

RESEARCH ARTICLE OPEN ACCESS

Screening of Ceramic Filler Materials for a Packed-Bed Thermal Energy Storage System With Lead as Heat Transfer Fluid

Annette Heinzel¹  | Anisa Purwitasari¹  | Renate Fetzner¹  | Alfons Weisenburger¹ | Klarissa Niedermeier² 

¹Institute for Pulsed Power and Microwave Technology (IHM), Karlsruhe Institute of Technology (KIT), Eggenstein-Leopoldshafen, Germany | ²Institute for Thermal Energy Technology and Safety (ITES), Karlsruhe Institute of Technology (KIT), Eggenstein-Leopoldshafen, Germany

Correspondence: Annette Heinzel (annette.heinzel@kit.edu)

Received: 27 March 2026 | **Revised:** 19 August 2026 | **Accepted:** 16 September 2026

Keywords: ceramic | corrosion | liquid metal | material science | packed bed | thermal energy storage

ABSTRACT

Liquid lead (Pb) is an attractive heat transfer fluid (HTF) for packed-bed thermal energy storage (TES) systems aimed for high temperatures. However, liquid Pb is corrosive and its corrosivity increases with rising temperature. Therefore, compatibility tests of possible filler materials with Pb are mandatory. This study tested the corrosion and thermal alteration of seven ceramic materials (two alumina materials, one alumina zirconia composite material, two zirconia ceramics stabilized with either yttria or ceria, and two zirconium silicates in different compositions) in liquid Pb at 650°C and 750°C in a reducing environment for up to 5000 h. The results showed that the tested zirconium silicates are not suitable due to the high glass content and the ceria stabilized ZrO₂ revealed a poor thermal shock resistance. In contrast, the yttria stabilized ZrO₂ and the alumina zirconia composite showed a very good compatibility with a negligible reaction with Pb.

1 | Introduction

High-temperature thermal energy storage (TES) can be used in a wide application range. One field of application is the use of excess heat in industrial processes, resulting in cost savings and a reduction of CO₂ emissions by increasing energy efficiency [1]. When using fluctuating renewable energies like, for example, in concentrating solar power (CSP) plants, TES systems enable a 24/7 electricity generation. Most commercial CSP systems use two-tank molten salt storage systems [2, 3]. The so-called solar salt, consisting of the eutectic mixture of 60 wt.% sodium nitrate (NaNO₃) and 40 wt.% potassium nitrate (KNO₃), serves as both the storage medium and the heat transfer fluid (HTF). A drawback of solar salt is its limited operating temperature in the range between 290°C and 565°C because of the decomposition of the salt at higher temperatures with the formation of toxic nitrous gases (NO_x) [4–6]. Recent studies show that a higher

concentration of NO_x gas above the liquid salt can stabilize the solar salt, which may allow the use up to 645°C. This method requires that the salt and gas phase composition are carefully monitored and controlled [7–9].

Next-generation CSP plants are foreseen to operate at temperatures above 700°C to improve the solar-to-electricity efficiency and to reduce the levelized cost of energy [10–12]. Regarding the use of industrial excess heat, even higher temperatures of 1000°C should be achieved [13, 14]. For these higher temperatures, liquid metals are possible HTFs due to their chemical stability over a wide temperature range and their excellent heat transfer properties [1, 15–18]. Lead, the liquid metal proposed here, has a melting point of 327°C and a boiling point of 1743°C. This allows operation temperatures between 400°C and 1000°C. Liquid metal HTFs are foreseen to be combined with suitable filler materials of high storage capacity to form a thermocline

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2026 The Author(s). *Energy Storage* published by John Wiley & Sons Ltd.

packed-bed TES system. The low-cost and high-temperature stable filler material stores the available sensible heat, while at the same time helping to maintain the required temperature gradient of the single-tank thermocline system. This results in reduced storage costs [19].

A challenge when using liquid metals as HTFs is their corrosiveness, which increases with temperature. Liquid metals have a high solubility for the alloying elements of structural materials, leading to leaching of these alloying elements from the structural materials and penetration of liquid metal into the weakened materials [1]. These corrosion processes are accompanied by a loss of mechanical properties and may result in material failure. Further corrosion phenomena include the formation of intermetallic compounds between liquid metal and alloying elements or the interaction with liquid metal impurities. Here, oxygen plays a crucial role, as it may oxidize steel alloying elements and form protective oxide scales when available in sufficient concentrations in the liquid metal. In systems with liquid metal flow, erosion of solid components might be a further issue to be considered [20–22]. The corrosion of structural materials, in particular steels, in liquid Pb and lead bismuth eutectic (LBE) has been extensively investigated in the temperature range around 550°C [1, 23–26], and further research for higher temperature is on-going [27–29]. However, little research has been carried out on the behavior of possible filler materials in contact with liquid metals.

