2nd Clarification Questionnaire Exemption Ex. No. 7(c)-II

"Lead in dielectric ceramic in capacitors for a rated voltage of 125 V AC or 250 V DC or higher"

Abbreviations and Definitions

AC	Alternating Current
DC	Direct current
EEE	Electrical and Electronic Equipment
RoHS	Directive 2011/65/EU on the Restriction of Hazardous Substances in Electrical and Electronic Equipment

Background

The Oeko-Institut has been appointed by the European Commission, within a framework contract[1], for the evaluation of applications for exemption from Directive 2011/65/EU (RoHS), to be listed in Annexes III and IV of the Directive.

Your organisation, Murata Electronics Europe B.V, in the name of the Umbrella Project, has submitted two requests for the renewal of the above-mentioned exemption, one for categories 1-10 and one for category 11 of Annex I of RoHS. We have received your confidential contribution, dated 5 and 7 Feb 2021, providing information on unsuccessful attempts to find lead-free substitutes.

We have reviewed the information you have provided and compiled questions where we need additional information and/or clarification.

Clarification Questions

In the name of the Umbrella Project, your organisation Murata Electronics Europe B.V requests the exemption 7(c)-II for high temperature / high voltage ceramic capacitors, arguing that the addition of lead to ceramic dielectrics is indispensable to produce capacitors that exhibit the following properties:

(a) High dielectric constant at high operating voltage,

(b) High energy storage capability (also at high temperatures),

(c) Low leakage at high voltage and high temperatures, and

(d) Low loss at high current, frequency, and temperatures.

[1] The contract is implemented through Framework Contract No. ENV.B.3/FRA/2019/0017, led by Ramboll Deutschland GmbH.

From your exemption request and the response to our clarification question we derive that "*further substitution of lead in dielectric ceramic in capacitors for a rated voltage of 125 V AC or 250 V DC or higher could not be accomplished in the scope of exemption 7(c)-II.*" You explain that "*There are lead-free dielectric ceramics for high voltage applications that have scientific and pure technical potential*". You argue that "*industry still has to find applicable substitutes which can be used in practice*" but "*and industry has not been able to find cases proposing lead-free substitute materials in published papers available*". You assert that "*only limited examples have been published since the last renewal request in 2015*".

However, your assertion quoted above is in stark contrast to the results of our review of the scientific literature on this topic. Over the last decade, a wealth of research and development work has been carried out in the field of advanced materials, addressing candidates of lead-free dielectric ceramics. This has resulted in numerous publications in peer-reviewed scientific journals. To pick out a few, below are some examples of lead-free dielectrics reported in the literature.

- Dittmer et al. (2011) investigated a group of materials 1–*x* $0.94Bi_{1/2}Na_{1/2}TiO_3$–$0.06BaTiO_3$_–$xK_{0.5}Na_{0.5}NbO_3$ (BNT–BT–*x*KNN) as a potential candidate for high-temperature capacitors with a working temperature far beyond 200 °C. The researchers conclude that the tested compositions present a good starting point for the development of high-temperature capacitor materials.
- Correia et al (2013) demonstrate a very high energy density and high temperature stability capacitor based on $SrTiO_3$ substituted $BiFeO_3$ thin films. The lead-free material is evaluated as a promising candidate for high temperature applications in power electronics up to 200 °C.
- Kumar et al. (2015) report the development of multilayer ceramic capacitors based on relaxor $BaTiO_3$-$Bi(Zn_{1/2}Ti_{1/2})O_3$ (BT-BZT) for high temperature applications, which were evaluated in a temperature range of 50 to 350 °C.
- Sun et al (2017) describe the fabrication of lead-free $BaZr_{0.2}Ti_{0.8}O_3$ epitaxial thin films on Nb doped SrTiO3 substrates, The BZT film capacitors exhibit great thermal stability, high breakdown voltage, and high fatigue endurance. The authors assert that this material exhibits excellent properties compared to other $BaTiO_3$-based energy storage capacitor materials and even Pb-based systems, making it a good candidate in the application of modern
- Yang et al (2017) present (1-x)SrTiO3-xBi0.5(Na0.82K0.18)0.5Ti0.96Zr0.02Sn0.02O3 lead-free ceramics. These results indicate that the (1-x)ST-xBNKTZS ceramics may be promising lead-free materials for high energy storage capacitors.
- Correia et al (2017) investigate a lead-free $BiFeO_3$-$SrTiO_3$ ceramic that exhibits unprecedented low dielectric loss and high thermal stability, while maintaining high energy density and fast discharge rates up to 200 °C. The researchers conclude that these unique properties clearly outperform other state of the art ceramics and potentially create significant new markets for high capacity ceramic capacitors at high frequencies and high temperature operations.
- Jia et al (2018) review various contemporary lead-free dielectrics for ceramic capacitors with upper operating temperatures far beyond 200°C. The authors compare various lead-free perovskite capacitor dielectrics based on BT, BNT, BKT, and KNN and summarise their properties. They discuss the trade-offs between frequency stability, loss factor and resistivity

at high temperature. An outlook on further research needs is provided to overcome prevailing obstacles in their technical applicability and fabrication technologies.

