, the applications that come under this exemption involve approx. 2–5 grams of lead per vehicle, without PZT injectors, which contain higher amounts of lead (see Table 22 on page 187).

The stakeholders put forward (CLEPA et al. 2010) that a further regulative reduction can only be obtained once an expiry date for a corresponding application has been defined, which does not rule out the basic option of voluntary substitution as soon as alternatives are known and available.

The automotive industry believes (CLEPA et al. 2010) that it is neither beneficial nor expedient to further detail exemption 10 with regard to covered applications on the basis of the existing information. Even defining a fallback option (cf. proposed wording for b) above) makes no sense from the automotive industry's perspective, because:

- there is currently no application known that would require the fallback option;
- and, if an application were to be identified, there would not be sufficient time to search for and implement alternatives before the expiry of the exemption in 2014.

Therefore, the automotive industry proposes the following approach:

1. Retain the generic material-specific exemption for the time being;
2. start discussions with decision makers on how to improve revision of Annex 2 in general;
3. and then decide about future handling of this exemption.

The stakeholders claim that in any case, the current collection and evaluation of information would be a sound basis for future evaluations (CLEPA et al. 2010).

4.18.7 Critical review of data and information

Use of lead in dielectric ceramic materials of low voltage capacitors

The stakeholders plausibly explain why lead is used in such capacitors (see page 189). The use of lead in ceramics is linked to noble metal electrode (NME) capacitors in the low voltage area. These NME capacitors, however, can be replaced by base metal electrode (BME) capacitors, which can be produced and used with lead-free dielectric ceramics. The use of lead thus is avoidable, and Art. 4 (2) (b) (ii) of the ELV Directive does no longer justify an exemption.

The stakeholders point out that there may be cases where specific mechanical stability and electrical requirements make the use of lead-containing NME capacitors indispensable due to reliability reasons. They can, however, not put forward either clear cases or clear evidence. The use of ceramics in electrical and electronic components, however, is a complex field, which is difficult to overlook in all its application cases and component variations. Additionally, the replacement of such lead-containing capacitors requires a redesign of entire electrical systems, which may take time given the long redesign cycles in the automotive industry.

It was hence agreed with the stakeholders to recommend an expiry date as late as in 2016 to accommodate the situation.

As was shown in the previous review of Annex II of the ELV Directive (Gensch et al. 2008), the redesign of existing electrical and electronic modules is not possible. It is hence recommended to repeal the exemption for vehicles type approved after 31 December 2015.

The reviewers recommended the following wording for this exemption:

Lead in dielectric ceramic materials of capacitors with a rated voltage of less than 125 V AC or 250 V DC in vehicles type approved before 1 January 2016, and in spare parts for these vehicles

Use of lead in the ceramic of piezoelectric components

During the previous review of Annex II (Gensch et al. 2008) and the review of the annex of the RoHS Directive (Gensch et al. 2009), the stakeholders plausibly explained that lead currently cannot be substituted in the ceramic of piezoelectric devices. There are not hints that this situation has changed since the last reviews. A viable technical solution currently is not foreseeable.

The use of lead in this application hence is unavoidable and Art. 4 (2) (b) (ii) of the ELV Directive would justify an exemption without setting an expiry date. The recommended wording for this exemption is:

Lead in the ceramic material of piezoelectric components

Critical review of other uses of lead in ceramics

The following other uses of lead were identified and discussed with the stakeholders:

- lead in dielectric ceramic materials of high voltage capacitors (page 191)
- lead in PZT based dielectric ceramic materials of capacitors being part of integrated circuits (ICs) or discrete semiconductors (page 194)
- lead in the PZT ceramic passivation layers of multilayer ceramic varistors (page 199)
- lead in the ceramic materials of PTC components (page 200)

In several meetings, phone conferences and information exchanges via e-mail, the above uses of lead in ceramics were identified and casted into a clear and unambiguous exemption wording. Within the available time and budget and the information submitted by the stakeholders, no evidence was found that lead could be substituted in the above ceramic materials, or that viable substitutes will be available in the near future.

Given this background, the use of lead in these applications must be considered as unavoidable, and Art. 4 (2) (b) (ii) of the ELV Directive would justify granting exemptions without setting an expiry date.