Beside a good material compatibility with the liquid metal, potential filler materials have to fulfill additional criteria. The most important are the thermophysical properties; they should have a high volumetric heat capacity, but a relatively low thermal conductivity (depending on the size of the material), high thermal fatigue, and a high thermal shock resistance. Additionally, the price of the material should be low to target maximum investment costs for the overall storage system of 15€/kWh as proposed by the Strategic Research Agenda 2020–2025 of the European Solar Thermal Electricity Association [30]. In this study, we focus on ceramic bead materials, as they have the advantages of having a homogeneous chemical composition, being commercially available, and being phase stable at the chosen temperature, which is often not the case for the cheaper natural material and slag [31]. Phase changes often cause volume changes, which can lead to cracks and crumbling under thermal cycling. Additionally, during long-term operation with cyclic thermal charging and discharging, thermal ratcheting is often expected, caused by a mismatch in thermal expansion coefficients between the storage tank and the solid material [32]. During charging, the filler material and the tank expand, which leads to a rearrangement of the filler material. If the tank expansion is higher than that of the filler material, empty spaces occur, which lead to a downward movement of the filler material driven by the weight of the overlaying particles. During discharging, the now compact filler material layer impedes the tank from going back to its initial size. This leads to mechanical stresses between particles and between the tank and the particles. Typical for natural material and slags are sharp edges, which might cause problems during filling, reduce the bulk density, and increase the risk of the ratcheting effect. According to Garitaonandia [32], higher mechanical stresses occur between the first and the seventh year of operation when using a

nonuniform steel slag. By choosing a smooth, bead-shaped filler material for packed-bed with liquid metal, no thermal ratcheting is expected since the ceramic is floating because it is less dense than the HTF (here: liquid Pb) and no interlocking occurs. Additionally, spheres are chosen with a narrow size distribution, so that for the application in a packed-bed TES, the porosity distribution is also very predictable.

A previous paper [33] describes the investigation of suitable filler materials for thermocline packed-bed TES systems using LBE as the HTF. These investigations were carried out for a lab-scale experiment [34]. As filler material, two glasses (diamond pearls and borosilicate glass) and four ceramics (aluminum oxide (90%), magnesium silicate ceramic (steatite), yttria stabilized zirconium oxide, zirconium silicate ceramic) were chosen and exposed in LBE at 500°C up to 4 weeks under reducing conditions, that is, with dissolved oxygen concentrations too low to form an oxide scale. Both glasses revealed corrosion attack and chipping of the surface. Therefore, the glasses were not included in the current study. For the ceramics, it was also shown that any glass phase present has a negative impact on the corrosion resistance. Although the 90% alumina material showed a very low corrosion attack, further investigations were recommended to determine its corrosion resistance. Zirconium silicate and zirconium oxide exhibited a high corrosion resistance.

In contrast to the previous study, the current paper describes results for candidate filler materials exposed in liquid Pb instead of LBE. Using Pb instead of LBE reduces the HTF's investment costs and reduces the corrosivity due to the fact that Bi is more aggressive than Pb. As before, the exposure tests were performed under reducing conditions. Furthermore, the exposure temperature was increased from 500°C to 650°C and 750°C, which corresponds more closely to the desired temperatures for a future packed bed energy storage system, and the exposure duration was raised to 1000, 2000, and 5000 h. As the temperature rises, the solubility of the elements in the liquid metal also increases, making it more corrosive, even though Pb is the only element being used at present. For this reason, some of the materials tested before [33] had to be tested again under the new conditions. Based on the former results, only ceramic beads were tested. The screening tests are a first step toward finding a suitable filler material for the use of Pb for high temperature application. Thermal cycling tests are the next step, which will be the scope of future studies.

2 | Materials and Methods

2.1 | Materials

The selection of filler material depends on various criteria. Based on previous theoretical investigations and numerical simulations [15, 19], the material needs to be low cost, have a high volumetric heat capacity, relatively low thermal conductivity, high thermal fatigue resistance, and a high thermal shock resistance. In the case of Pb as HTF, the filler material should also be resistant against liquid metal corrosion, especially at temperatures above 600°C. Regarding the previous tests [33], ceramics are a promising option. Therefore, seven ceramics were chosen, which can be divided into four groups.

