Exemption Request Form

Date of submission: 27 July 2015

1. Name and contact details

1) Name and contact details of applicant:

Company:	EUROMOT	Tel.:	(+32 2) 234-6315, Mobile: +49 175 269 7819
Name:	Peter Scherm	E-Mail:	peter.scherm@euromot.eu
Function:	General Manager	Address:	Rond Point Schuman 6/5 1040 Brussels - Belgium

2) Name and contact details of responsible person for this application (if different from above):

Company:	Caterpillar	Tel.:	(33) 4 76 23 82 33
Name:	Jean-Jacques Janosch	E-Mail:	Janosch_Jean-Jacques@cat.com
Function:	Standards & Regulations Manager	Address:	40, Avenue Léon-Blum B.P. 55 F38041 Grenoble Cedex 9, FRANCE

This exemption request is submitted with the support of:

EUROMOT	The European Association of Internal Combustion Engine Manufacturers
EUROPGEN THE EUROPEAN GENERATING SET ASSOCIATION	European Generating Set Association
CECE COMMITTEE FOR EUROPEAN CONSTRUCTION EQUIPMENT	Committee for European Construction Equipment
NATIONAL ASSOCIATION OF Manufacturers (see separate letter)	National Association of Manufacturers
AEM ASSOCIATION OF EQUIPMENT MANUFACTURERS	AEM – Association of Equipment Manufacturers
CCMA 中国工程机械工业协会 CHINA CONSTRUCTION MACHINERY ASSOCIATION www.cncma.org | www.工程机械协会.中国	CCMA – China Construction Machinery Association

2. Reason for application:

Please indicate where relevant:

☒ Request for new exemption in: Annex III

☐ Request for amendment of existing exemption in

☐ Request for extension of existing exemption in

☐ Request for deletion of existing exemption in:

☐ Provision of information referring to an existing specific exemption in:

☐ Annex III ☐ Annex IV

No. of exemption in Annex III or IV where applicable: _____

Proposed or existing wording: Lead in bearings and bushes of professional-use non-road equipment engines that meet the following criteria:

- 15 litre and larger total displacement professional use
- Less than 15 litre engines for professional non-road equipment designed for use where the time between a signal to start and full load is required to be less than 10 seconds, for example in emergency, standby generators and peak shaving generators
- Less than 15 litre engines for professional non-road equipment designed for operation in harsh and dirty environments such as construction sites, quarries, mines, etc. for example, in drills, air compressors, rock crushers, irrigation pumps and tub grinders

Duration where applicable: Maximum validity period required

☐ Other: _____

3. Summary of the exemption request / revocation request

Internal combustion engines are used as components of a variety of types of equipment that is in scope of the recast RoHS Directive. Large size engines and those that are required to be used in harsh or demanding environments need to use bearings and bushes that contain lead in order to achieve satisfactory reliability. Engines that are specifically designed for road vehicles (a form of transport) however, which are out of scope of RoHS, are able to use lead-free bearings, due to the different use conditions that are experienced.

Research has shown that the lead-free bearing materials have a higher tendency of seizing, are less able to conform when misalignment occurs and are less able to cope with particulate debris in the lubricant. Engine manufacturers have carried out extensive bench tests to investigate these phenomena as well as field testing engines with lead based and lead-free bearings. The bench tests show that lead-based bearings give the best reliability, but field testing clearly shows that in harsh and demanding conditions, engines with lead-free bearings failed on average much sooner than engines with leaded bearings. This exemption is therefore requested on the basis of the inferior reliability of lead-free substitutes.

---

4. Technical description of the exemption request / revocation request

(A) Description of the concerned application:

1. To which EEE (Electrical and Electronic equipment) is the exemption request/information relevant?

Name of applications or products: Bearings and bushes in internal combustion engines designed for professional use. This would include all diesel and gaseous fuel powered internal combustion engines with a capacity of 15 litres and greater as well as engines with a smaller capacity that are designed for specific applications that require lead to provide the required reliability. These applications exclude commercial road vehicles and include industrial machinery where the engine provides power via a mechanical drive or by a hydraulic drive. These applications include:

- >15 litre total displacement professional use
- <15 litres professional off-road use where the time between signal to start and full load is required to be less than 10 seconds. For example emergency power generators such as for hospitals and uninterruptable power system (UPS) installations. It is essential that the time between power failing and being restored is as short a time as possible in these applications. Other applications are when the engine is connected directly to a flywheel or a drive belt.
- <15 litres designed for professional off-road operation in harsh and dirty environments, such as for drills, compressors, rock crushers, irrigation pumps, , tub grinders and other similar types of equipment. Harsh and dirty environments

would include construction sites, farms, quarries, mines, some types of factories, desert regions, etc.

Stationary engines that are specifically designed to be installed into large-scale fixed installations and large-scale stationary industrial tools are excluded from RoHS. These will include fairly large size engines used for continuous duty, such as with generators installed in large installations. However, those designed for smaller fixed systems are in scope of RoHS. Also, many engines are used in rented equipment which by its nature is often not permanently installed so cannot be regarded as a fixed installation, but is also not mobile machinery.

It is not possible to define “harsh and dirty” environments quantitatively, as engine manufacturers do not use such values for engine design. The experience they have gained over many years has indicated the types of operating environment where lead bearings are needed to cope with the dust and dirt that is present. The environment inside mines is especially harsh as the engine is operating in dirty air almost continuously. Quarries and construction sites are two other examples where the machinery itself may be the source of the dust in which it is required to operate. Engines of moving vehicles do not experience the same level of dust and dirt as equipment that operates at fixed locations. Vehicles usually move into and out of dusty areas so that for most of the time, they are not located in the harshest conditions whereas a rock crusher, for example creates dust and operates continuously in dusty air.

a. List of relevant categories: (mark more than one where applicable)
(1 is large household appliances, 2 is small household appliances, 3 is IT and communication equipment, 4 is consumer equipment, 5 is lighting equipment, 6 is electrical and electronic tools, 7 is toy, leisure, and sports equipment, 8 is medical device, 9 is monitoring and control equipment, 10 is automatic dispensers,11 is all other EEE)

☐ 1	☐ 7
☐ 2	☐ 8
☐ 3	☐ 9
☐ 4	☐ 10
☐ 5	☒ 11
☐ 6	

Classification of engine driven machinery into a category is not straightforward. We have assumed that all types of equipment that require this exemption are in category 11.

b. Please specify if application is in use in other categories to which the exemption request does not refer: _____

c. Please specify for equipment of category 8 and 9:

The requested exemption will be applied in

☐ monitoring and control instruments in industry

☐ in-vitro diagnostics

☐ other medical devices or other monitoring and control instruments than those in industry

2. Which of the six substances is in use in the application/product?

   (Indicate more than one where applicable)

   ☒ Pb ☐ Cd ☐ Hg ☐ Cr-VI ☐ PBB ☐ PBDE

3. Function of the substance:
   Contributes a tribological interface that provides the required reliability and performance by absorbing damaging debris and provides conformability in critical bearings. These properties support reliability and facilitate service and rebuild of non-road engines to extend practical service life.

4. Content of substance in homogeneous material (%weight): The thin overlay coating contains up to 90% lead by weight and the inner lining material contains typically 20% lead by weight. Some bearings omit the outer overlay layer. Copper alloys containing up to 4% lead are used for some applications but this application is currently covered by RoHS exemption 6C of Annex III and so is not discussed in this exemption request.

5. Amount of substance entering the EU market annually through application for which the exemption is requested:

Estimate EU consumption is 6.4 tonnes in new engines.

Estimated global lead consumption is 52 tonnes per year in new engines

Please supply information and calculations to support stated figure.

The amount of lead for products in scope of the RoHS directive varies depending upon bearing and engine design and the engine displacement (larger engines would typically utilize more lead due to larger component size). An audit of a representative electronic fuel injection diesel engine producing approximately 1800 kW of electricity revealed 176 grams of elemental lead to be present in the entirety of the 20 tonne assembly.
Below is a table of published worldwide market data representative of all power generation equipment regardless of manufacturer.

2013 Diesel Genset Market, Parkinson's Data						
(annual turnover and units)						
	World		Europe		Europe % World	
Power Band (kVA)	Euro 000's	Units	Euro 000's	Units	Euro	Units
<7.5	910,928	608,705	54,295	33,266	6%	5%
7.5-250	3,357,914	507,664	408,023	50,241	12%	10%
251-750	1,989,620	71,025	242,811	8,453	12%	12%
751-2000	2,096,338	23,782	240,945	2,410	11%	10%
2000+	2,142,948	5,067	356,196	667	17%	13%
Total	10,497,747	1,216,243	1,302,270	95,037	12%	8%

The quantity of lead used is based on the Parkinson Genset data and calculated using the following assumptions:

- Non-genset applications add 25% of numbers sold
- 5% of units of >275 kW are not “installed” (i.e. semi-mobile) and so are in scope of RoHS (>375kW installed are defined as large-scale fixed installations so excluded)
- Lead content of bearings is determined by chemical analysis of representative bearings.

Results are as follows:

Table 1. Calculation of amount of lead in bearings used in engines in scope of this exemption request

Power Band (kVA)	Average engine mass, kg	Average lead content from bearings (% by total engine mass)	Annual genset sales in EU market	Annual engine sales in EU market, add 25% for other applications	Percent in Scope of RoHS	Units in Scope	Engine mass in scope, kg	Annual Lead quantity into EU market, kg
7.5-250	447	0.0008%	50,241	62,801	100%	62,801	28,072,159	225
251-750	1020	0.0200%	8,453	10,566	47%	4,966	5,065,460	2,156
751-2000	4506	0.0200%	2,410	3,013	5%	151	678,716	2,715
2000+	7500	0.0200%	667	834	5%	42	312,656	1,251
							Total	**6,346**

The above calculation indicates that 6.4 tonnes of lead is needed in bearings of new engines that are in scope of this exemption request which are placed on the EU market. Based on Parkinson’s genset data using the proportion if genset units that sold in the EU, global lead use is calculated at 52 tonnes per year.

Note that professional engines may be rebuilt several times in their lifetime and the bearings replaced. This means that old bearings are removed and recycled and new spare part bearings installed. However lead in spare parts is not included in the above calculations.

6. Name of material/component: _____

Various compositions of alloys containing lead, copper, tin and / or other metals in bearings and bushes. More details are given in answer to Q6.

7. Environmental Assessment: Not applicable to this exemption request.
   LCA: ☐ Yes
   ☒ No

(B) In which material and/or component is the RoHS-regulated substance used, for which you request the exemption or its revocation? What is the function of this material or component?

This exemption is requested for use of lead in professional use engine bearings and bushings. These engines have a wide variety of applications but are not intended solely for transport (vehicles) or for non-road mobile machinery as defined by RoHS. Lead coatings and alloys give bearings low friction and high load absorbing properties which provides seizure resistance and conformability not replicated by any currently known alternatives. Lead also provides resistance to debris failures. Debris may be introduced during service procedures or from the environment the engine operates in.

Lead is present as an alloy element or thin layer in such bearings and bushings. As a thin coating, lead provides a tribological interface which helps prevent seizure and can absorb debris which might otherwise cause engine failure. As an alloy element in bearing and bushing materials, lead provides conformability to help the bearing deal with slight mis-alignments that may occur following service or extreme high load operation. There are no currently known materials suitable for a typical tri-metal bearing for professional heavy duty application, the very thin overlay may contain up to 90% lead and the bearing alloy may be up to 20% lead. Lead would typically comprise between 1 and 3% of a complete leaded bearing (based on total part weight). Lead from all these components would typically comprise less than 0.025% of a complete engine.

Internal combustion engines have a very wide variety of uses, but many of these are excluded from the scope of RoHS. For example, the RoHS Directive excludes "forms of transport" and "professional non-road mobile machinery". Furthermore, small engines used in consumer equipment with lead-free bearings are sufficiently reliable for normal consumer uses. Only engines that use diesel and gaseous fuels for in-scope applications require this exemption. Engines that are not designed for transport applications or for the types of equipment that is defined by the RoHS directive definition of non-road mobile machinery includes; standby and emergency generators;

Figure 1. Small, medium and large size generators that are used at fixed locations, sometimes on a temporary basis

The generators shown in Figure 1 do not appear to meet the definition of non-road mobile machinery as defined by RoHS, although they may be in scope of the Directives on Emissions from Non-road Mobile Machinery (97/68/EC)e. This is because the RoHS directive's definition is for equipment that is; "*machinery, with an on-board power source, the operation of which requires either mobility or continuous or semi-continuous movement between a succession of fixed working locations while working*". These generators are stationary when in use and may be used at one location for long periods or permanently[1]. The large size generator (on the right of the image) generates more than 375kW so is intended to be used in large-scale fixed installations and so may be excluded from RoHS if they are permanently installed. However these very large generators are also used at temporary locations such as for disaster relief and so some designs will not be excluded from RoHS. The EC's RoHS FAQ guidance[2] states that installations with rating >375kW would be regarded as large-size, but they are not excluded if they do not meet the RoHS definitions of "stationary industrial tools or fixed installations". These "Gen-sets" contain an internal combustion engine and an electricity generator along with the necessary ancillary equipment. These may be used as a permanent or temporary power source or be used only intermittently as a standby or emergency generator. High reliability is essential, especially when these are used as emergency back-up generators for hospitals in case of a power cut.