The following wordings are recommended for these exemptions:

- *Lead in dielectric ceramic materials of capacitors with a rated voltage of 125 V AC or 250 V DC or higher.*
- *Lead in PZT based dielectric ceramic materials for capacitors being part of integrated circuits (ICs) or discrete semiconductors.*
- *Lead in the PZT ceramic passivation layers of multilayer ceramic varistors.*
- *Lead in the ceramic materials of PTC components.*

The current state of knowledge suggests that the above exemption covers all uses of lead in ceramics, where it is indispensable. Nevertheless, the following temporary exemption is recommended additionally as a fall-back option in case any use or application is not listed:

Lead in the ceramic material of electrical and electronic components, which are not listed under the above exemption, in vehicles type approved before 1 July 2014, and in spare parts for these vehicles.

This temporary fallback option shall offer enough time for the stakeholders to find lead-free solutions or to apply for additional exemptions in case the use of lead in the ceramic materials of other components is unavoidable.

Lead in the ceramics of compensation capacitors of ultrasonic systems

The stakeholders' request to exempt lead in compensation capacitors of ultrasonic systems (see page 201) was discussed in order to check, whethr alternatives might be available.

Alternative ultrasonic systems

JEITA et al. (2009d) explain the advantages and disadvantages of different ultrasonic systems.

Technology A: Ultrasonic system with lead-containing compensation capacitor

This ultrasonic sonar system demonstrates high sensitivity over a wide temperature range. Additionally, it detects obstacles reliably in the distance of 0,1 to 7 m, which is crucial for parking assistance systems.

This system hence is most appropriate to be used in parking assistance systems.

Technology B: Ultrasonic system without compensation capacitor

JEITA et al. state that in an alternative system, the lead-containing compensation capacitor can be foregone, if the detector signal is amplified with a higher factor. The reflected signal can then easier be detected and differentiated from the transmitted signal. The background noise of the system, however, is amplified as well. The system can be used over a wide temperature range, and it is appropriate to detect nearby objects. The reflected echo from such objects is large and strong, so that the strong amplification can resolve it. The weak echo from a more distant obstacle, however, cannot be detected reliably. The strong amplification increases the background noise together with the weak signal from the distant object. The signal cannot be reliably differentiated from this background noise. For parking assistance systems, technology B thus is not appropriate, as it shows weaknesses in the distance measurement for obstacles in the range of 1 to 7 m behind the car (JEITA et al. 2009d).

Technology C: Ultrasonic systems with lead-free compensation capacitors

According to JEITA et al. (2009d), ultrasonic systems with lead-free compensation capacitors are under development. They have a high sensitivity, but over a small temperature range only. Such systems therefore are not yet commercially available.

Alternative compensation mechanisms in ultrasonic systems

It was discussed with the stakeholders why the vehicles' signal processor or board computer cannot compensate the ultrasonic sensor's temperature shift. Modern vehicles have thermometers measuring the outside temperature. The board computer could thus correct the sensor signal for the temperature shift and thus calculate the correct distance (calculated correction).

The stakeholders say (JEITA et al. 2009c) that this is impossible as the ultrasonic ceramic sensor at the same time is sender and receiver. After having generated and sent the ultrasonic signal, the sensor must stop vibrating as soon as possible (short decay time, see b) in Figure 67). Otherwise, the sensor is still vibrating when the signal comes back (long decay time, see c) in Figure 67) and the signal cannot be differentiated from the sensor's reverberation vibration. A distance measurement in particular on short distances is impossible. The sensor does not work.

As the decay time (see Figure 67 on page 202) increases with the capacitance, an insufficient compensation of the temperature-related capacitance shift makes the measurement impossible on shorter distances. A subsequent temperature-correction of the sensor signal in the signal processor cannot solve this problem.

Separation of transmitter and receiver

The calculated correction does not work because the transmitter at the same time is the receiver. Thus, separating the sending ultrasonic ceramic from the receiving one, could be a solution enabling a calculated correction of the signal.