The first group contains alumina (Al_2O_3) with two different purities (90% and 92%). Secondly, an alumina zirconia composite based ceramic named Minerax is investigated. The third group consists of zirconia (ZrO_2), stabilized with either yttrium oxide or cerium oxide ($\text{Y}_2\text{O}_3\text{-ZrO}_2/\text{ZirmilCe}$), and the last group is based on zirconium silicate in different compositions named Rimax and ER120. All of the materials with exception of the zirconium silicate ER120 have a spherical shape with a narrow size distribution, which allows a prediction of the porosity distribution in the packed bed for simulations. To determine the size, 10 beads per sample were measured. The material, size, and supplier of the beads are listed in Table 1. All ceramic beads are industrially used for milling.

2.2 | COST Estimation

This cost estimation of the storage material (lead and filler) is an initial estimate. If the price for the filler material or the lead changes, this has a significant impact due to the large volume of these materials. Equation (1), which was already described in [31], was used for a cost estimation of the material C_{TES} costs per kWh^{-1} in €:

$$C_{\text{TES}} = 3.6 \cdot 10^6 \cdot \frac{\rho_l \cdot \varepsilon \cdot C_l + \rho_s \cdot (1 - \varepsilon) \cdot C_s}{(\rho_l \cdot c_{p,l} \cdot \varepsilon + \rho_s \cdot c_{p,s} \cdot (1 - \varepsilon)) \cdot \Delta T} \quad (1)$$

C_s as material cost in €/kg, ε the porosity, ρ the density in kg/m^3 and c_p the specific heat capacity in J/(kg K) , while the subscripts l and s denote liquid and solid respectively. ΔT is the temperature gradient of the loop, in this case 300 (max. temperature 700°C , the middle between the tested temperature 650°C and 750°C). The data relevant for the calculation and the results are given in Table 2. The specific heat capacity and the density for the materials alumina 90%, $\text{Y}_2\text{O}_3\text{-ZrO}_2$ and Rimax were measured and published in [33]. For the calculation, it is assumed that the specific heat capacity of alumina 92% is similar to that of alumina 90%. A similar approach was taken with ER120 and Rimax. In the case of ZirmilCe, the molar heat capacity of $\text{Ce}_{0.124}\text{Zr}_{0.876}\text{O}_2$ was obtained from literature [36]. Minerax is a zirconia toughened alumina (ZTA), so the specific heat capacity was taken from a supplier of ZTA ceramics [35]. Where density measurements were missing, the supplier details were used instead. The prices for the beads are indicated figures from the supplies for July 2026. Concerning Pb, at 700° the specific heat capacity is 146 J/(kg K) and the density 10545 kg/m^3 [1]. The material cost of the heavy liquid metal is assumed to be 2 €/kg , since the monthly average value has consistently been around 2 € in recent years [37]. A porosity value of 0.26 (26%) was chosen for the packed bed, which is the minimum value of a monodisperse bed.

The significant price difference (€/kg) between the aluminum oxides is reflected in the costs per kWh (€/kWh). A similar pattern is observed with the two stabilized zirconia materials; here,

TABLE 1 | Bead material, size, and supplier.

Materials	Content (wt.%)	Bead diameter (mm)	Supplier
Alumina 90%	90% Al_2O_3 , 4.5% SiO_2 , 5% alkaline metal oxides	2.4–3.5	Mühlmeier GmbH & Co. KG
Alumina 92%	92% Al_2O_3 , 2.5% SiO_2 , 2.5% MgO , 2% CaO , 1% others	3.0–3.24	Final Advanced Materials
Minerax	66% Al_2O_3 , 18% ZrO_2 , 16% others	2.4–2.7	Saint-Gobain ZirPro
$\text{Y}_2\text{O}_3\text{-ZrO}_2$	95% ZrO_2 , 5% Y_2O_3	3.1–3.2	Final Advanced Materials
ZirmilCe	82% ZrO_2 , 16% CeO_2 , 2% others	2.65–2.8	Saint-Gobain ZirPro
Rimax	58% ZrO_2 , 37% SiO_2 , 5% others	2.67–2.87	Saint-Gobain ZirPro
ER120	66% ZrO_2 , 29% SiO_2 , 5% others	1.8–2.6 (round beads) 5.4–8.8 (elongated)	Saint-Gobain ZirPro

TABLE 2 | Specific heat capacity, density, and costs of the tested materials together with their estimated cost estimation of the storage material.