Another example of applications for engines is shown in the figure below:

---

[1] Note that the Non-Road Mobile Machinery Directive 97/68/EC uses a different definition of non-road mobile machinery that includes "transportable industrial equipment" which would include these generators.

[2] http://ec.europa.eu/environment/waste/rohs_eee/pdf/faq.pdf

Figure 2. Diesel engine powered compressor

The compressor shown in Figure 2 is professional transportable industrial equipment but is not excluded from RoHS as it is stationary when in use. Other professional applications that may be considered to be in scope of RoHS is for engines that are used for pumps used in professional installations that are too small to be large-scale fixed installations, for example irrigation pumps used in farms. Some irrigation pumps are moved from one location to another, but are used at a fixed location. Other applications that require lead bearings include machinery that is used in very dirty environments because lead bearings are more tolerant of dirt or other solid particles that accumulate in the lubrication fluid. Applications include drilling machines, rock crushers and welding sets that are mounted onto trailers. More examples are shown below:

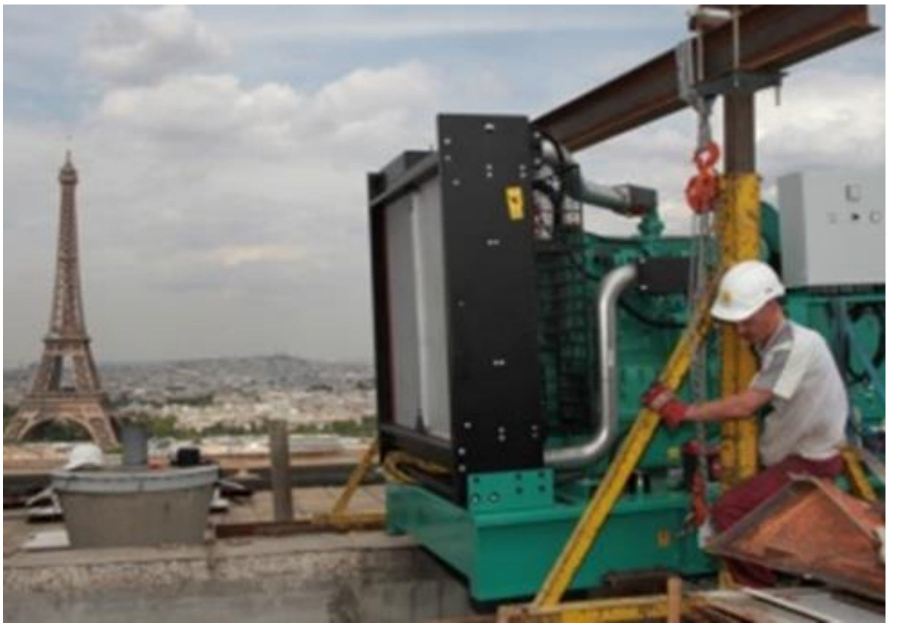


Figure 3. Temporary power source with 6.7 litre diesel engine used in a construction site. Dirt and dust are an issue at these locations.

Figure 4. “Leaf vacuum” is stationary in use, although is moved between locations where it is used

Figure 5. Almond tree shaker: operates while stationary and is not a form of transport

There are many types of engine used in road vehicles (cars, vans, trucks, buses, etc.) and also vehicles that meet the definition of non-road mobile machinery of the RoHS directive 2011/65/EU (see examples below) and these are not included in this exemption request as they are better suited to use lead-free bearings although on road applications are out of scope of RoHS. Their use conditions and engine parameters are different to the engine designs that need this exemption and are described in this document.

Figure 6. Examples of non-road mobile machinery as defined by the RoHS directive which are currently excluded from scope of the RoHS directive

Each engine contains many different designs of bearings and an illustrative example engine is shown below:

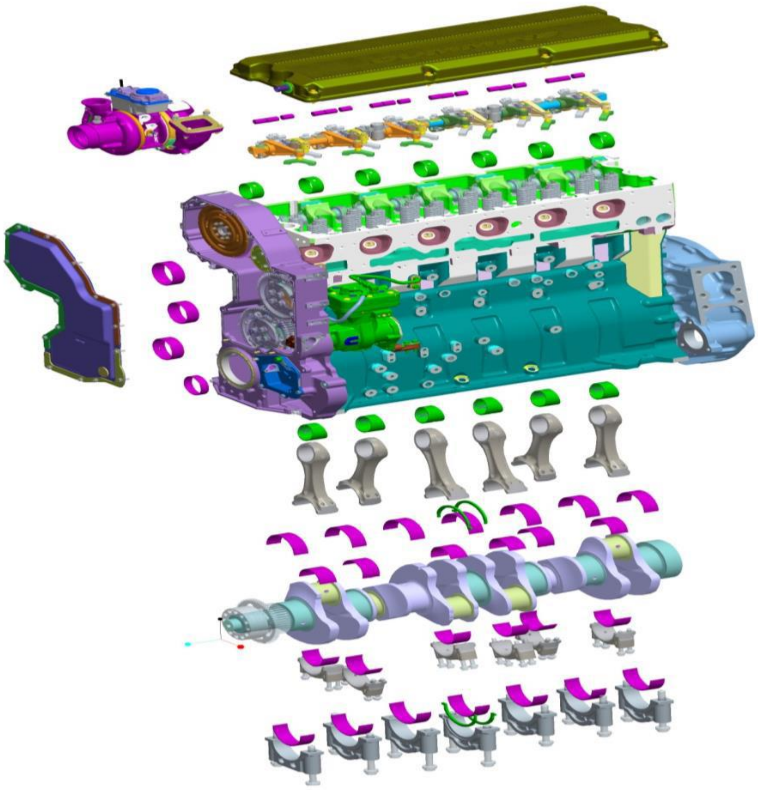


Figure 7. Parts of a typical internal combustion engine with bearings and bushes shown in pink in this example

Figure 7 shows that bearings are constructed in many different shapes, designs and sizes. Some are constructed in two parts, one each side of the crankshaft whereas others are press-fit in place single piece round or more complex shapes. The types of bearings used that may contain lead in engines in scope of this exemption request include:

- Turbo Bushings[3]
- Cam Follower Roller Pins
- Gear Bushings
- Connecting rod small end bushings
- Connecting rod big end bearings
- Crankshaft thrust bearings (bushings)
- Main bearings
- Gear bushings

Larger size engines may also use lead in the following applications, although these are not used in automotive applications and in lighter duty applications:

- Rocker arm bushings
- Piston pin bushings
- camshaft bushings

[3] Note that these single piece bearings are referred to as either bushings (more common in North America) or bushes (more common in Europe)

Lead is needed in bearings and bushes to achieve the required reliability and this depends on the engine design and use conditions. For example, the small end bearings shown in the example engine in Figure 7 above are lead-free (green coloured), but in engines designed for harsh dirty conditions or for fast start-up applications, lead is necessary to achieve good reliability. Bearings are also used in alternators, coolant pumps and other components that are attached to engines.

Bearings may be constructed in three layers as shown in the two figures below:

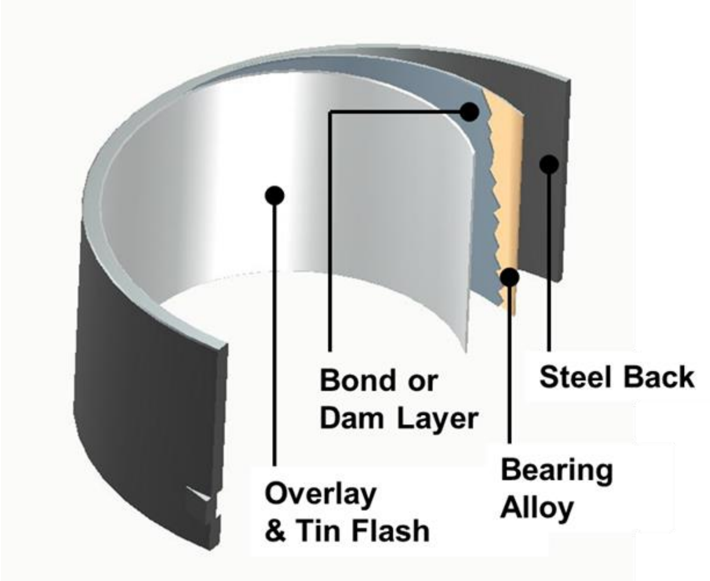


Figure 8. Construction of trimetal bearing

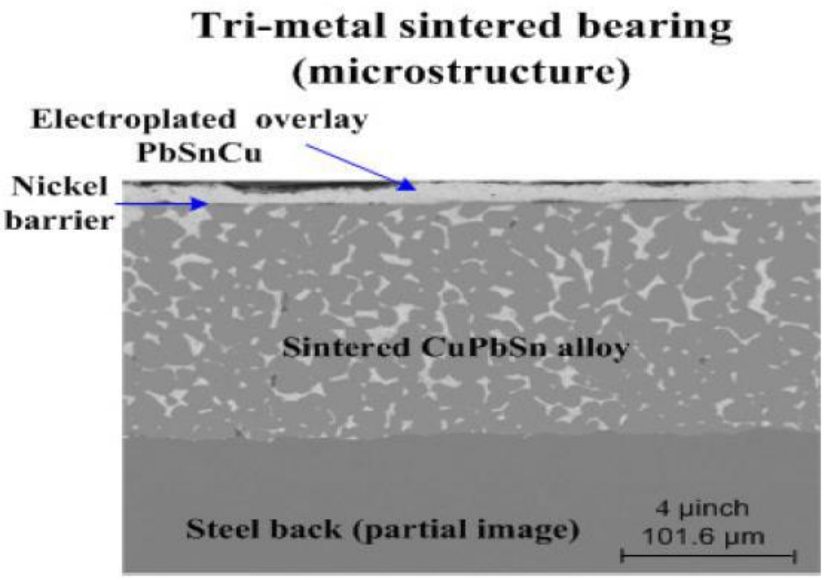
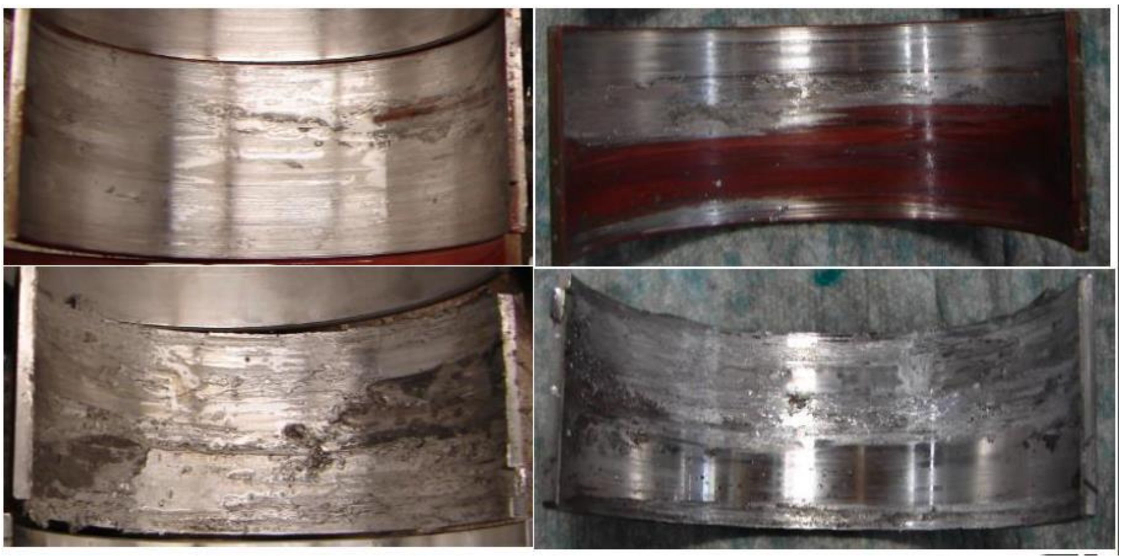


Figure 9. Cross-section through tri-metal bearing with PbSnCu (up to. 90% lead) electroplated overlay, nickel barrier layer, CuPbSn alloy layer (typically with ca. 20% lead) and steel backing.