- Cai et al (2019) describe a two-step sintering process for the production of lead-free multilayer capacitors based on lead-free relaxor ferroelectric ceramic $0.87BaTiO_3$-$0.13Bi(Zn_{2/3}(Nb_{0.85}Ta0.15)_{1/3})O_3$ (BT-BZNT). The created dielectric exhibits high energy density of and an ultrahigh efficiency at a temperature range up to 170 °C,
- Li et al (2019) prepare a novel lead-free $0.88BaTiO_3$-$0.12Bi(Li_{1/3}Zr_{2/3})O_3$ (0.12BLZ) relaxor ferroelectric ceramic for dielectric capacitor application. The material shows excellent frequency and temperature stability in different frequencies and temperatures (25–140 °C).
- Wang, Lu et al (2020) demonstrate that lead-free capacitors can be made from (0.7 x)$BiFeO_3$–$0.3BaTiO_3$–$xBi(Li_{0.5}Nb_{0.5})O_3$ (BF–BT–xBLN). The multilayer ceramics show promise for practical use in capacitors for pulsed power systems.
- Wang, Pu et al (2020) describe a method for the fabrication of $Ca_{0.5}Sr_{0.5}Ti_{0.97}Sn_{0.03}O_3$ (SnCST3) ceramics with enhanced energy storage performance. The material is a competitive candidate for the application in lead-free high-power capacitors.

While the research cited above does not suggest that these lead-free dielectric ceramics are immediately suitable for the substitution of lead-containing dielectrics addressed in the current 7(c)-II exemption, it does show that a variety of promising candidate materials and fabrication methods are available.

Against the background of the above examples, it is difficult to understand why no substitution or elimination options could be identified. The present application for exemption fails to substantiate the reasons why the available candidate materials and manufacturing processes have not been taken up for further development to higher technology maturity and commercialisation.

Questions:

1. Please substantiate why none of the numerous candidate materials for lead-free ceramic dielectrics reported in the literature can be used as substitutes for capacitors under exemption 7(c)-II. In doing so, please provide detailed examples of parameter ranges (not just percentages) that illustrate the discrepancy between the technical requirements for capacitors for a rated voltage of 125 V AC or 250 V DC or higher and the properties of the candidate materials reported in the literature.

Answer by UP Exemption #7(c)-II WG Participants:

We are aware that there are several examples of "lead-free" dielectric ceramics in relation to the scope of Exemption 7(c)-II in several papers, including the paper you have given as an example. However, most of these papers report only the results of laboratory-scale basic research, and we are not aware of any published information that indicates that mass production has been achieved.

Few of these papers describe materials in terms of the full electromechanical property matrix, the aging characteristics, electrode compatibility, machinability, and process cost that would enable device engineers seeking to incorporate high voltage capacitors into electrical and electronic devices to judge the suitability of a material to replace lead-containing dielectric ceramics in a given application. In addition, many of these papers have not been sufficiently studied and evaluated for reliability. Considering the fact that device engineers will not utilize lead-free material without practical applicability for the evaluation of their devices, at least for companies involved in Umbrella projects, this is not

yet feasible.

Based on the content of the papers and the knowledge of the participating companies of the Umbrella Project, the following are the items that seem to be insufficient in the papers illustrated in this Clarification Questionnaire compared with the high voltage capacitor using lead-containing dielectric ceramics. To the best of the knowledge of the companies participating in the Umbrella Project, there are examples of research where it is not clear why mass production has not been achieved. However, the Umbrella Project is not aware of the mass-produced products based on these research examples.

1. Dittmer, Robert; Wook Jo; Dragan Damjanovic and Jürgen Rödel (2011). Lead-free high-temperature dielectrics with wide operational range. Journal of Applied Physics 109, https://doi.org/10.1063/1.3544481

   The ceramics in this study contain potassium and sodium in their composition. These alkali metal elements are highly volatile and volatilise during the sintering process, causing a composition shift. This compositional shift causes a variation in the properties of the ceramics. Experience has shown that the volatility of volatile components is unstable and therefore does not allow for a stable mass production of the product.