This separation, however, does not solve the problem either. The stakeholders (JEITA et al. 2009c) say that the receiving sensor would not be able to differentiate the transmitted signal coming directly from the sender from the signal reflected by an obstacle. The transmitted signal already would cause vibration in the sender, thus making the distance measurement impossible.

Alternative sensor materials

Possibly, other than the lead-containing piezoelectric sensors could be used, which are less temperature dependent or can be compensated with lead-free capacitors.

The stakeholders explain (JEITA et al. 2009d) that the piezoelectric device is the best material to generate high sound pressures with minimum power. Alternatives like audio speakers and microphones use the magnet/coil technique to make sounds. This system, according to the stakeholders (JEITA et al. 2009d), consumes high current power, and is not sufficiently reliable for the harsh conditions in a vehicle. Lead-free alternatives to the currently used lead-containing piezoelectric ceramics have been studied, but are not available at industrial level yet. The stakeholders say they do not know another system to generate high sound levels with the same quality like the piezoelectric device used in the current ultrasonic sonars (JEITA et al. 2009d).

Alternative sensor systems

Possibly, other than ultrasonic systems can serve the same function without using compensation capacitors. Table 23 shows different systems and their basic properties.

Table 23 Comparison of systems (JEITA et al. 2009d)

Technology	Feature
Ultrasonic	Detectable range is 0,3 to 2,5 m Stable against rain drops and mud Most popular in the world at this moment
Microwave (radar)	Detectable range is 10 to 100 m Cannot detect near distance and thus cannot be used for parking assistance
CCD camera	Detectable range is wide and 0 to 5 m (Driver have to check monitor or distance) Does not work in the dark or when lens is dirty
Capacitance	Detectable range is 0 to 0,5 m (not clear at this moment) Unstable against rain drops and mud

Thus, alternative systems currently cannot be used The ultrasonic sonar is the most appropriate and reliable system (JEITA et al. 2009d).

The stakeholders claim (Bosch 2010) that ultrasonic sonars are simple, light-weight and cheap compared to other systems like e. g. the radar systems. Besides the technical features, the higher complexity of alternative systems burdens the environment, and it may well compensate the possible environmental impacts of lead used in the ultrasonic sonar systems, as explained in Table 24.

Table 24 Comparison of ultrasonic sonar and radar systems (Bosch 2010)

	Ultrasonic system	Radar system
Weight	15 to20 g	~460 g
Number of electronic components	Around 20 on 1 PWB, mostly standard components	Around 300 on 2 printed wiring boards (PWB), partially specific components
Lead content	Ceramics of components incl. compensating capacitor: 0,5–3 mg High melting point solder in components: none Piezo-ceramic (sensor): 40 mg Aluminium (less than 0,05% of lead as alloying element): less than 1,5 mg Cu-based punch scrap: less than 0,1 mg Total lead in electrical/electronic components: ~40 mg Overall total: ~45 mg	Ceramics of components: 25–60 mg High melting point solder in components: <10 mg Aluminium (less than 0,05% of lead as alloying element): max. 100 mg Cu-based punch scrap: 0,5–1 mg Total lead in electrical/electronic components: ~30 to 70 mg Overall total: 130 to 170 mg

	Ultrasonic system	Radar system
Cost		Around 10 times more expensive compared to ultrasonic sonar systems

The stakeholders explain (Bosch 2010) that the above data for lead contents are taken from the IMDS (International Material Data System), a database used in the automotive industry to declare material data. These are generic data based on averages.

The above figures show that alternative, more complex systems like radars may use at least equal amounts of lead in the electronics components compared to ultrasonic sonars with compensating capacitors. Additionally, higher weights increase the energy consumption of vehicles.

Conclusions

The above technical information shows that ultrasonic sonar systems are the best and most reliable option. Some alternative systems can cover part of the functionalities, but not the whole range of functions in the quality and reliability necessary in this automotive application. Environmental data illustrate that alternative, more complex systems like radars may use the same or even higher amounts of lead. Higher weights of such systems additionally increase the energy consumption of vehicles and the burden the natural resources.

The stakeholders show that the use of piezoelectric systems is required in ultrasonic sonars. Such systems depend on the use of lead-containing compensating capacitors.