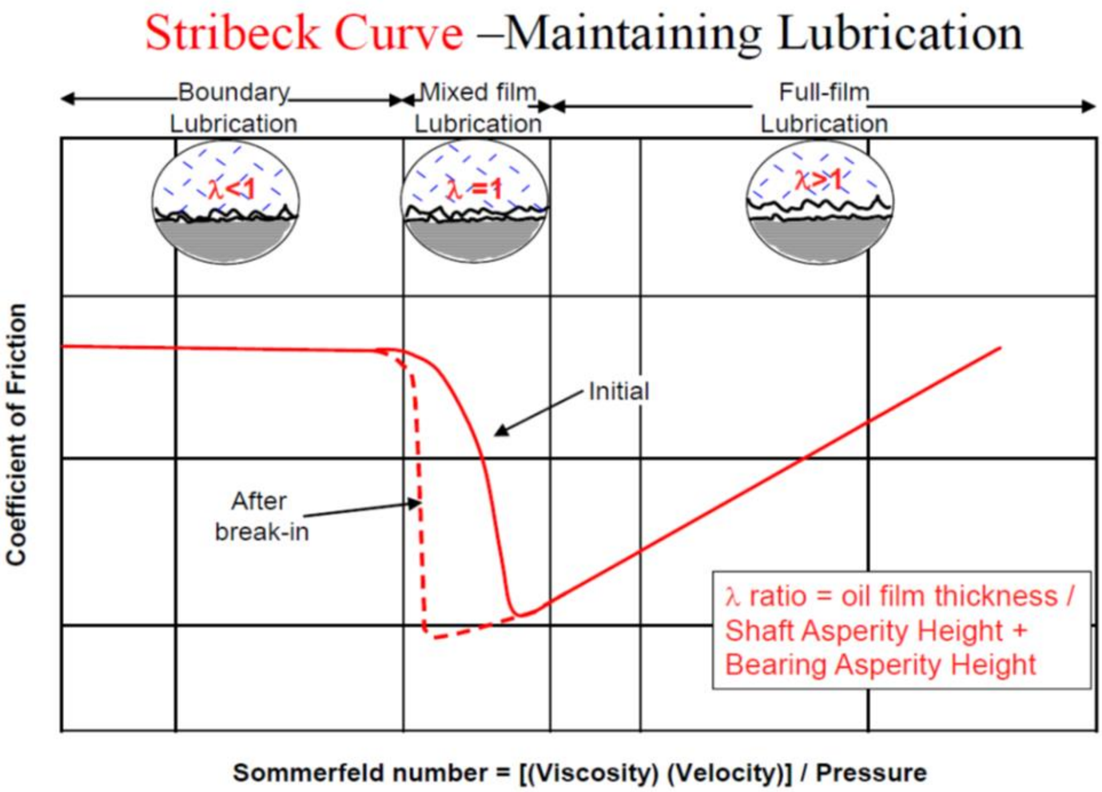
(C) What are the particular characteristics and functions of the RoHS-regulated substance that require its use in this material or component?

Bearings and bushes are required to have many important properties to provide the required performance and reliability for the intended conditions of use and lifetime. The specific requirements for each specific property depends on one or more of many variables including engine capacity, conditions of use, conditions during rebuild and servicing, rotation velocity, loading, etc. The most important properties required for bearings used in applications that require this exemption are:

- **Seizure resistance and resistance to damage** - All bearings experience some metal-to-metal contact, especially when cold started and lubrication oil has drained away. A good bearing material is one which will not weld easily to the shaft material. When the engine is running, especially at high speed, heat will be generated at the bearing surface and this can cause the metal surfaces to melt and then bond causing the engine to seize. Seizure can cause catastrophic damage to an engine as parts such as connecting rods may fracture and can penetrate through the side of the engine. The image below shows the results of an experimental lead-free bearing seizure.



- **Conformability** – Conformability is the ability of a bearing to accommodate irregularities in mating surface. This is especially critical at start-up and the wear in period of an engine. At start-up, the metal surfaces likely have little or no lubrication. The soft properties of lead allow the bearing to conform to variation when there is metal to metal contact.

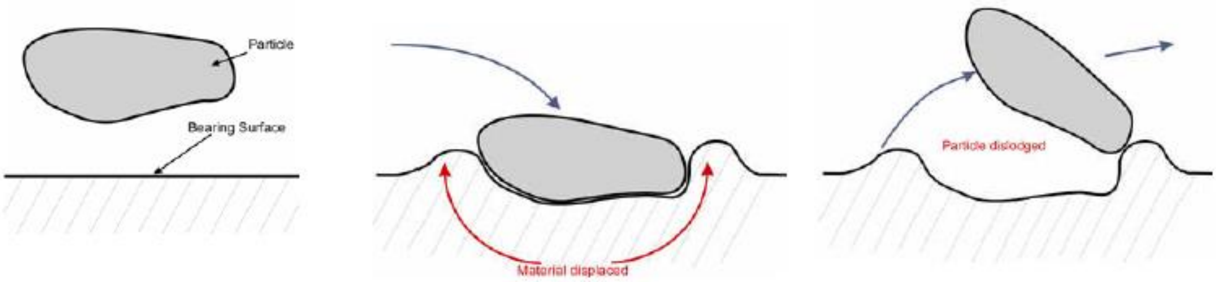


There are three phases shown in the Stribeck curve which are explained as:

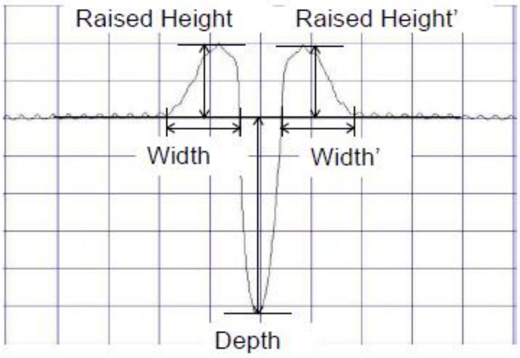
- Boundary Lubrication = Oil is not present across the entire tribological surface, metal to metal contact occurs.
- Mixed Film Lubrication = Minimal oil is present and not yet to full oil saturation levels required to protect tribological surfaces.
- Full Film Lubrication = Oil is present across entire bearing surface at specified film thickness and pressure necessary to protect against metal to metal contact

Conformability is a soft property requirement of professional use engines, especially for larger size engines where very small variations in dimensions can result in misalignment of parts that require some conformability to enable the engine to function correctly. Because critical internal components of professional heavy duty diesel engines are generally many times larger than those found in passenger cars, components such as bearing journals, crankshafts, rods, and bearings must maintain their machining tolerances over greater distances and surface areas. Conformability is a term used to describe the ability of a bearing to “wear in” to the microscopic differences in internal mating surfaces. This may also be described as “misalignment” of the mating surfaces or components. Good conformability is a characteristic of soft material leading to permanent conformity, or materials with a low modulus of elasticity, result in elastic conformity. Poor conformability of the bearing material can result in premature failure of the bearing and catastrophic failure of the engine.

- **Embeddability –** This is defined as the ability of a bearing to accept debris or particles in the bearing clearance area. When these particles come in contact with the surface of the bearing, a localized impression is made in the bearing surface raising the bearing surface where the bearing material is displaced as depicted in the graphic below.



When the peaks created by this displaced material interfere with the reciprocating parts, seizure can occur if the bearing material is too hard and will not conform to the reciprocating surfaces.



*The peaks created in the bearing surface are equal to the depth of the embedded particle.

Soot and debris are inherent in the operation of internal combustion engines. This debris in the form of metal shards or "chips" can be introduced during engine running-in, during servicing (dirt ingress as "clean-room" conditions are impossible in these environments), by deferring recommended service, and through general wear and tear as mating internal components conform to mating surfaces. The substandard embedability characteristics of lead free bearings is of particular concern as the ability to absorb dirt and other foreign particles is needed to avoid scoring and accelerated wear which significantly shortens engine lifetime. Usually, in metallic bearing material, good embedability is found in material with good conformability (i.e. soft materials). This is an ability to allow for dirt and contamination that can occur when engines are manufactured (but can be avoided) and during servicing, repairs and rebuilds (where dirt cannot be avoided). Many of the types of engine in scope of this exemption are used in industrial locations where there are significant amounts of fine dust that it is difficult to prevent from entry into the engine. This property is independent of engine capacity, speed or load and is especially important for all engines that are used and serviced in environments where dirt cannot be avoided.

- Load Capacity - A measure of the maximum hydrodynamic pressure which a material can be expected to endure. Important for some types of bearings and as mentioned above, high loads can cause misalignment which lead based bearings can more easily accommodate.

Lead-based bearings give superior performance particularly to the first three properties; compatibility, conformability and embedability.

Internal combustion engines are required to comply with emission legislation. As these engines are specialised designs and are sold in relatively small numbers, each design is sold globally and so must comply with the emissions legislation in all destination markets, not only in the EU. Because of the difference in definition of “non-road mobile machinery” used for RoHS and for the non-road mobile machinery directive, there will be some engines that need to comply with both directives. Changing a bearing material may affect emissions and so compliance must be confirmed before a new design can be placed on the market. The USA, Canada, China, Japan and many other countries all have their own specific emissions legislation[4].

---

5. Information on Possible preparation for reuse or recycling of waste from EEE and on provisions for appropriate treatment of waste

1) Please indicate if a closed loop system exist for EEE waste of application exists and provide information of its characteristics (method of collection to ensure closed loop, method of treatment, etc.)

Within the commercial internal combustion engine sector, there is in effect a closed loop system for the recycling of mixed metal components generated during the rebuild process and at end of life. Bearings at end of life have a positive metal value whereas disposal to landfill entails a cost and so close to 100% of bearings are collected and recycled. Mixed metal components including those mentioned in 7(B) are harvested from the engine or associated components as wear items. These items are placed in a mixed metal recycling bin where they are collected for processing by metal recyclers. The closed-loops are industry-wide as it is not possible for bearing or engine manufacturers to guarantee take back of their own bearings for recycling, however the metals are recovered by traditional metal recycling processes that occur within the EU and are reused, although not necessarily in bearings.

Following “scrap or wear” part removal from the engine, the items are placed in the appropriate material bin for recycling. Many metal recyclers will collect and recycle alloys containing lead and this includes used bearings[5].

---

[4] https://www.dieselnet.com/standards/

[5] For example http://www.omnisource.com/products/?p=nonferrous , http://www.cfbooth.com/Recycling/ and http://www.simsmm.co.uk/Contact-Us/Midlands/~/media/Documents/Items%20Accepted%20List/Acceptable%20Items%20-%20Metals%20UK.ashx

Mixed metals such as lead scrap contained in bearings are commonly processed through pyrometalurgical processes in which assemblies containing more than one metal or alloy are separated with heat into their constituent substances based upon melting point and the separated metals are further refined before reuse (more details in part 3 below).

2) Please indicate where relevant: To be inserted

☐ Article is collected and sent without dismantling for recycling

☐ Article is collected and completely refurbished for reuse

☐ Article is collected and dismantled:

☐ The following parts are refurbished for use as spare parts: _____

☒ The following parts are subsequently recycled:

- Turbo Bushings
- Cam Follower Roller Pins
- Gear Bushings
- Main and Rod Bearings

☐ Article cannot be recycled and is therefore:

☐ Sent for energy return

☐ Landfilled

3) Please provide information concerning the amount (weight) of RoHS substance present in EEE waste accumulates per annum:

☒ In articles which are refurbished No data published, but based on one manufacturer, this is likely to be approximately 1 tonne of lead in bearings removed from engines that are refurbished

☒ In articles which are recycled Professional engines at end of life are recycled as steel scrap and lead is recovered in the EU by steel recycling processes. However, the number of engines and quantity of lead are uncertain as these are not recorded consistently in the EU. Industrial engines reaching end of life today will be old (>30 years) and so all will have been made with lead bearings. No data is available for the quantity of lead in these engines. There will have been some market growth during the last 20 – 30 years and also, some engines originally placed on the EU market may have been resold to non-EU users. Therefore the quantity of lead per year is likely to be less than the 6.4 tonnes placed on the EU market annually, calculated to answer Q4 (A)5 above. About 3 - 4 tonnes may be a more realistic estimate.

☐ In articles which are sent for energy return _____

☐ In articles which are landfilled _____

Lead from bearings is recycled and therefore no lead is intentionally released into the environment.

The elemental lead contained in turbo bushings, cam follower roller pins, gear bushings, main & rod bearings becomes exposed outside of the engine only during remanufacturing or in the event of catastrophic failures.