   In addition, niobium and bismuth, which are included in the composition, have a resource supply problem. For details, please refer to "Supply of Niobium and Bismuth Resources" below.

2. Correia, Tatiana M.: Mark McMillen; Maciej K. Rokosz; Paul M. Weaver; John M. Gregg; Giuseppe Viola; Markys G Cain (2013). A Lead-Free and High-Energy Density Ceramic for Energy Storage Applications, Journal of the American Ceramic Society, Vol. 96, Iss. 9, pp 2699-2702. https://doi.org/10.1111/jace.12508

   Bismuth, which is included in the composition in this study, have a resource supply problem. For details, please refer to "Supply of Niobium and Bismuth Resources" below.

   The thin-film capacitors in this study have a lower dielectric constant than existing lead-containing ceramic capacitors. Therefore, even if mass production becomes feasible, the capacitance may not be sufficient to replace existing lead-containing dielectric ceramics.

   In addition, the capacitor manufacturing process using the PLD method, which is a common film formation method employed in this study, is extremely poor in productivity and would be an obstacle to mass production.

3. Kumar, Nitish; Ionin, Aleksey; Ansell, Troy; Kwon, Seongtae; Hackenberger, Wesley; Cann, David (2015). Multilayer ceramic capacitors based on relaxor BaTiO3-Bi(Zn1/2Ti1/2)O3 for temperature stable and high energy density capacitor applications. Applied Physics Letters, 106(25), 252901–. doi:10.1063/1.4922947
   1. https://aip.scitation.org/doi/abs/10.1063/1.4922947

   The composition of this study, relaxor BaTiO3-Bi (Zn 1/2 Ti 1/2) O3 (BT-BZT), has a high firing temperature for barium titanate. As a result, zinc, which volatilizes at a lower temperature than barium titanate, volatilizes during the firing process, causing a composition shift. This compositional shift causes a variation in the properties of the ceramics. Experience has shown that the volatility of volatile components is unstable and therefore does not allow for a stable mass production of the product.

The composition of ceramics in this study has a lower dielectric constant than existing lead-containing ceramic capacitors. Therefore, even if mass production becomes feasible, the capacitance may not be sufficient to replace existing lead-containing dielectric ceramics.

4. Sun, Zixiong; Ma, Chunrui; Wang, Xi; Liu, Ming; Lu, Lu; Wu, Ming; Lou, Xiaojie; Wang, Hong; Jia, Chun-Lin (2017). *Large Energy Density, Excellent Thermal Stability and High Cycling Endurance of Lead-Free BaZr0.2Ti0.8O3 Film Capacitors. ACS Applied Materials & Interfaces, (), acsami.7b03263–.* doi:10.1021/acsami.7b03263
   2. https://pubmed.ncbi.nlm.nih.gov/28471645/

The thin-film capacitors in this study have a lower dielectric constant than existing lead-containing ceramic capacitors. Therefore, even if mass production becomes feasible, the capacitance may not be sufficient to replace existing lead-containing dielectric ceramics.

In addition, the capacitor manufacturing process using the sputtering method, which is a common film formation method employed in this study, is extremely poor in productivity and would be an obstacle to mass production.

5. Yang, Haibo; Yan, Fei; Lin, Ying; Wang, Tong (2017). Improvement of dielectric and energy storage properties in SrTiO 3 -based lead-free ceramics. Journal of Alloys and Compounds, (), S0925838817330529–. doi:10.1016/j.jallcom.2017.09.022
   3. https://www.sciencedirect.com/science/article/abs/pii/S0925838817330529

The ceramics in this study contain potassium and sodium in their composition. These alkali metal elements are highly volatile and volatilise during the sintering process, causing a composition shift. This compositional shift causes a variation in the properties of the ceramics. Experience has shown that the volatility of volatile components is unstable and therefore does not allow for a stable mass production of the product.

In addition, niobium and bismuth, which are included in the composition, have a resource supply problem. For details, please refer to "Supply of Niobium and Bismuth Resources" below.