The use of lead at the current state of science and technology is unavoidable in this application, and Art. 4 (2) (b) (ii) would justify an exemption.

The recommended wording for this exemption is proposed as:

Lead in the ceramics of capacitors compensating the temperature-related deviations of sensors in ultrasonic sonar systems

As alternative systems using lead-free compensation capacitors are under development, it is suggested to review the exemption in 2014.

Lead in glass and glass-ceramic materials or matrix compounds

Lead in glass and glass ceramic materials or in matrix compounds has important functions, as the stakeholders explained (page 201). Within the available time, and based on the available information, no evidence could be found that lead-free alternatives are commercially available or foreseeable for the near future.

The use of lead in these applications currently must be considered as unavoidable, and Art. 4 (2) (b) (ii) of the ELV Directive would justify granting exemptions without setting an expiry date.

Given the multitude of glass and glass-ceramic applications, a component-related wording of the exemption was not possible at the time being. The recommended wording of the exemption therefore must be related to the functions of the glass and glass-ceramic materials. The following wording is recommended for this exemption:

Electrical and electronic components, which contain lead in a glass, in a glass matrix compound, in a glass-ceramic material, or in a glass-ceramic matrix compound, forming a functional layer on a substrate, or a sealing, bonding or encapsulation. This exemption does not cover the use of lead in glass of bulbs and in glaze of spark plugs.

The current state of knowledge suggests that the above exemption covers all functions of materials, in which the use of lead is indispensable. Nevertheless, the following temporary exemption is recommended additionally as a fall-back option in case any function would have been forgotten:

Electrical and electronic components, which contain lead in a glass, in a glass matrix compound, in a glass-ceramic material, or in a glass-ceramic matrix compound for any other purposes than those listed above in vehicles type approved before 1 July 2014, and in spare parts for these vehicles.

This fallback option shall offer enough time for the stakeholders to find lead-free solutions or to apply for an additional exemption in case the use of lead in glass and glass-ceramic materials is unavoidable in any other function.

Stakeholders' request to leave exemption 10 unchanged

<u>*Basic settings and approach for exemption reviews*</u>

The basic requirement of this review is to adapt exemptions under the ELV Directive to scientific and technical progress. Banned substances shall only be allowed, "[…] if the use of these substances is unavoidable", as stipulated in Art. 4(2)(b)(ii) ELV Directive. The past reviews, following the requirements of Art. 4(2)(b)(ii) and the Commission's specifications, were conducted based on the following basic principles:

- The ELV-Directive stipulates a minimum allowable concentration of the banned materials, which is at 0,1%, with the exemption of cadmium, for which the threshold limit is 0,01% of weight in the homogeneous material.
  Any use of a banned substance in a concentration higher than the above maximum concentrations is only allowed if the use of this substance is unavoidable according to Art. 4(2)(b)(ii).

- The interpretation of “unavoidable” uses was aligned to the provisions of Art.5(1)(b) of the RoHS Directive. The use of a banned substance thus is unavoidable,
  - if its elimination or substitution via design changes or materials and components which do not require the banned substance is technically or scientifically impracticable,

    or
  - where the negative environmental, health and/or consumer safety impacts caused by substitution are likely to outweigh the environmental, health and/or consumer safety benefits thereof .
- Exemptions hence need to be as application-specific as possible to clearly delimitate avoidable from unavoidable uses of banned substances in order to prevent uses of banned materials in applications where their use is avoidable.
- Generic, material-specific exemptions hence should be transferred to application-specific ones, as long as the specific applications can be defined clearly and unambiguously.

The reviewers have evaluated the stakeholders’ arguments and the proposal to leave exemption 10 unchanged in the light of these basic settings in the following sections.

Plausibility of figures on lead usage

The stakeholders claim that repealing the exemption of lead use in low voltage capacitors only would avoid 25 mg of lead.

CLEPA et al. do not specify the reference of this figure. For plausibility reasons, the 25 mg must be the amount of lead per vehicle. Assuming that such capacitors are used in every vehicle, the cancellation of this exemption would avoid 425 kg of lead worldwide (~ 17 mio new cars per year according to ACEA), and around 25 kg in Europe (around 1 mio new vehicles per year, according to ACEA).