Although exact engine lifespan may vary dependent upon actual hours in operation, maintenance, and environmental factors, engines utilized in power generation equipment intended for professional use are designed for up to 20 years of service between major overhaul events. Additionally, these engines are designed to be overhauled up to three times, extending the useful life of the major components for up to 60 years. This is significant as the equipment used in this example (professional use diesel generator producing 1800 kW of power) weighs approximately 20 tonnes.

As mentioned in Section 5, bearings are recycled during each overhaul event. Because of the long useful life of a diesel engine in professional use applications, overhaul events are generally infrequent.

The efficiency of lead recovery from copper recycling and from steel recycling is high but as described below:

Steel scrap: The EU Industrial Emissions Directive (IED) regulates certain industrial processes in the EU including metals recycling. Steel scrap is usually recycled by melting in electric arc furnaces. Lead is relatively volatile under these conditions so is emitted as a fume (dust) which is collected by bag houses for refining to recover metals including the lead content. The IED limits emissions of hazardous substances including lead by specifying maximum emission levels and these are described in IED Best available REFerence (BREF) guidance[6]. The IED BREF guide (2012) for iron and steel processes describes the heavy metals present in dust emissions (Pb, Cu, Sb, Mn, Cr, Se, V, etc.). It also indicates that for nine EAF installations the bag filters separated at least 95% of dust and up to 99% of emitted dust. This document also indicates that 10 - 30 kg of dust is emitted per tonne of steel processes but the measured lead content is too low to be specified in the BREF Guidance (presumably because the very low concentration is difficult to measure). Therefore, only 1 to 5% of lead in steel scrap is emitted to air from steel recycling.

Copper alloy scrap: The IED BREF for non-ferrous metals[7] states that recycling of copper alloys that contain lead is very efficient and lead is recovered. An example given for an EU secondary copper smelter in the 2013 draft IED BREF Guidance states that it produced 185,000 tonnes of copper and 2500 to 3000 tonnes of tin/lead alloys that were reused. The IED BREF Guide also states that dust collected from copper smelters contains from 2 – 30% lead depending on type of furnace and types of feedstock. The IED BREF guide also states that copper recycling emits 10 to 60 g of lead per tonne of copper refined and this is refined and recovered. Depending on the type of process and feedstock most lead is recovered as slag or in dust and is further processed to recover the lead content for reuse. The IED BREF does not

---

[6] http://eippcb.jrc.ec.europa.eu/reference/BREF/NFM_Final_Draft_10_2014.pdf

[7] http://eippcb.jrc.ec.europa.eu/reference/BREF/NFM_Final_Draft_10_2014.pdf

specify lead air emissions from copper smelting, because these are too low to measure.

---

6. Analysis of possible alternative substances

(A) Please provide information if possible alternative applications or alternatives for use of RoHS substances in application exist. Please elaborate analysis on a life-cycle basis, including where available information about independent research, peer-review studies development activities undertaken

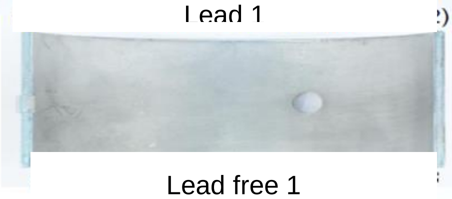
Research carried out during the last 20 years has developed lead-free bearings that are used in some types of internal combustion engine. These are used mainly in road vehicles such as those in scope of the EU End of Life Vehicle Directive as well as larger commercial vehicles. This has been achieved only by utilising almost “clean-room” conditions for engine manufacture, service and rebuilds because lead-free bearings and bushes are much more susceptible to damage by dirt.

Many examples of lead-free bearings obtained from bearing manufacturers have been tested in the types of engines that are covered by this exemption request, but the results show that they give inferior performance and reliability that is unacceptable for the intended uses. Lead was originally utilized in heavy duty diesel engine bearings and bushings for its “soft” properties. These properties include superior resistance to seizure, debris acceptance, conformability, and embedability. Although research into lead-free bearings has been successful for small diesel engines that are used in road vehicles (cars and trucks), lead free bearing and bushing technology has not been developed as a suitable replacement for existing leaded designs. The bearings that have been evaluated are representative professional heavy duty engine bearings.

Current leaded bearings used in professional heavy duty diesel engines have evolved the technology over many years and manufacturers have settled on the general construction consisting of a steel backing, a copper/tin/lead alloy layer, a nickel dam (or barrier) layer, and a final electroplated tin/copper/lead alloy overlay (Figure 9). A wide array of proprietary materials are under development for professional use applications by bearing manufacturers and the figure below shows the variation in appearance of new bearings.

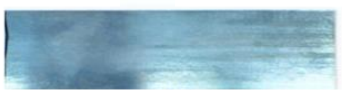
Lead 1

Lead free 8



Lead free 1

Lead free 4



Lead free 2

Figure 10. Inner surfaces of examples unused lead-based and lead-free bearings

Lead-free bearing materials have not matured to the required level to meet the reliability requirements of diesel engines used in professional applications.

Additionally, because these formulations and constructions are proprietary to the bearing manufacturer, competition will be reduced. Availability will depend upon the given suppliers ability and willingness to produce. All conditions which will have direct effect on the consumer in terms of cost and availability of spare parts.

Reported below is a series of comparative tests of bearings carried out by an engine manufacture in the laboratory using lead based bearings and lead-free versions specially made for these tests to evaluate lead-free bearing materials. When parts or materials are changed in engines, the first stage is bench testing which is used to simulate the conditions seen in service, but with accelerated test conditions that cannot truly reflect real engine conditions. These tests will however eliminate bearing materials that will fail engine tests. Bench tests are used to identify bearings that may be suitable and so are worthwhile also testing in engines which will assess the new design under realistic conditions. These two stages of development are described below.

Seizure Resistance testing

Seizure resistance tests are designed to simulate the ability of a bearing to continue to function properly as various real world environmental conditions are introduced to the bearing including; oil starvation, damage or scoring, increased loads, and foreign material entering the bearing clearance area. Figure 11 depicts a typical bench test rig to measure seizure resistance. In this test, the load on a test bearing can be gradually increased until it fails (seizes). Also, bearings with damage from scoring can be compared and the method used to form a groove using a load of 7.5kN is shown in the right image of Figure 11, below.

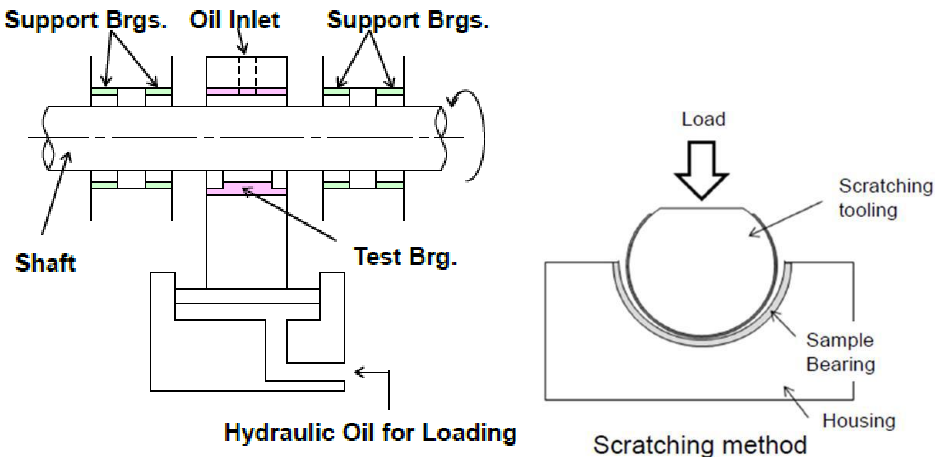


Figure 11. Seizure plane and Groove test arrangement

Test results for groove seizure test designed to simulate the bearings ability to perform under load with damage to the surface are shown in the figures below. Figure 12 represents the baseline test with no damage and Figure 13 represents the same bearings with a 7.5kN groove introduced to the bearing surface. In Figure 12 and Figure 13 below, the red dots represent actual values for individual bearings and the grey bars are the average values.

Note the lead bearing material (Lead 2) with a groove maintained similar performance characteristics to new undamaged bearings and had more samples falling into the grouping range as compared to the next closest product (Lead-free 8). All other lead-free products failed extremely early in testing and/or load carrying capabilities were profoundly diminished.

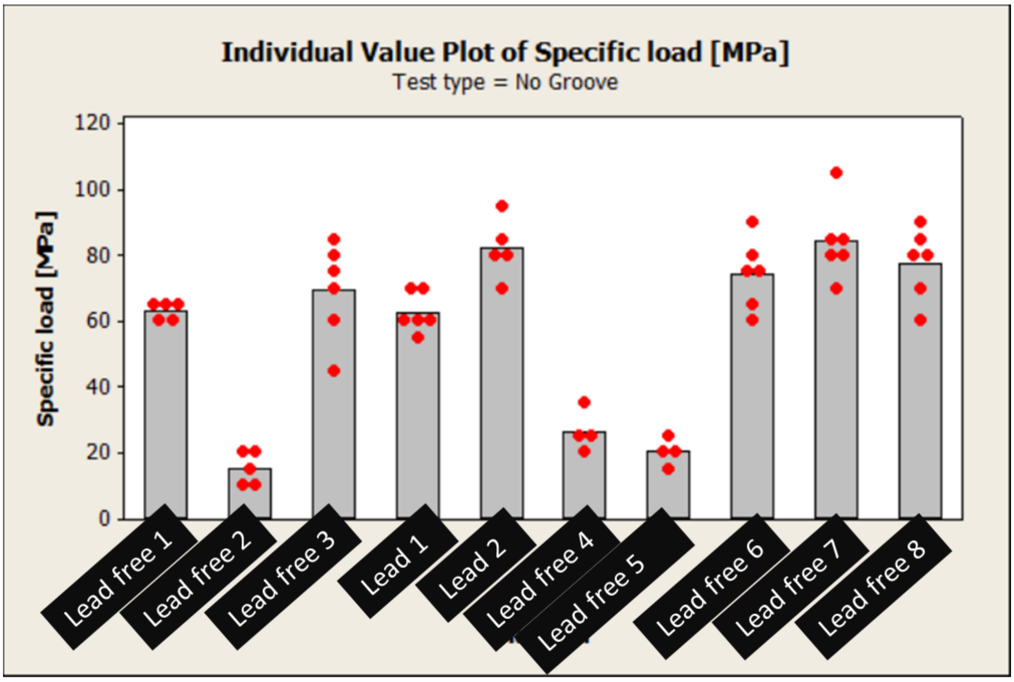


Figure 12. Seizure results with no damage – test to failure

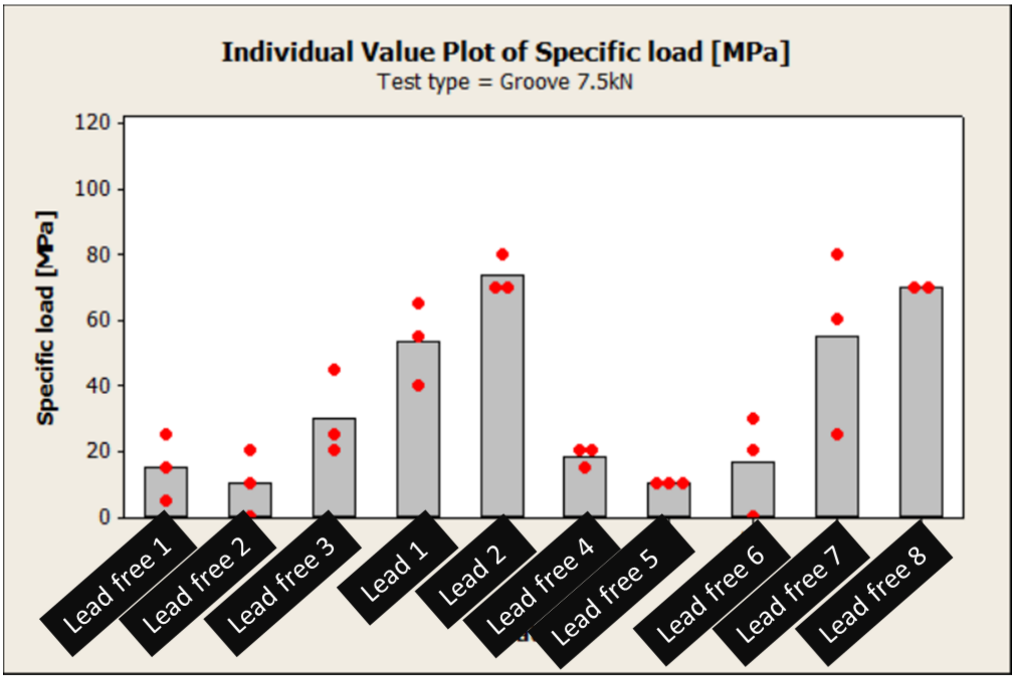


Figure 13. Seizure Resistance with 7.5kN groove in bearing surface

Bearings were sourced from bearing manufacturers for these tests. In the tests with a groove, many of the lead-free bearings failed with very low loads.