6. Correia, Tatiana; Stewart, Mark; Ellmore, Angela; Albertsen, Knuth (2017). Lead-Free Ceramics with High Energy Density and Reduced Losses for High Temperature Applications . Advanced Engineering Materials, (), 1700019–. Doi:10.1002/adem.201700019
   4. https://onlinelibrary.wiley.com/doi/abs/10.1002/adem.201700019

Bismuth, which is included in the composition in this study, have a resource supply problem. For details, please refer to "Supply of Niobium and Bismuth Resources" below.

The composition of this study is in the same series as that of No. 2, and it is known that the dielectric constant tends to be lower than that of lead-containing dielectric ceramics. Therefore, even if mass production becomes feasible, the capacitance may not be sufficient to replace existing lead-containing dielectric ceramics.

7. Jia, Wenxu; Yudong Hou; Mupeng Zheng (2018). Advances in lead-free high-temperature dielectric materials for ceramic capacitor application. IET Nanodielectrics 1(1) DOI: 10.1049/iet-nde.2017.0003
   5. https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/iet-nde.2017.0003

The description in this paper appears to be a review article, and cannot be compared with existing lead-containing high-voltage capacitors as examples of independent studies.

8. Cai, Ziming; Zhu, Chaoqiong; Wang, Hongxian; Zhao, Peiyao; Chen, Lingling; Li, Longtu; Wang, Xiaohui (2019). High-temperature lead-free multilayer ceramic capacitors with ultrahigh energy density and efficiency via two-step sintering. Journal of Materials Chemistry A, 10. 1039. doi:10.1039/C9TA04317A
   6. https://pubs.rsc.org/en/content/articlelanding/2019/ta/c9ta04317a#!divAbstract

   A gradient in the firing temperature, as shown in this study, does not allow for a stable mass production as the firing varies with the heating time due to the heat capacity of the product.

9. Li, Xu; Chen, Xiuli; Sun, Jie; Zhou, Mingxing; Zhou, Huanfu (2019). Novel lead-free ceramic capacitors with high energy density and fast discharge performance. Ceramics International, (), S0272884219329049–. doi:10.1016/j.ceramint.2019.10.055
   7. https://www.sciencedirect.com/science/article/pii/S0272884219329049

   The ceramics in this study contain lithium in their composition. Lithium is a highly volatile element and volatilise during the sintering process, causing a composition shift. This compositional shift causes a variation in the properties of the ceramics. Experience has shown that the volatility of volatile components is unstable and therefore does not allow for a stable mass production of the product.

   In addition, bismuth, which is included in the composition in this study, have a resource supply problem. For details, please refer to "Supply of Niobium and Bismuth Resources" below.

10. Wang, Ge; Lu, Zhilun; Yang, huijing; Ji, hongfen; Mostaed, Ali; li, linhao; wei, yiqi; Feteira, Antonio; Sun, Shikuan; Wang, Dawei; Sinclair, Derek; Reaney, Ian M (2020). Fatigue resistant lead-free multilayer ceramic capacitors with ultrahigh energy density. Journal of Materials Chemistry A, (), 10.1039.D0TA00216J–. doi:10.1039/D0TA00216J
    8. https://pubs.rsc.org/en/content/articlelanding/2020/ta/d0ta00216j#!divAbstract

    The ceramics in this study contain lithium in their composition. Lithium is a highly volatile element and volatilise during the sintering process, causing a composition shift. This compositional shift causes a variation in the properties of the ceramics. Experience has shown that the volatility of volatile components is unstable and therefore does not allow for a stable mass production of the product.

    In addition, niobium and bismuth, which are included in the composition, have a resource supply problem. For details, please refer to "Supply of Niobium and Bismuth Resources" below.

11. Wang, Wen; Pu, Yongping; Guo, Xu; Shi, Ruike; Yang, Mengdie; Li, Jingwei (2020). *Combining high energy efficiency and fast charge-discharge capability in calcium strontium titanate-based linear dielectric ceramic for energy-storage. Ceramics International, (), S0272884220301784–.* doi:10.1016/j.ceramint.2020.01.174
    9. https://www.sciencedirect.com/science/article/pii/S0272884220301784

    The composition of ceramics in this study has a lower dielectric constant than existing lead-containing ceramic capacitors. Therefore, even if mass production becomes feasible, the capacitance may not be sufficient to replace existing lead-containing dielectric ceramics.

The table below lists the disadvantages of the lead-free capacitors proposed in the research cases cited in papers 1 to 11 in comparison with existing high voltage capacitors using lead-containing dielectric ceramics.