It can be discussed whether these amounts of lead are worth the expense of substitution, however, not on the exemption review level. The ELV Directive requires avoiding lead wherever possible. Neither does it specify a minimum amount of lead nor a maximum of cost that would allow foregoing substitution if the use of lead technically and scientifically is avoidable.

The same applies for the stakeholders’ statement that exemption 10 only would deal with milligrams of lead. This is correct for the single applications, but in total, the amount of lead used sums up to more than 300 t per year worldwide, or more than 20 t in Europe.

Status of lead reduction

The stakeholders' argue that they have reduced the amount of lead in vehicles from around 2 kg down to 300 g and that a further reduction would generate an effort that is not proportionate to the environmental benefit generated. The ELV-Directive allows maximum threshold levels of banned substances, as explained above. A permitted "residual content", as the stakeholders demand, thus is in place already. The contractors cannot decide about an increase of such threshold levels. This would require an amendment of the ELV Directive, or of the maximum threshold levels in Annex II of the ELV Directive. The contractors do not have the mandate to evaluate such threshold levels.

Socioeconomic arguments, efficiency and cost-benefit analysis

The ELV Directive only allows the use of banned materials, where their use is unavoidable. Cost-benefit analysis (cost versus environmental benefit), or socio-economic criteria, as the stakeholders request, thus cannot be base for a positive recommendation for an exemption.

The stakeholders' demand cannot be taken into consideration on the exemption review level, but needs an amendment of the ELV Directive itself. The current ELV Directive would not cover such evaluation criteria. It is clearly beyond the reviewers' mandate and competence to introduce new evaluation criteria.

It may nevertheless be useful if the policy makers and legislators reconsider the material bans and their implementation under efficiency criteria to avoid that valuable research and financial resources are channeled towards tasks where they possibly only yield minor environmental successes.

Hampering innovation

The stakeholders put forward that more detailed exemptions might hamper innovation (see section They doubt that the current review criteria would allow an exemption for the use of banned substances in new applications contributing to improvements of societal problems.

The contractors do not put forward evidence for this, but express their fears. In the reviewers opinion, if a new technology provides clear benefits, an exemption for such an application of a banned material could be recommended in line with Art. 4 (2) (b) (ii). Material bans, and specific exemptions, on the other hand can spur innovation by promoting the competition towards components and technologies that do not depend on the use of heavy metals.

An assessment of whether and how far the current regulation and exemption review practices actually could hamper innovations is beyond the reviewers' mandate. It must be stated, however, that the material bans as such may then hamper innovation to the same degree as application specific and focused exemptions. This would require an evaluation of the material bans of the ELV Directive itself, which is clearly beyond the reviewers' mandate.

As technical and technological innovations, however, can be part of a solution for environmental, resource and societal problems, it is recommended to review the existing regulations and exemption review guidelines to make sure the evaluation procedures are adequate not to hamper innovation. Possibly, there could be a timely mismatch between the time from development to marketing on the one hand, and the time from application for an exemption until this exemption is granted. Introducing an initial grace period for new applications, e. g. for four years, could mitigate the problem.

If desired, the reviewers are ready to contribute with their experiences and knowledge from several years of exemption assessments to improve the situation.

Feasibility

The feasibility of exemptions and of their monitoring is an aspect, which at least in parts is relevant for the contractor's exemption assessments. It is part of the reviewer's mandate to recommend exemptions, which

1. are clear in their scope and wording.
2. can be implemented in the supply chain.

At least partially, the reviewers must also take care that

3. compliance with exemptions can be monitored.

Expense for implementation

The stakeholders express their concerns that in practice it may be difficult to implement application-specific exemptions in some cases. The decision-making generates large efforts since it is sometimes not clear how to achieve compliance (see section "Feasibility" on page 208).

Within their mandate, the reviewers are obliged to minimize such effects by clear scopes and wordings of exemptions. The contractor is not entitled to decide about how much effort actually is reasonable to achieve compliance, as long as the necessary expense does not make compliance impossible. Taking into account the expense for the implementation of an exemption would introduce economical arguments as an additional criterion, which does not have ground in Art. 4 (2) (b) (ii) and in the Commission's basic settings for the review.