Embedability

Soot and debris are inherent in the operation of internal combustion engines. This debris in the form of metal shards or “chips” can be introduced during engine break-in (also called running-in), service events, by deferring recommended service, through general wear and tear as mating internal components conform to mating surfaces, using unclean oil, etc. The substandard embedability characteristics of lead free bearings is of particular concern for the critical power applications serviced by professional power generation equipment.

Test rigs (Figure 14) are designed to introduce “dirt shocks” into bearing clearance areas. The more dirt shocks a bearing is capable of accepting without seizing is indicative of good embedability and therefore a more reliable product for the user.

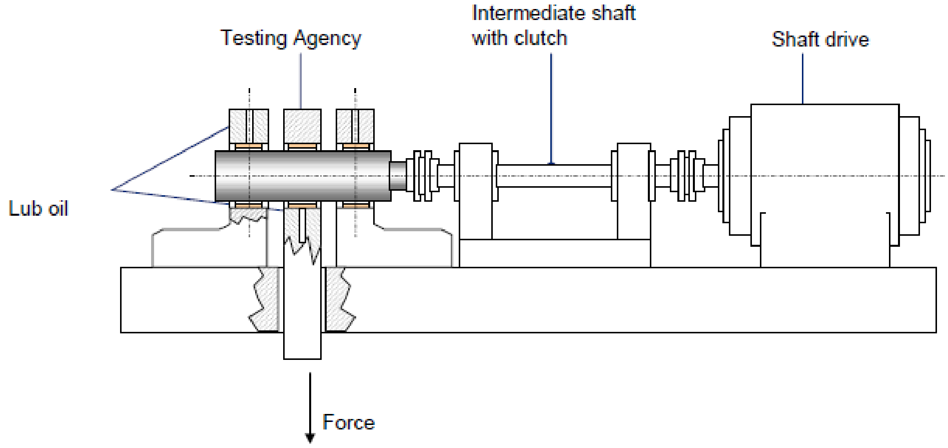


Figure 14. Dirt shock embedability test apparatus.

For the purpose of this test, dirt shocks are administered into the bearing clearance area through the lubrication oil supply in the test rig. These shocks are administrated until the embedding capacity of the bearing is exceeded and the bearing fails (seizure Figure 15). This same test is repeated with a load simulating combustion loads placed upon the bearing (Figure 16). As in the results from seizure resistance testing, red dots are results from individual tests and the grey bars are averages of these results.

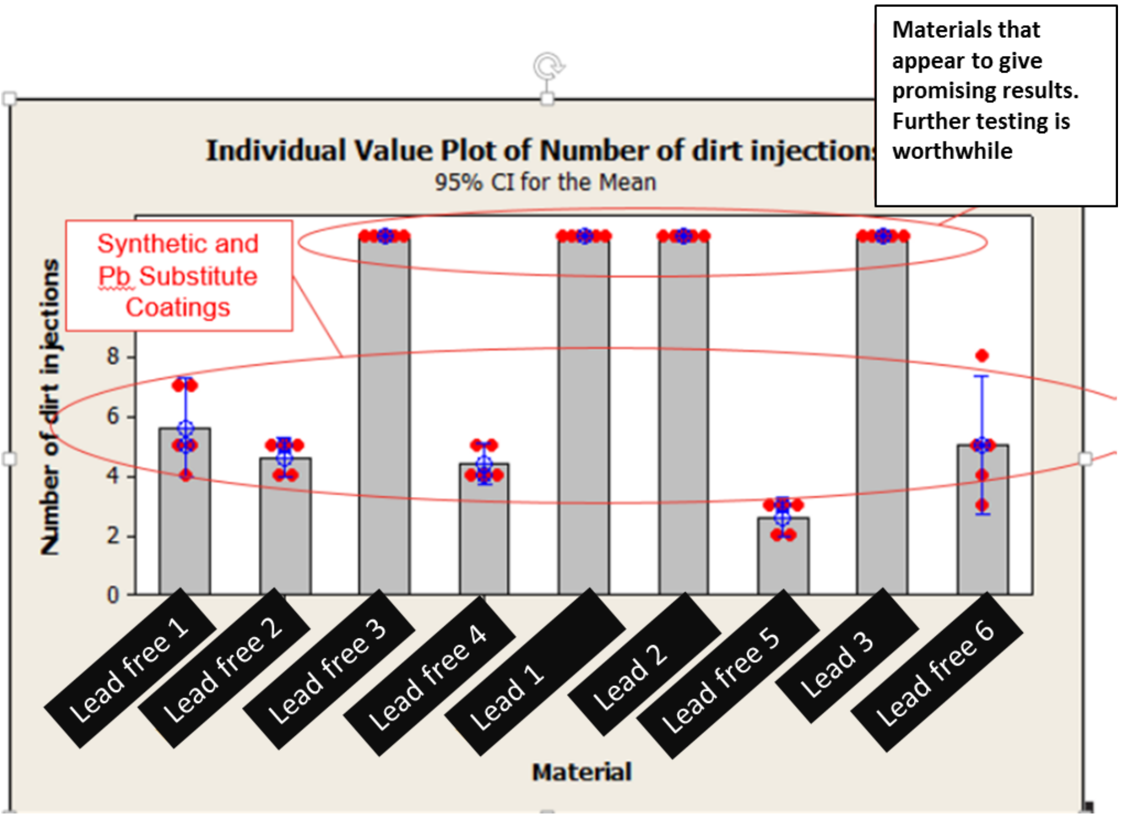


Figure 15. Test Results, Embedability – Shock count with no load on bearing

The above results are from bench tests which cannot reliably reflect the conditions experienced by bearings in real engines so although lead-free 3 appears to perform as well as the lead-based bearings, this is useful only as an indication that lead-free 3 is worthwhile testing under different conditions and possibly also in engines as described below.

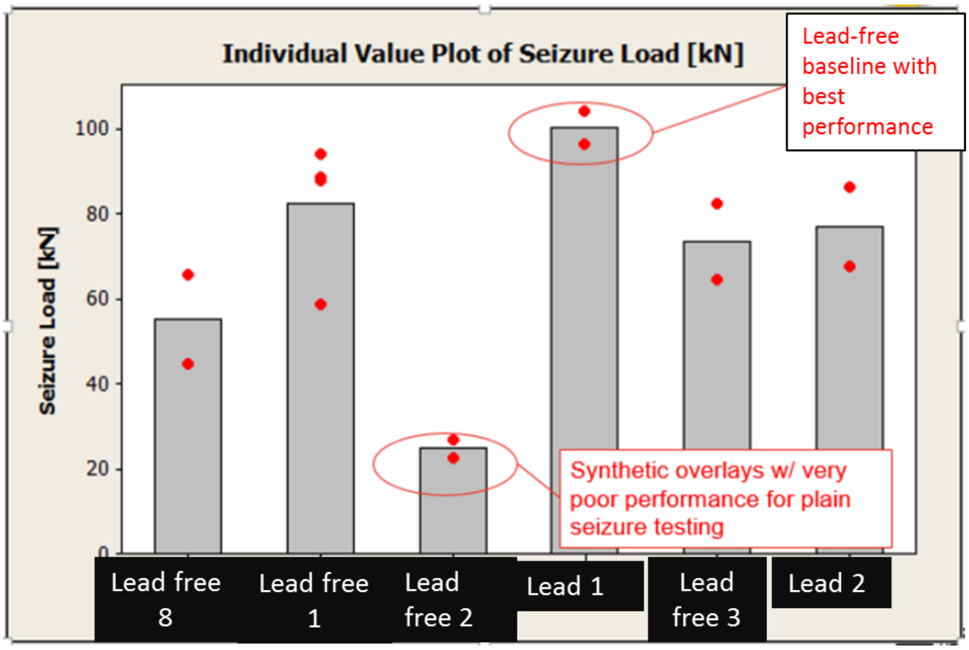


Figure 16. Test Results, Embedability – Shock count with a realistic load

Figure 16. shows tests of some of the materials used to produce Figure 15 but under a constant load. Note that in real engines, bearings experience cyclic load so this test only gives an indication of which materials are worthwhile carrying out further tests. Overall, the results in Figure 16 are inconclusive taking into account the variation in results and that bench tests are not truly representative of conditions in real engines. However, this was enough to suggest which lead-free materials might be worthwhile assessing in engine tests, however, as described below for the 15 litre engine tests, all lead-free bearings had an unacceptably high failure rate.

Shown below are published comparative test results which show the number of “dirt shocks” that can be injected until failure occurs[8].

Table 2. Average number of dirt shocks before failure of one leaded and four lead-free bearings

Bearing alloy / coating	Average number of dirt shocks survived before failure
Lead bronze trimetal bearing	13.0
AlSn25CuMn (lead-free)	11.5
Lead-free bronze with sputter coating	8.0
Lead-free sputter with synthetic coating	4.5
AlSn20Cu with sputter coating (lead-free)	3.2

The results in Table 2 are comparable to those achieved by the engine manufacturer tests described above, although the bearings were probably designed for an engine with a different capacity, although this is not specified in the publication (this refers to a high speed gaseous fuel engine).

From these tests, we can see that the synthetic “sputter coated” and Pb free substitutes such as copper tin or aluminium alloys, offer 20-80% less debris holding capability as compared to bearings constructed with a lead overlay.

This reduced debris holding capacity and dramatic difference in performance with lead free bearings is of particular concern for proposed use in power generation applications. Note that all lead free options failed with approximately half of the dirt shocks of leaded options. This is further exacerbated by the reduced load capabilities illustrated in Figure 16. The consumer could expect equipment to fail early in the product life cycle and failures to occur at start up or shortly after as load is applied to the engine during the power generation process. This

[8] “Modular Bearing Designs to Cope With the New Engine Designs Demanding High Performance, Lead-Free Solutions, and Robustness”, Rainer Aufischer, Rick Walker, Martin Offenbecher and Gunther Hager, J. Eng. Gas Turbines Power 136(12), 122505 (Jul 15, 2014).

would have very serious implications, for example in a hospital where the generator is needed as an emergency back-up supply if there is a power cut.

Conformability

Conformability is another soft property requirement of professional use engines. Conformability is the ability of a bearing to accommodate irregularities in mating surface. This is especially critical at start-up and the wear in period of an engine. At start-up, the metal surfaces likely have little or no lubrication. The soft properties of lead allow the bearing to conform to variation when there is metal to metal contact.

Poor conformability often results in premature failure of the bearing and catastrophic failure of the engine. Very little comparative test data could be found to show the difference between leaded bearings and lead-free. One publication[8] from a bearing manufacturer describes their "misalignment" tests of their bearings. Results are not straightforward, as three types of lead-free bearings having synthetic polymer coatings suffered significant wear (up to 21 µm), whereas the only leaded bearing tested seized in two out of the three tests, although this was superior to the equivalent lead-free version without a polymer coating that seized in all tests. The soft properties of lead will allow for slight variation in alignment without total failure. The results shown in reference 8 show a complete failure of the bearings resulting in material transfer between tribological surfaces. This failure mode can be minimized with the use of leaded bearings. As described above, the synthetic polymer coatings used for the conformability tests described in reference 8 gave inferior reliability when debris was present in the lubricant, so this material is not always suitable as a substitute. In practice, only realistic long-term testing in engines is able to determine if a bearing will be reliable.

Engine bearings are required to have a combination of performance parameters in order to provide the required reliability for the heavy duty engine applications in scope of this exemption. Figure 17 below summarises the results of bench tests that are described above.