Table. Disadvantages of the cited studies

No.	Mass production	Volatilization of constituents during firing process				Process	Supply of Resources		dielectric constant
		Li	K	Na	Zn		Nb	Bi	
1	N/A		X	X			X	X	
2	N/A					X		X	X
3	N/A				X			X	X
4	N/A					X			X
5	N/A		X	X				X	
6	N/A							X	X
7	review paper (trend summary)								
8	N/A					X			
9	N/A	X						X	
10	N/A	X					X	X	
11	N/A								X

X: disadvantages

As a result, we have not been able to find a lead-free high-voltage capacitor that can be practically mass-produced.

Technical requirements of capacitors are defined for (finished) capacitors as such and cannot be directly compared to the properties of the material. As a result, discrepancies and conformities between technical requirements of capacitors and the properties of lead-free alternatives reported in the papers (literature) can only be qualitatively expressed. Consequently, it is not possible, in principle, to describe detailed parameter ranges.

In other words, at a practical industrial level, the information provided for lead-free alternative materials reported in the cited papers is insufficient to explain with our knowledge the range of parameters that are adapted to the technical requirements of capacitors for rated voltages above 125 V AC or 250 V DC.

[Reference]

The Umbrella Project described risks in the supply of niobium and bismuth in its application for exemption 7 (c) -I. The contents are quoted below:

Supply of Niobium and Bismuth Resources

Lead exists abundantly in the outer layers of the earth's crust as sulfide ores such as galena, etc. Considering that a recycle system centered on lead batteries for automobiles has already been established, the risk of resource depletion is relatively low, and it is possible to procure lead at low cost. In addition, as there is no uneven distribution of resource ores by geographical areas, the risk of supply of resources being disrupted due to political instability in certain countries is low.

In comparison, niobium and bismuth can be mentioned as examples of potential substitute elements for lead-free electronic ceramics. However, when compared to lead, risks concerning supplies of resources are higher.

The production amount of niobium resources has a strongly uneven distribution with 90% in Brazil and 9% in Canada, so it is classified as a critical raw material by the EU[2].

[2] https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

Since bismuth is obtained as a by-product in the production mainly of lead from ores, substitution to bismuth-type materials does not lead to a reduction in the extraction amounts of lead. Moreover, differently from lead there is no established recycling system, so producing bismuth in amounts just enough for production of E&E components will rather increase the amount of lead extraction and smelting[3].

Also, similarly to niobium, bismuth resources are unevenly distributed between China (75% of the world's reserves), Mexico, Bolivia and Peru, and so it is classified as a critical raw material by the EU[4]. In the event that the supply of niobium or bismuth is stopped or restricted, it is expected to have a significant impact to the EU industry.

As shown in the cases above, when E&E components using lead-free electronic ceramics are compared with those using lead-containing electronic ceramics, energy and resource consumption during the product lifecycle is large, and the risk of depletion is also significant. From this perspective, elimination of lead from E&E components incorporated in EEE is not appropriate as it rather increases environmental load than decreases it.

2. Please explain in detail what operating conditions of EEE are required from capacitors in the scope of 7(c)-II to withstand a breakdown voltage of 10kV (AC) / 20 kV (DC) and why in the design of circuits it would not be possible to use protective aids (e.g. a fuse) to protect lead-free capacitors with lower breakdown voltage.

Answer by UP Exemption #7(c)-II WG Participants:

As explained in the application, these capacitors are used in a wide variety of electrical and electronic equipment and systems. The operating conditions of capacitors covered by Exemption 7(c)-II depend mainly on the use conditions and requirements of the equipment and systems they are used.

Per definition in the International Standard related to fixed capacitors (IEC 60384-1) the rated voltage is either the

- **maximum DC voltage which may be applied continuously to a capacitor at the rated temperature;**
- **maximum RMS alternating voltage which may be applied continuously to a capacitor at the rated temperature and at a given frequency.**

Concerning the requirements to the voltages these capacitors must withstand, it is important to differentiate between the

- **operating voltage, which is applied continuously to the capacitor during its normal operation – this voltage shall below the rated voltage of the capacitor and**
- **pulses of current or voltage occurring during operation – the peak pulse voltage shall as well be below the rated voltage, if repeated frequently, and**
- **peak impulse voltage – single high voltage or high current pulses, which must not**

[3] http://mric.jogmec.go.jp/public/report/2012-05/34.Bi_20120619.pdf

[4] https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

damage the capacitor, but shall not occur continuously, and

- **breakdown voltage – the voltage where typically a dielectric breakdown occurs, and the capacitor gets destroyed.**

We could not identify the source of the statement in your question, the capacitors have "to withstand a breakdown voltage of 10kV (AC) / 20 kV (DC)". Such information was neither contained in our application, nor in the (public) inputs provided in the stakeholder consultation.