As the proposed recast of exemption 10 was discussed and agreed upon with the stakeholders, it must be assumed that, despite of some problems possibly arising, the recast exemption 10 can be implemented in the supply chain. It must be pointed out additionally, that the RoHS Directive as well contains application-specific exemptions for electrical and electronics appliances, which the respective industries have implemented successfully.

Monitoring

The stakeholders additionally claim problems with monitoring. They say that application specific exemptions like 8 a) or as recommended for the recast of exemption 10 cannot be identified and monitored by laymen, and that even for experts, it might be difficult sometimes.

It is very likely that laymen are overburdened with such a complex task. The reviewers must assume, however, that personnel responsible for the identification and monitoring of exemptions is sufficiently qualified for this task. The producers are responsible to contribute to the good implementation in the supply chain by e.g. delivering proper documentation regarding the use of exemptions so that they can be identified and monitored.

Nevertheless, the monitoring of exemptions beyond doubt may create practical problems. This phenomenon is well known from the RoHS Directive. In particular, there are problems with the definition of homogeneous materials in the context of sampling and analyzing the contents of banned materials, as well as with the necessary minimum amounts of sampling material necessary for the analysis. This applies especially in cases where small components with thin layers of homogeneous materials or with low volumes are involved. The European Parliament in its draft report on the Commission's proposal for the recast of the RoHS Directive (European Parliament) proposes introducing minimum volumes or areas for homogeneous materials. This could indicate a possible solution for the stakeholders' concerns. The reviewers cannot solve such principal problems related to the implementation and monitoring of substance bans on the review level.

The reviewers therefore propose to tackle this problem in the recast of the RoHS Directive and to transfer such solutions to the ELV Directive, or otherwise to give the reviewers clear guidance so that they can take into account this problem. The review process then would remain transparent and comprehensible, whereas otherwise, in the absence of clear criteria, recommendations might become arbitrary.

Nevertheless, if the stakeholders can clearly prove that sampling and analyzing and thus monitoring are impossible not only for some cases covered by an exemption, but generally, they should submit this evidence and the reviewers will certainly try to take it into account within the possibilities of their mandate.

Alternative proposal of the stakeholders

The stakeholders propose to retain exemption 10 in its current generic status, without further specification to applications. Their main argument is that for none of the specified applications besides for the low voltage capacitors, an expiry date could be defined, because there are no suitable substitutes. (Remark of reviewers: The exemption request for lead in compensation capacitors, for which lead-free alternatives are under development, had not yet been reviewed by the time the stakeholders submitted their request to leave exemption 10 unchanged).

The stakeholders affirm that the proposed list of applications under exemption 10 will not result in any further lead reduction. No substitutes or alternative technologies are available, and therefore none of the listed applications besides the low voltage capacitors have an expiry date. As the application specific wording of exemption 10 does not result in foreseeable lead reductions, the stakeholders argue to leave the exemption 10 unchanged. It just increases their expenses for compliance without any environmental benefit. The stakeholders say that a material specific, generic exemption wording does not rule out the basic option of voluntary substitution as soon as alternatives are known and available.

It must be highlighted that the substitution of banned substances is not voluntary, as the stakeholders put forward, but obligatory as soon as alternatives are available. To affirm and to promote this, applications are made specific, not just generic. The specification of exemptions increases the incentives to search for alternatives and to apply them as soon as they are available.

There may be reasons as well, why some exemptions in Annex II were made generic, not application specific, at the time when the ELV Directive was enacted. If these reasons still persist and are still valid after almost a decade of scientific and technical progress, the stakeholders should have put them forward in the exemption review processes, or discuss with the Commission, whether they are still sufficient to leave exemption 10 unchanged.

Finally, the stakeholders argue that the fallback option (recommended exemption 10 b, see page 223) does not make sense because there is currently no application known that would require the fallback option. They further argue that, if an application were to be identified, there would not be sufficient time to search for and implement alternatives before the deadline of 2014.