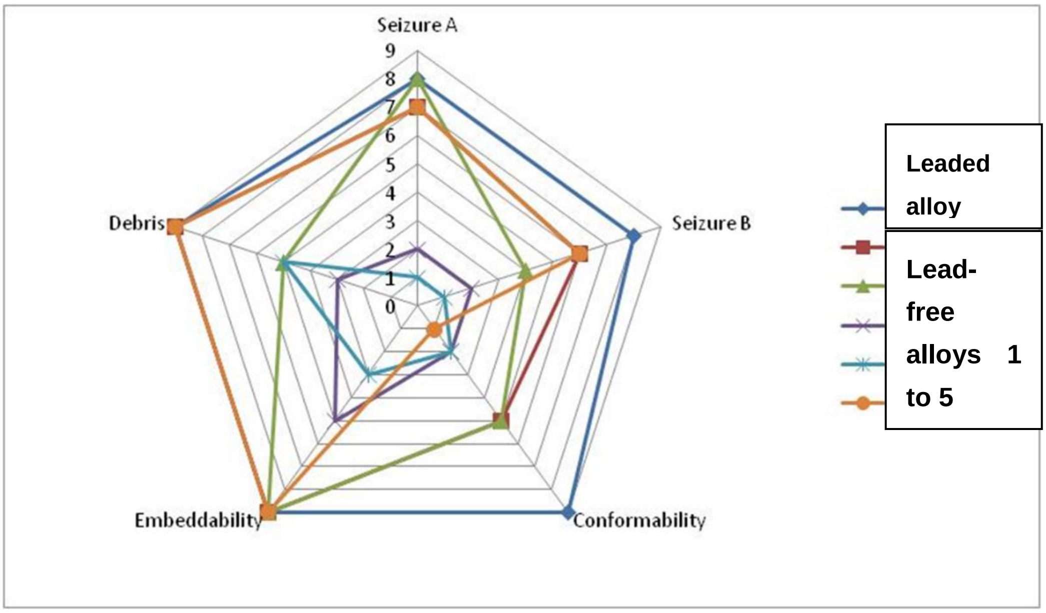


Figure 17. Summary of bench test results, Leaded vs. Lead Free Material Testing

In Figure 17;

- Seizure A is without groove (see Figure 12)
- Seizure B is with groove (see Figure 13)
- Conformability of bearings is from reference 7
- Embedability (of debris) is from the engine manufacturers tests described in Figure 15 and Figure 16
- Debris tolerance - ASME research results shown in Table 2 (reference 7)

Synthetic bearing overlays designed to mimic soft properties of lead underperformed all other designs. Other lead free designs utilizing a combination of alloys designed to replicate the tribological properties of lead were also found to be not equivalent and below the reliability benchmarks of current leaded material.

In summary, bench testing concludes that lead free products are not capable of matching the seizure resistance, conformability, embed ability, or debris holding capacity without compromising other attributes critical to reliability.

On Engine Testing in an Engine Manufacturer's Laboratories

The above described tests were conducted using test rigs designed to assess bearings by replicating the environment of a heavy duty diesel engine. Testing must also be conducted on actual diesel engines to identify failure modes which can only be identified with loads and conditions that are consistent with the entire reciprocating engine assembly working as a complete engine system. These tests are routinely executed by engine manufacturers as a manner of procedure whenever one of the following conditions are true:

- Change in material specification or source

- Change in supplier's manufacturing location or process
- Change in OEM's manufacturing location or process

Test carried out by two engine manufacturers are reported below:

i) 15 litre diesel engine tests

The tests described below were conducted on or with bearings/bushings utilized on the Cummins ISX15 diesel engine. This is a 15 litre, in-line six cylinder, turbocharged, electronic fuel injection engine, which is used in applications that are both in scope of the 2011/65/EU RoHS Directive and are also used in excluded applications (e.g. transport).

Note the bearing samples referenced in the test results above were also with the same types of bearings intended for use in the Cummins ISX15.

Tests are conducted under the following conditions:

- Over Speed (exceeding an engines rated maximum operating revolutions per minute)
- Torque peak (maximum engine torque output as measured at crankshaft at a given engine speed)
- Lug Down to 600 RPM (Reducing engine speed to 600rpm)
- Lug Down to Stall (Reducing engine speed until it stalls)
- Start / Stop (repeated stopping and starting the engine)
- Cold Start (Starting an engine after an extended period of rest. This could simulate an engine resting for a work shift in an NRMM application or a genset starting in an emergency power mode after a period not in use)

These conditions are repeated over a total of 500 – 3,000 (depending upon application) hours in a "cyclical" test as depicted below (see Figure 18 and Figure 19). In the case of the Cummins ISX engine, these tests are conducted and repeated over a 1,000 hour engine rig test cycle. Regularly scheduled maintenance is performed on the engine as specified by the manufacturer.

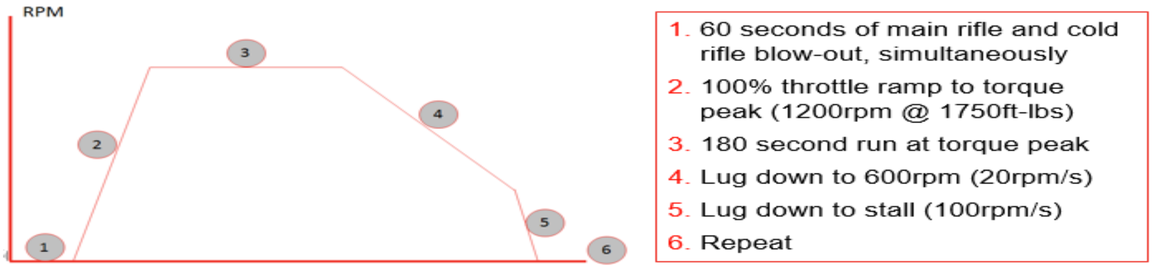


Figure 18. Cyclical engine test cycle using 15l, 6 cylinder engine

The test cycles used in shown above in Figure 18. The X-axis is time and the y-axis is engine speed in revolutions per minute. The terminology used for each of the six stages of a test cycle is explained below:

- The main rifle is the primary oil passage within an engine. Other secondary oil passages or "rifles" branch off this main passage to supply the engine with oil for lubrication and cooling.

- Cold Rifle is a rifle which is not charged with oil. During a cold start situation, a cold rifle would contain no oil. Likewise all downstream lubrication points on the engine would also be without oil.
- Throttle ramp is the increase in engine speed until the torque peak is reached. In this test, this occurred at 1200 rpm and the torque was 1750ft-lbs
- Lug down as explained below is the reduction in engine speed, initially to 600rpm and then to stall speed when the engine stops.

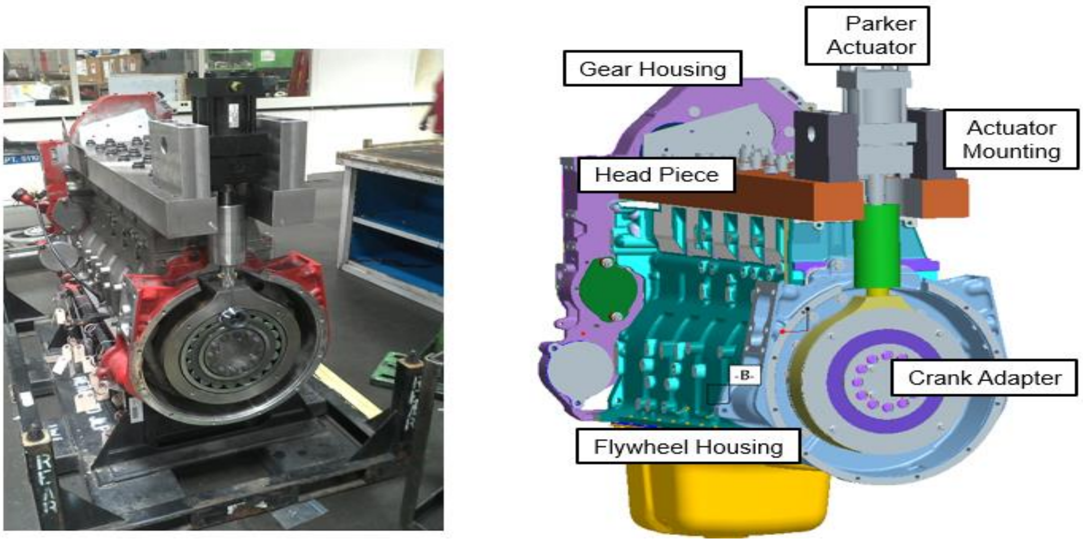


Figure 19. 15l engine test rig used for testing bearings

Components are considered to have failed the engine rig testing if any of the following conditions are true:

- The engine catastrophically fails
- Engine performance is observed outside of specifications (reduced power output, higher heat, greater fuel consumption, unfavorable exhaust emissions)
- Abnormal wear to internal components is observed which may cause premature failure of the engine, result in undesirable performance, or exhaust emissions. This abnormal wear is measured by visually and dimensionally inspecting then weighing the reciprocating components for pre-determined out of specification conditions.
- All of the above must be equal to or better than existing component performance to achieve a "passing" test result.

Field testing of engines

In addition to the engine test rigs, final validation of changes to internal engine components must be validated through a field test of approximately 50 engines. The exact quantity of engines field tested may depend upon; expected volumes, duty cycle, applications served, and other environmental factors.

Field testing is conducted in equipment for which the engine is designed. Representative equipment is obtained and the engines are installed by qualified technicians. Prior to installation, all internal reciprocating components are measured by technicians and tolerances are documented. Any components found to be out of specification are replaced with ones which conform to quality standards prior to installation.

Table 3 is a summary comparison of leaded bearing failures within a population of 68, 15L ISX engines with experimental lead free bearings which are compared with a population of 108 engines utilizing current production bearings containing lead. Note that field tests reflect the wide variation in operating conditions that are seen by engines and so are the most realistic tests that can be carried out. Inevitably, the severity of conditions experienced by individual engines varies and this will be reflected in the wide variation in time to failure.

Table 3. Results of field testing of ISX 15l engines with experimental lead-free bearings compared with lead-based bearings.

	Total hours in use	Maximum hours in use for an engine of each type	Total miles of engines	Maximum miles for best performing engine of each type	Number of engines tested	Number of main bearing failures in service
Engines with unleaded main bearings	326,950 (average of 4,808 per engine)	6,653	3,493,360	251,681	68	11 (16.1%)
Engines with leaded bearings	609,216 (average of 5,641 per engine)	4,614	2,578,107	313,098	108	0

Summary of comparative field testing results:

- 16.1% of test engines utilizing lead free bearings failed during testing. Of the other engines with lead-free bearings, these required more frequent servicing and repairs and operated for fewer hours than the lead bearing counterparts, as shown in Table 3. A rate of 83.7% of engines passing these test requires is unacceptably poor.
- The main bearing failures of engines utilizing lead free bearings occurred in a range of 0.8 hours to 1,380 hours (~20% or less of expected useful life). Expected life of an engine used in an industrial application is typically upwards of 50,000 hours (e.g. genset operating intermittently for 20 years), but with lead-free bearings, first failures occur after less than 200 hours and some after much less time.
- Failures occurred in both light and heavily loaded engine applications

- Improper formation of main bearing relief (conformability) was found to be a contributing factor in post failure evaluation.
- Lead free bearings were found to be less tolerant to lube system excursions as compared to current leaded bearing offerings. In service, oil can become dirty and this restricts the flow to bearings (e.g. as oil filters become blocked) and this occurs in all engines irrespective of bearing composition. When this occurs, lead-free bearings are more likely to fail than lead-based bearings.

It is worth pointing out here that oil filter blockages that restrict oil flow are fairly common. To ensure that emergency generators operate even if this occurs, engines can be designed to by-pass the oil filter and circulate dirty oil, in order to ensure that the generator operates when needed. As shown above, lead-free bearings are however less tolerant of debris or dirt and are more likely to seize than leaded bearings and so filter by-pass cannot be used with lead-free bearings.

The on engine testing concludes the lead free bearing materials are not equivalent to the leaded products on the market in conformability or seizure resistance. These characteristics are critical to reliability and of particular concern in applications such as back-up emergency power and other professional-use applications. Additional detail regarding failures is contained in the table below.

Table 4. Examples of results of manufacturer's engine tests

Engine running hours	Lead-free bearings	Main bearing hours	Comments
872	Main and rod	0.8	Main bearing failure suspected to be due to blockage of oil passages
988	Main	988	Shut down due to low oil pressure due to debris in filter
411	Main and rod	411	Catastrophic engine failure due to connector rod bearing seizure causing it to penetrate side of engine
716.6	Main	716.6	Main bearings failed, oil filter flow restricted
728	Main	11.4	Cause not identified
716.6	Main and rod	716.6	Blocked oil filter before main bearing failure
1073	Main	1073	One main bearing failed and the rest contained debris. Catastrophic engine failure as connecting rod penetrated side of engine
1380	Main and rod	1380	Main and connector rod bearings seized so that connector rod penetrated side of engine after oil filter flow restricted
693	Main and rod	694	Main and rod bearings seized after oil pressure low due to debris in filter

The results shown in Table 4 show that premature failure often occurs when oil pressure drops, due to blocked filters. There is no reason why a lead free engine would mean more filter plugging or blocking, but lead-free bearings are more susceptible to failure when this occurs causing bearing seizure and sometimes catastrophic damage to the engine..

A plugged filter[9] is not uncommon in harsh/dirty environments due to the increased probability of external dirt being introduced into the engine internals.