As explained above, the breakdown voltage is a voltage range in which a capacitor typically is destroyed. That means, the breakdown voltage must be well above the peak voltages, which can occur during operation. The needed safety margin depends on the type of ceramic material, the design of the capacitor and the safety requirements from the application, e.g. if the breakdown of the capacitor would cause electrical shock hazard or fire.

Those safety requirements to capacitors are provided in the components & equipment safety standards, for example,

- **EN 60384-14, Fixed capacitors for use in electronic equipment - Part 14: Sectional specification - Fixed capacitors for electromagnetic interference suppression and connection to the supply mains,**
- **EN 62368-1, Audio/video, information and communication technology equipment - Part 1: Safety requirements**

To answer the question:

Capacitors in the scope of 7(c)-II must withstand the voltages occurring during normal operation, specified overvoltages (pulses) and in addition to provide a safety margin as required by the individual application. In so far, a specific capacitor used in a specific application cannot be replaced by capacitor with less performance (e.g. lower dielectric strength), because it has to operate safely under the specified conditions, i.e. rated voltage and peak pulse voltages. Using a device with protective function would not change the situation, because it is the primary function of the capacitor to damp or cut those pulses. Other protective devices, like surge protectors and varistors are added anyway to electric and electronic equipment in case excessive overvoltages exceeding the specified peak voltages, like lightening strikes or switching high power engines and so on, can occur.

The specified rated voltage, peak pulse voltage, etc. are given in the component specifications. They depend on the material and design of the capacitors. The operating conditions in applications shall be within this range, including an appropriate safety margin to ensure safe and reliable operation of the equipment. It is impossible to "protect" a lower performance part in order to fulfil the same requirements.

3. In particular, please provide examples of type specifications for ceramic capacitors falling under 7(c)-II, at least for those components containing significant amounts of lead (e.g. large-sized capacitors).

Answer by UP Exemption #7(c)-II WG Participants:

See attached a number of specifications for ceramic capacitors falling under the scope of exemption #7(c)-II. This is not a representative selection, it shows some of the types produced in highest quantities. Besides that, a high number of special and customized specifications may exist, which cannot be compiled by UP members.

4. Please provide a roadmap on how and in what timeframe the industry intends to proceed, based on lead-free substitution candidates presented in literature, with the development and market introduction of lead-free substitutes for ceramic capacitors under the scope of the current exemption 7(c)-II.

Answer by UP Exemption #7(c)-II WG Participants:

As quoted in our renewal request:
“At present, there are no prospects concerning the technical scope of exemption 7(c)-II for a comprehensive substitution to “lead-free” ceramic at least until the end of the next validity period.”
Since the situation remains unchanged as of today, we cannot provide roadmaps depicting actual year milestones as that would be a mere conjecture without sound scientific basis.
As a reference, we show below a representative roadmap including the hypothetical achievement of substitute materials as a starting point.
Please notice the required periods until commercialization will vary from product to product.

Representative Roadmap for Substitution of Lead in Dielectric Ceramics of High-Voltage Capacitors

High voltage capacitors have to fulfil the safety requirements related to the EEE where they are incorporated even in case of fault condition, e.g., short circuit or overheating. Thus, high temperature performance is essential for electrical safety of the EEE, otherwise unreliable designs and early failures will occur in the market, e.g., for new compact power electronics designs and for existing legacy electronic products and spare part products for the repair of existing EEE. As currently available alternatives cannot guarantee these high performance requirements, they are not suitable for new compact power electronics nor as a (plug and play) alternative component for existing legacy products and spare part designs.
High Voltage Capacitors are still needed for many years to come.

In case parts of your contribution are confidential, please provide your contribution in two versions (public /confidential). Please also note, however, that requested exemptions cannot be granted based on confidential information!

References:

Dittmer, Robert; Wook Jo; Dragan Damjanovic and Jürgen Rödel (2011). Lead-free high-temperature dielectrics with wide operational range. Journal of Applied Physics 109, https://doi.org/10.1063/1.3544481

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Wang, Wen; Pu, Yongping; Guo, Xu; Shi, Ruike; Yang, Mengdie; Li, Jingwei (2020). *Combining high energy efficiency and fast charge-discharge capability in calcium strontium titanate-based linear dielectric ceramic for energy-storage. Ceramics International, (), S0272884220301784–.* doi:10.1016/j.ceramint.2020.01.174