It must be stated that the fallback option 10 b) on page 223 was introduced on demand of and in agreement with the stakeholders to prevent problems in case a specific application would have been forgotten in 10 a). During the review, it became clear that the knowledge about the use of leaded ceramics was distributed in the supply chain, and not centrally available. As it is impossible to reach and to involve each and every user of leaded ceramics worldwide, it was plausible to introduce exemption 10 b) as a fallback option.

The time frame for expiry of exemption 10 c) (see page 223) was set in order to allow applying for a further exemption, in case this is needed and justifiable in line with Art. 4 (2) (b) (ii). It was never thought only to give enough time to search for and to come up with alternatives by then.

Conclusions

The stakeholders request to leave exemption 10 unchanged. Arguments brought forward by stakeholders are to be addressed to decision makers since they go beyond the mandate of this review.

The contractor reviewed the stakeholders' proposal in the previous chapter in the light of the basic settings and approaches that have been applied so far in the past reviews of exemptions based on Art. 4 (2) (b) (ii). Accepting the stakeholders' proposal in the reviewers' opinion would require introducing new and additional review criteria.

In case the Commission draws different conclusions from Art. 4 (2) (b) (ii) with respect to the recast of exemption 10 and from the stakeholders' reasoning, the following wording is recommended for exemption 10:

10 a) Electrical and electronic components, which contain lead in a glass or ceramic, in a glass or ceramic matrix compound, in a glass-ceramic material, or in a glass-ceramic matrix compound.
This exemption does not cover the use of lead in
- glass of bulbs and in glaze of spark plugs.
- dielectric ceramic materials of components listed under 10 b), 10 c)and 10 d)

10 b) Lead in PZT based dielectric ceramic materials of capacitors being part of integrated circuits or discrete semiconductors

10 c) Lead in dielectric ceramic materials of capacitors with a rated voltage of less than 125 V AC or 250 V DC in vehicles type approved before 1 January 2016, and in spare parts for these vehicles

10 d) Lead in the dielectric ceramic materials of capacitors compensating the temperature-related deviations of sensors in ultrasonic sonar systems; review in 2014

This wording would take out the low voltage capacitors and the compensating capacitors from the generic exemptions, where a sunset date can be defined, or where substitutes are foreseeable. In the face of the minor amounts of lead involved in exemption 10, this part of the exemption could be cancelled as well, if the Commission wishes to follow the stakeholders' efficiency and cost-benefit approaches.

Exemption 10 b) has been added upon request of the stakeholder ESIA (European Semiconductor Industry Association) to the above wording proposal, since the capacitors addressed in this exemption operate at low voltages and hence may be affected by the restriction of lead use in low voltage capacitors (covered by 10 c which expires end of 2015), depending on the interpretation of "dielectric" ceramics, which, in the absence of a clear and internationally accepted terminology, is not quite clear (ESIA 2010). In case substitutes would not be available by 2016, this application would thus no longer be exempted. In the long version recommended below, ESIA's proposal is already included and mentioned separately (10 a) iv). In both the long and the shorter version, the exemption is in line with the requirements of Art. 4 (2) (b) (ii), as substitutes currently and in the foreseeable future are not at hand and the use of lead is therefore unavoidable. An expiry date can not yet be set. .

4.18.8 Final recommendation

The contractor recommends transferring exemption 10 from a generic to an application-specific exemption following the example of other exemptions in Annex II of the ELV Directive. This recommendation is in line with the review criteria derived from Art. 4(2)(b)(ii), the Commission's settings for the review process, and the approaches applied in the past review processes (see page 216 for details). Several applications were identified in cooperation with the stakeholders, where the use of lead is currently unavoidable. Art.4(2)(b)(ii) would hence justify an exemption.