The main emphasis of research has been into alternative bearing alloys and bearing designs, although this also sometimes necessitates some redesign of engines. More drastic engine resdesign would be very difficult and may not avoid the need to use lead in bearings. The

[9] Plugged Filter = The filter's capacity to hold dirt and debris is exceeded and fluid will no longer pass through the filtration system at the required volume. Some engines have a filter bypass feature. This is designed into an engine in which fluid is routed around the filter to continue supplying the engine with oil if the filter is plugged. Not bypassing the filter means the engine would be starved for oil should the filter become plugged, however dirty oil will reach the bearings.

design of internal combustion engines is now very mature with very little scope for changes to bearing materials that would not also negatively affect performance, exhaust emissions and fuel consumption, all of which have been improved in the past decades by refinement of engine design.

ii. 9 litre diesel engine field testing

Manufacturers have attempted to produce engines smaller than 15 litres capacity with low-lead bearings but experience has shown that in severe field applications, failures are common. A different manufacturer (to the one whose 15 litre engine results are described about) has manufactured 9 litre engines with bi-metal bearings based on steel backed aluminium alloy with 1 – 2% lead, but experienced multiple field failures. When the failed engines were examined, the fault was found to be due to seized main bearings that in some causes caused the crankshaft to break. Between 2004 and 2007, at least 16 engines catastrophically failed and this occurred in several EU countries as well as in the USA. One typical example application was in a rock crusher which uses a direct mechanical drive belt connection to the engine where failure occurred after 1,400 hours of service. Failure analysis of the engine showed that severe over-heating of bearings had occurred. As a result of this reliability issue, comparative testing was carried out to compare the steel aluminium bimetal bearings with trimetal bearings based on a steel back with copper alloy containing 20% and a thin overlay coating with 90% lead.

Comparative field testing has been carried out by the second manufacturer using a 9 litre diesel engine. Engine reliability was assessed using the standard trimetal lead bearing compared with steel / aluminium bimetal bearings. The field tests were carried out with a side load such as would occur when the engine is fitted with a drive belt that operates a machine. The force from the side belt was varied to determine its impact.

The test procedure used for engines with lead-free and leaded bearings was as follows

- Set belt force to 7.1kgf and 34mm belt deflection
- Start, run for 1 minute then stop. Repeat to obtain 10 stop starts
- 2 hours running with clutch engaged then 2 hours with clutch disengaged
- Start, run for 1 minute then stop. Repeat to obtain another 10 stop starts
- Remove one main bearing and keep for examination (as described in table below)
- Repeat cycle with 10kgf and then again with 13kgf

Results are summarised below. Note that main bearings are constructed in two halves, referred to below as the lower and upper parts.

Belt force	Steel aluminium bimetal bearings	Leaded bearings
7.1 kgf	Lower part – slight shininess of rear edge Upper part – slight shininess to rear edge and larger area 10mm above top side on rear edge	Lower part – small shiny patch Upper side – Larger shiny patch
10kgf	Lower part – no sign of wear Upper part – Large shiny area 25 mm above tab side from rear edge. This is 10 times larger than the shiny area from 7.1kgf	Lower part – shiny patch, larger than at 7.1kgf Upper part – two small shiny patches
12 – 13 kgf	Lower part – badly damaged (see image below) Upper part – failed completely on tab side. Steel back has become detached from aluminium alloy. Bearing surface extruded and surface hardened likely to be due to overloading the bearing	Lower part – shiny patch, larger than at lower force and one small area of smearing. Upper part – Larger shiny patch

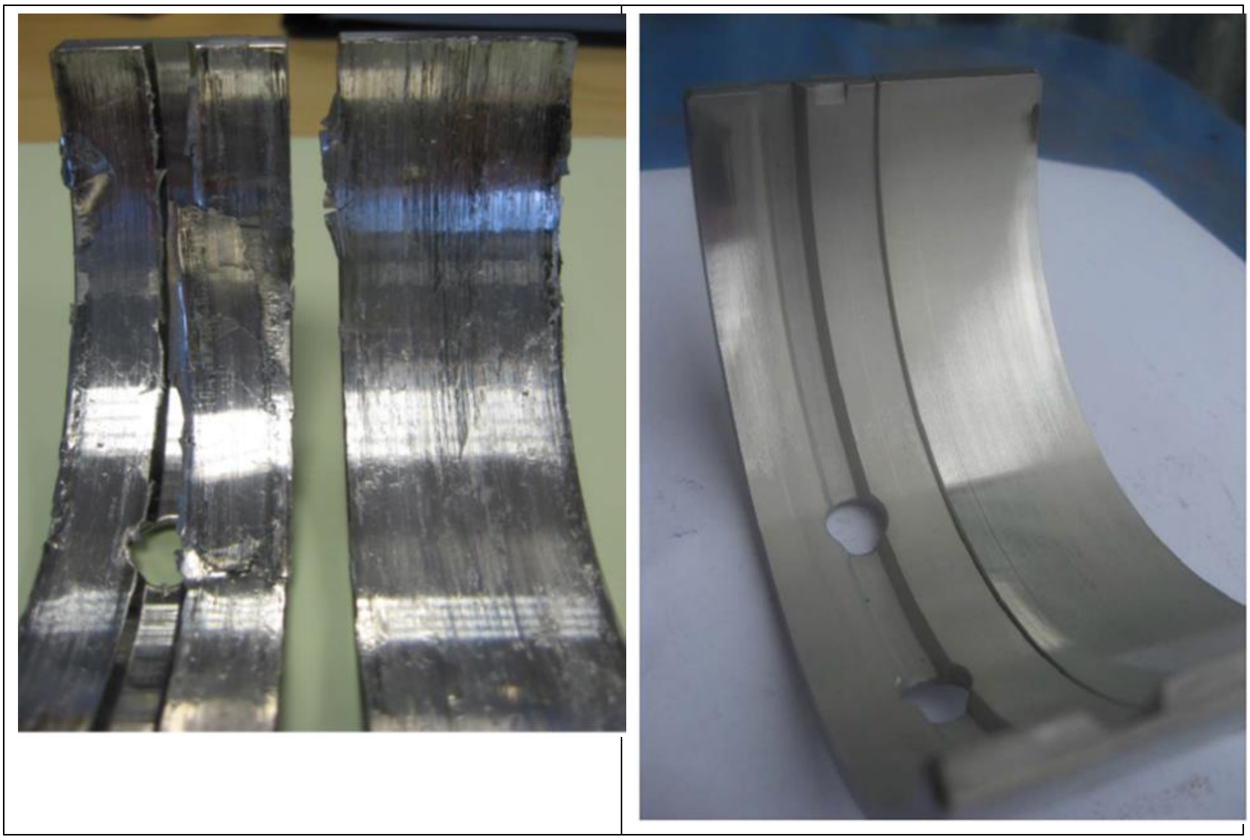


Figure 20. Photographs of steel aluminium bimetal bearing (left image) and leaded bearing (right image) after tests at 13 kgf.

These tests use relatively severe conditions to accelerate lifetime behaviour. Stop – start is the most demanding period of a bearing's life, as there will be little to no oil on bearing surfaces and these comparative tests clearly show the technical performance advantage of lead in the bearing materials. Engines using the lead-based trimetal bearing are now used in engines for the applications where failures occurred previously with the bi-metal low lead bearing and give much better reliability. Engines with lead bearings operate reliably for their planned design lifetime.

iii. Smaller capacity engines

No tests with engines having capacity <9 litres have been carried out as all of the bench tests with lead-free bearings showed that their performance is inferior to lead bearings with regard to the two main failure modes that are independent of engine size; debris tolerance and seizure resistance.

(B) Please provide information and data to establish reliability of possible substitutes of application and of RoHS materials in application

Bearings used in engines have either two layers or three layers (tri-metal). All have a steel backing and the lining layer and tri-metal bearings also have the overlay, which is essential for more demanding applications.

Overlay:

An ideal material will be relatively soft to provide conformance and embedability but a higher melting point to avoid seizure. In general, soft materials have low melting temperatures so a compromise is needed. The most commonly used bearing metals contain the following elements and their melting points and Brinell hardness values are given below:

Table 5. Melting point and hardness values of metals used in overlay materials[10]

Metal	Melting point ˚C	Brinell hardness (MPa)
Lead	327.5	38.3 MPa
Bismuth	271.4	94.2 MPa
Tin	231.9	51 MPa
Indium	156.6	8.8 MPa

Pure elements usually have higher melting temperatures than the same metal with minor additions of other metals, but additives to soft metals can increase hardness. No other soft metallic elements exist that can be used in bearings (the alkali metals are also soft, but much too reactive) and so lead is the optimum metal with the highest melting point but is softer than tin or bismuth and also has a superior resistance to “sticking” (cold weld) to steel and iron surfaces so that seizure is less likely to occur. A higher melting point is an advantage as this makes seizure due to cold welding or melting of the metal less likely. The melting point of indium is too low for it to be used as a major constituent, but it is used as a minor ingredient with lead to make alloys softer, or in some cases is added to improve fatigue strength. In this example, tin increases hardness but indium reduces hardness. The addition of aluminium oxide is for wear resistance.

[10] Brinell hardness of metallic elements from http://periodictable.com/Properties/A/BrinellHardness.v.html

The hardness of coatings is best measured as the Vickers hardness is a measure of the properties of the thin coating without a contribution from the substrate[11]. Rockwell hardness measurements are applicable to bulk materials so give an indication of the debris tolerance and conformability of bearings. The Rockwell hardness of several commercial bearing materials has been measured and average values are given below:

Table 6. Rockwell surface hardness of commercial bearings

Material	Average Rockwell Hardness
Lead 1 (PbSn10In14 + Al_2O_3)	71.5
Lead free 1 (SnCu6)	83.3
Lead free 3 (SnCu)	72.1
Lead free 4 (AlSn20:synthetic)	82.7
Lead free 8 (Bismuth)	84.8

Embedability for trapping debris requires a soft material so the above data shows that lead alloys are superior to all other materials.

Lining materials

Copper alloys are used as lining materials. Lead is practically insoluble in copper so is present as a fine dispersion which acts as a lubricant and gives the alloy ductility which is needed for conformance (copper with high lead content is sometimes referred to as “plastic bronze”).

Most lead-free lining alloys are copper based with tin plus bismuth or zinc, but copper nickel silicon alloy is also used as a bearing alloy. Tin, nickel and bismuth all makes copper significantly harder and less ductile so the lead-free lining alloys will all give inferior conformance performance. Alloys with these elements added are however stronger than pure copper, but nickel and bismuth and to a lesser extent zinc can reduce thermal conductivity[12] which is important for preventing overheating at the bearing surface to prevent seizure. Properties of alloys used as bearing materials are summarised below, however note that the exact values depend on measurement method. As several information sources were used, these may not be quantitatively comparable.

Table 7. Examples of lining alloys and their physical properties[13]

---

[11] This data is not available for bearing coating materials at present.

[12] http://www.matweb.com/reference/copper-alloys.aspx

[13] Various sources including http://www.matweb.com/search/datasheettext.aspx?matguid=60df37d9942a469e868c6bc6f5f7b320 , http://www.concast.com/green-alloys.php , etc.

Alloy	Tensile strength (MPa)	Yield Strength (MPa)	Elongation (MPa)	Brinel Hardness	Thermal conductivity (W/mK)
CuNi2Si	450	360	8 – 16%	130 - 180	84
C89325 (CuSn10Bi3.2)	240	124	20%	73	-
C89835 (CuSn7Zn3Bi2.5)	207	97	6%	65	65.8
C94300 (CuSn5.5Pb25)	145 -186	87 - 103	7 – 10%	42 - 55	62.7

Other bronze alloys are also available, but none exist that match the combination of properties of the standard high lead bronze C94300 that is used in applications in scope of this exemption request. C94300 is ductile when subjected to relatively low forces (i.e. relatively low strength and hardness values) so is able to conform if dimensions within a large engine are not perfect. Lead gives good lubricity and combined with moderately good thermal conductivity makes this a good choice of bearing alloy. Good lubricity is very important for bearings, especially during a cold start when there may be no oil on the bearing surface. The only other metal that gives reasonable lubricity is bismuth in bismuth bronzes which can be polished to a very smooth and bright surface. However bismuth bronzes are less ductile than lead bronzes sue to their higher strength and hardness, as shown above in Table 7.

7. Proposed actions to develop possible substitutes

(A) Please provide information if actions have been taken to develop further possible alternatives for the application or alternatives for RoHS substances in the application.

Engine manufacturers do not make or design bearings but will evaluate any new types that become available. Bearing manufacturers have developed a range of lead-free bearings primarily for use in vehicles to comply with the EU End of Life Vehicle

(ELV) Directive. Lead-free bearings have also been developed for use in commercial vehicles, such as those used by Federal Mogul, As described in section 6, several types of lining alloy and overlay have been evaluated and are suitable for many applications but their long term reliability in applications covered by this exemption request either cannot be assured or is known from R&D to be inferior. Therefore more research is needed.