The reviewers recommend the following recast and rewording of exemption 10:

10 a) Lead in

- *i. ceramic materials of piezoelectric components;*
- *ii. ceramic materials of PTC components;*
- *iii. PZT ceramic passivation layers of multilayer ceramic varistors;*
- *iv. PZT based dielectric ceramic materials of capacitors being part of integrated circuits or discrete semiconductors;*
- *v. dielectric ceramic materials of capacitors with a rated voltage of 125 V AC or 250 V DC or higher;*
- *vi. dielectric ceramic materials of capacitors with a rated voltage of less than 125 V AC or 250 V DC in vehicles type approved before 1 January 2016, and in spare parts for these vehicles;*
- *vii. dielectric ceramic materials of capacitors compensating the temperature-related deviations of sensors in ultrasonic sonar systems; review in 2014.*

10 b) Electrical and electronic components, which contain lead in a glass or a glass matrix compound, in a glass-ceramic material, or in a glass-ceramic matrix compound, forming a functional layer on a substrate, or a sealing, bonding or encapsulation.
This exemption does not cover the use of lead in glass of bulbs and in glaze of spark plugs.

10 c) Lead in the ceramic materials of components, which are not listed under exemption 10 a), in vehicles type approved before 1 July 2014, and in spare parts for these vehicles

10 d) *Electrical and electronic components, which contain lead in a glass or a glass matrix compound, in a glass-ceramic material, or in a glass-ceramic matrix compound for any other purposes than those listed in 10 b), in vehicles type approved before 1 July 2014, and in spare parts for these vehicles*

Exemptions 10 a) and 10 b) are supposed to cover all relevant cases, where the use of lead is indispensable. Due to the complexity of the field, exemptions 10 c) and 10 d) are recommended as temporary fallback options, in case exemptions 10 a) and 10 b) should not cover any component or function, in which the use of lead is unavoidable. Stakeholders thus have a chance to either find lead-free alternatives in time or to apply for further specific exemptions to be added to 10 a) and 10 b), before exemptions 10 c) and 10 d) expire.

The stakeholders (CLEPA et al. 2010) submitted a request to leave exemption 10 unchanged. The stakeholders' arguments can be found in section 4.18.6 on page 207. The contractor reviewed these arguments based on the review criteria and practices applied so far to identify unavoidable uses of lead (see page 216).

In case the Commission decides to follow the stakeholders' arguments, the reviewers recommend the following wording:

10 a) *Electrical and electronic components, which contain lead in a glass or ceramic, in a glass or ceramic matrix compound, in a glass-ceramic material, or in a glass-ceramic matrix compound.*
This exemption does not cover the use of lead in
- glass of bulbs and in glaze of spark plugs.
- dielectric ceramic materials of components listed under 10 b), 10 c) and 10 d)

10 b) *Lead in PZT based dielectric ceramic materials of capacitors being part of integrated circuits or discrete semiconductors*

10 c) *Lead in dielectric ceramic materials of capacitors with a rated voltage of less than 125 V AC or 250 V DC in vehicles type approved before 1 January 2016, and in spare parts for these vehicles*

10 d) *Lead in the dielectric ceramic materials of capacitors compensating the temperature-related deviations of sensors in ultrasonic sonar systems; review in 2014*

4.18.9 References

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JEITA et al. 2009b	JEITA et al.; Stakeholder document "20090804_Exe-10_Attached file No2-JEITA.pdf"
JEITA et al. 2009c	JEITA et al.; Stakeholder document "Ultrasonic_Sensor_JEITA_et_al-2.pdf¨
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Ramtron 2009	Ramtron; Stakeholder document admincopier@ramtron com_ 20090914_113906.pdf

4.19 Exemption no. 13

"Absorption refrigerators in motor caravans"

The evaluation of exemption 13 under the current contract was based on results of former evaluations. Initial answers have been received from stakeholders in the context of the second stakeholder consultation (cf. http://circa.europa.eu/Public/irc/env/elv_4/library?l=/consultation_2/stakeholder_contribution/elv_exemption_13&vm=detailed&sb=Title). Further questions have been sent to stakeholders (Dometic and Thetford). Answers have since been received and conference calls with both stakeholders have been held.

The outcome of this information gathering exercise and of the exchange with the above mentioned stakeholders is reflected in the following.

4.19.2 Description of exemption

Absorption refrigerators are covered by the ELV Directive because they are inter alia used in motor caravans. Absorption refrigerators function solely from a single heat source, no compressor is necessary. This is permitted by the use of ammonia, water and hydrogen gas. Sodium chromate is mixed to the ammonia solution to protect the steel tubing from the mildly