(B) Please elaborate what stages are necessary for establishment of possible substitute and respective timeframe needed for completion of such stages.

Proposed actions to further develop lead free bearing technology

Because diesel and gaseous fuel engines utilized in professional applications are expected to be in service for up to 20 years and longer, and be fully remanufacturable, material testing and development activities necessarily take many years to complete to ensure long term reliability. Testing has concluded the lead free bearing / bushing material currently available is not technically or functionally equivalent in its seizure resistance and conformability to lead-based bearings and bushes. Continued research and development must be executed by bearing and bushing manufacturers to develop materials equivalent in tribological properties to lead and this needs to develop new designs with suitable materials before testing in engines can start.

Assuming the development of lead free material with tribological properties equivalent to the current state leaded bearing technology is technically possible, extensive "on-engine" and field testing must be executed to evaluate the reliability and durability of the substitute material. The aforementioned on-engine tests were conducted with bearings, mating parts of the reciprocating assembly, assembly procedures and engine fluids that are carefully inspected and ensured that they are well within acceptable design tolerance limits. This of course may not always be reflective of real world conditions where wider tolerances may exist.

The following additional conditions would necessarily need to be executed to ensure long term reliability:

- Two or more bearing / bushing manufacturers need to exist having suitable lead free technology equivalent to or exceeding the tribological properties of lead to ensure long term availability of new bearings and replacement spare parts.
- On engine testing with randomly selected components to accumulate a total of 500,000+ hours proving reliability that is at least equal to that of current leaded bearings / bushings.
- "Uncontrolled" testing by multiple end customers in which application and environmental factors can be experienced such as:
  - Deferred and prolonged maintenance intervals
  - Heat, cold, stop, start, over speed, and over torque intervals that cannot be anticipated by testing

- Contaminated service environments and uncontrolled re-assembly methods utilized in service events (especially important for debris resistance)

Bearings undergoing these field trials would need to be evaluated in nearly 100 displacement and power concentration configurations to ensure reliability across the board in all applications. This testing needs to include those applications that are currently excluded from the RoHS directive which utilize the same engines (and bearings) as those that will be in scope of RoHS from July 2019.

These tests would in turn need to be replicated on at least one alternate lead free equivalent material, from a different supplier, to afford engine manufacturers more than one option in the market should supply or quality issues impair the supply from the primary supplier. Currently there are greater than five global suppliers capable of supplying leaded bearings for professional applications to the many manufacturers of diesel and natural gaseous fuel engines. Multiple avenues of supply must be developed to avoid monopolistic situations and preserve healthy market competition which ensures high quality, and uninterrupted supply.

The stages required before alternatives become available are:

Stage	**Requirements**
1. Search for alternative lining and overlay alloys	Has been underway for many years, but none known that are suitable for applications in scope of this exemption. Therefore a completion date cannot be defined
2. Evaluation in bearings	Can start only when a suitable material is identified
3. Evaluation of lead-free bearings in engine assemblies	Can start if a suitable lead-free bearing is found to be satisfactory
4. Engine redesign	Alternative alloys may not be suitable as drop-in replacements, so time needed for engine design changes (descried below)
5. Evaluation of lead-free engines in the field	Can begin this phase only when bench testing of engines with lead-free bearings shows that these are reliable and performance and emissions are not adversely affected.

The timescale for re-design and validation of engine bearings is a major undertaking which can easily require about 6 years duration and this cannot start until a suitable bearing alloy has been identified. The process involves iterative steps in the lab and in field test to develop an effective design in each individual engine platform. Changing bearing materials will most

likely require changing the engine design, not just replacement of the bearing or bush and time will be needed for these changes and to ensure that reliability is not negatively impacted. For example, the mating material, oil film and tolerance will need to be redesigned to be compatible and this adds to the total development time.
Engine development, as with any heavy machinery development, is an iterative process that can take several years to be completed before a new engine or engine component is onto the market. Condensing current design processes, the primary design phases include Design Validation [DV], Product Validation [PV], Production, and Post-Production monitoring.[14]

Initial DV may begin with bench testing using destructive and non-destructive testing of components. Failure Mode Effects Analysis[15] [FMEA] is normally performed in conjunction with this bench testing. Following bench testing, potential candidate components are further evaluated in controlled testing in whole machinery, PV. Small numbers of prototype machine builds using potential component candidates are constructed and evaluated in controlled operations. Similarly, FMEA may be done on prototypes. After review, production may be begun on approved components. Finally, post-production quality monitoring provides a measure of the components adequacy and robustness.

Engines and engine component development and evaluation can take years to complete. Recent engine development has been required by EU legislation to meet Stage IV[16] of the Non Road Mobile Machinery Directive (and similar United States Tier IV Final[17] emissions) required engine and vehicle manufacturers years and takes many years of work.[18],[19] Although engine bearings and bushings may not be as sophisticated as other components used to meet Stage IV emission requirements, bearings and bushing use and robustness are critical to engine operation and durability. The iterative engineering validation processes noted above are critical to ensure the engine's durability.

Moreover, recent changes in engine design to meet these reduced emission requirements have raised issues of engine component robustness. Recent report by the California Air Resource Board cited higher warranty claims when new emissions standards took effect in California in 2004, 2007 and 2010.[20] Similarly, because these same base engine designs

---

[14] Vehicular Engine Design, Kevin L. Hoag M.S., ISBN: 978-3-211-21130-4 (Print) 978-3-211-37762-8 (Online) referencing AVL Engine Design. Also see http://link.springer.com/chapter/10.1007/3-211-37762-X_4#page-1. Note that the engine design validation process entails almost 42 months prior to market introduction and production.

[15] http://asq.org/learn-about-quality/process-analysis-tools/overview/fmea.html

[16] EU Non Road Mobile Machinery Directive 97/68/EC.

[17] 40 Code of Federal regulations 1039

[18] Non-Conformance Penalties for Heavy-Duty Engines Subject to 2010 NOX Emission Standard: Response to Comments 420r12015, p16 ("new engine development program … 22 months"); p22 ("years of resources").

[19] Draft Technical Support Document: Non-Conformance Penalties for 2004Heavy Duty Highway Diesel Engines 420D02001, p15 ("incorporation of all these technologies is not a simple task … requires several years of research and development").

[20] Evaluation of Particulate Matter Filters in On-Road Heavy Duty Diesel Vehicle Applications, CARB 08MAY2015, p12 http://www.arb.ca.gov/msprog/onrdiesel/documents/DPFEval.pdf.

and configurations are utilized in a myriad of applications in Non-Road Mobile Machinery (including equipment in scope of RoHS), the engineering evaluation process will require testing and validation of any components across those applications to ensure performance, robustness and durability. Introduction of mass-produced components such as Pb-free bearings and bushings will require extensive testing and evaluation across the myriad applications of Non-Road engines, not just mobile generator sets.

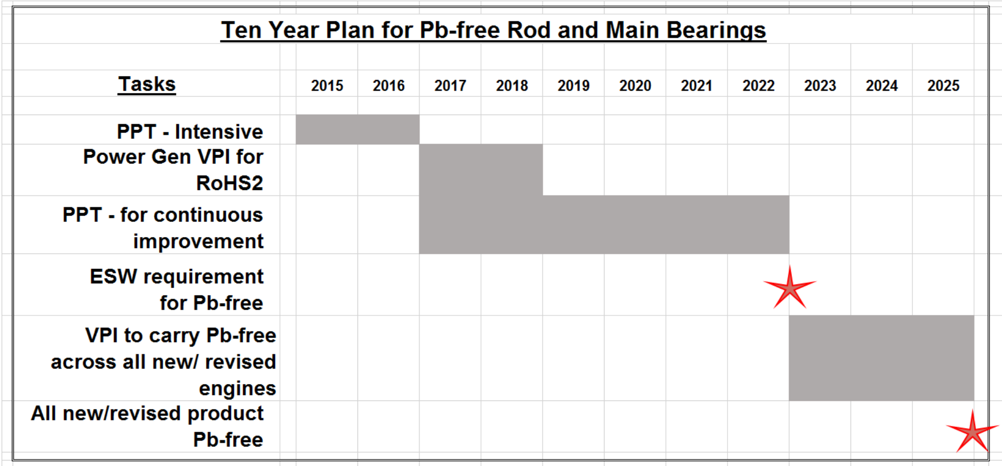
Timescale for redesign to accommodate any changes including new bearings and bushes varies and is very difficult to estimate, as this depends on the engines design and the extent of any changes to the bearing or bush design. Engine modification for alternative bearings may take at least 2 years, with 3 years being typical. If electronic software change is also required with appropriate validation, experience has shown that this alone can take anywhere from 25 to 60 weeks.

A typical timescale for one new bearing material in one engine design could be as follows, assuming that each stage gives satisfactory results to allow proceeding to the next stage.

The below chart represents an estimation of time that would be required to develop lead free technology; definitions of acronyms follow the chart. Note the times in this chart are for enterprise wide adoption of the technology where the existing technology is not RoHS compliant and PPT (Product Preceding Technology, see explanation below) activities successfully identify replacement technology. PPT activities are undertaken between engine manufacturers and bearing suppliers using bench tests and lab tests using representative engine models of various sizes to identify high potential replacement bearing technologies. Development and validation then proceeds to individual engine models and applications. In general, different bearing technologies may be required depending on engine size, engine application and basic engine design.

Note this chart does not include time necessary to upgrade the network of third party service providers currently performing routine maintenance and rebuild services to the cleanliness levels that would be necessary to support the requirements of lead free engines and so this time will be in addition and is at least one extra year.

The times represented in this chart are derived from history and experience by engine manufacturers with the development times required for similar internal engine components.



The above timescale will be extended if suitable technology is not found at any stage and so research into alternative materials or designs will need to start again.

Definitions:

PPT = Product Preceding Technology, this describes the development work of a given component technology prior to it being specified in a new product.

VPI = Value Package Introduction, this refers to the testing and development of a new product to market. Whereas PPT develops the component technology, VPI is the project management exercise of developing a new design for market.

ESW = Engineering Standard Work, this is a series of pre-determined tests and corresponding "acceptable" results for a given component change. These are the minimum requirements a replacement component must meet to be considered acceptable in a VPI program

---

8. Justification according to Article 5(1)(a):

(A) Links to REACH: (substance + substitute)

1) Do any of the following provisions apply to the application described under (A) and (C)? No, lead metal is not applicable to any of the criteria listed below

- ☐ Authorisation
  - ☐ SVHC
  - ☐ Candidate list
  - ☐ Proposal inclusion Annex XIV
  - ☐ Annex XIV
- ☐ Restriction
  - ☐ Annex XVII
  - ☐ Registry of intentions
- ☐ Registration

2) Provide REACH-relevant information received through the supply chain. None exists

(B) Elimination/substitution:

1. Can the substance named under 4.(A)1 be eliminated?

☐ Yes. Consequences? _____

☒ No. Justification: Lead is essential constituent of engine bearings and all potential substitutes are less reliable

2. Can the substance named under 4.(A)1 be substituted?

☐ Yes.

☐ Design changes:

☐ Other materials:

☐ Other substance:

☒ No.

Justification: See sections above

3. Give details on the reliability of substitutes (technical data + information): See answers to Q6.
4. Describe environmental assessment of substance from 4.(A)1 and possible substitutes with regard to
   1) Environmental impacts: _____
   2) Health impacts: _____
   3) Consumer safety impacts: _____

Not applicable because no alternatives exist that are sufficiently reliable for applications in scope of this exemption.

⇨ Do impacts of substitution outweigh benefits thereof? Not relevant to this exemption request

Please provide third-party verified assessment on this: _____

(C) Availability of substitutes: Not applicable to this exemption request

a) Describe supply sources for substitutes: _____

b) Have you encountered problems with the availability? Describe: _____

c) Do you consider the price of the substitute to be a problem for the availability?

☐ Yes ☐ No

d) What conditions need to be fulfilled to ensure the availability? _____

(D) Socio-economic impact of substitution: Not applicable to this exemption request

⇨ What kind of economic effects do you consider related to substitution?

☐ Increase in direct production costs

☐ Increase in fixed costs

☐ Increase in overhead

☐ Possible social impacts within the EU

☐ Possible social impacts external to the EU

☐ Other: _____

⇨ Provide sufficient evidence (third-party verified) to support your statement: _____

9. Other relevant information

Please provide additional relevant information to further establish the necessity of your request:

_____

---

10. Information that should be regarded as proprietary

Please state clearly whether any of the above information should be regarded to as proprietary information. If so, please provide verifiable justification:

_____