Materials	Specific heat capacity, J/(kg K)	Density, (kg/m^3)	Material cost, (€/kg)	Cost, (€/kWh)
Alumina 90%	$855_{T=50^\circ\text{C}}\text{--}1226_{T=1000^\circ\text{C}}$ [33]	2545 [33]	7	77.1
Alumina 92%	1109	3700	49 (Ø3 mm)	419.9
Minerax	720 [35]	3800	3	59.02
$\text{Y}_2\text{O}_3\text{-ZrO}_2$	$469_{T=50^\circ\text{C}}\text{--}651_{T=1000^\circ\text{C}}$ [33]	6020 [33]	153 (Ø3 mm)	2320.79
ZirmilCe	441 [36]	6200	20	412.57
Rimax	$626_{T=50^\circ\text{C}}\text{--}792_{T=1000^\circ\text{C}}$ [33]	4235 [33]	12	163.02
ER120	740	3800	20	255.92

a substantial price reduction can be achieved through material selection. However, the prices are generally much higher than those of the previously tested slags.

2.3 | Corrosion Test and Test Condition

For the corrosion tests the COSTA (CORrosion test stand for STagnant liquid Alloys) facility [38] was used, see Figure 1. It consists of tubular, three zone furnaces with two half-closed quartz tubes as reaction chambers. The three independently controllable heating zones guarantee a large isothermal ($\pm 5^\circ\text{C}$) area allowing up to nine samples to be tested simultaneously per quartz tube. The open ends of the quartz tubes are sealed by lids containing feedthroughs for the cover gas (in this study 100 mL/min of an Ar-5% H_2 mixture was used with an Ar and H_2 purity of 6.0). A moisture and an oxygen sensor were placed at the gas outlet to control the cover gas. Inside the COSTA facility, each sample to be tested is placed in one liquid metal filled alumina crucible located on a crucible carrier. For loading and unloading of the samples, a glovebox previously purged with Ar-5% H_2 is connected gas-tight to the quartz tube. For the tests presented here, each crucible was filled with 160–170 g of Pb (99.99% delivered by Feinhütte Halsbrücke GmbH) and with around 10–15 ceramic beads of one type. To avoid floating of the beads, they were pressed down with tantalum strips, which were additionally weighted with molybdenum rod sections.

For the experiments, two furnaces were used; one heated to 650°C , the other to 750°C . One quartz tube of each furnace was operated for 1000 and 2000 h; the other for 5000 h exposure. This

ensures that there is no disruption caused by taking out samples. After cooling down to room temperature, the beads were taken out of the glovebox. A photo of the beads after 1000 h exposure at 650°C is depicted in Figure 2.

2.4 | Analysis

Surfaces and cross sections of three beads each were examined before (as-delivered) and after exposure. For the cross-section analysis, the samples were prepared using standard metallographic techniques. For the post exposure examination of the surfaces, the beads were cleaned from the adherent Pb residual for 30 min with a 1:1:1 solution of ethanol, hydrogen peroxide (30%), and acetic acid (96%).

Surface and cross-section of the beads were investigated using the scanning electron microscope (SEM) Zeiss LEO 1530 VP with a Schottky-field emission gun and an integrated energy-dispersive X-ray analysis system (EDS).

3 | Results

3.1 | Alumina 90% and 92%

3.1.1 | As-Delivered

Cross section photos of Al_2O_3 90% and 92% are depicted in Figure 3. There is a difference in grain size, with the grain size of Al_2O_3 90% (Figure 3a) being smaller than that of Al_2O_3 92%

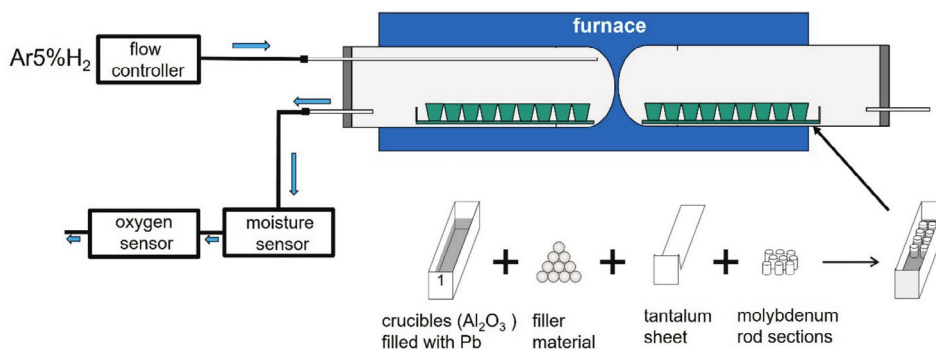


FIGURE 1 | Scheme of COSTA test facility with the procedure of filling the crucibles with the test material.

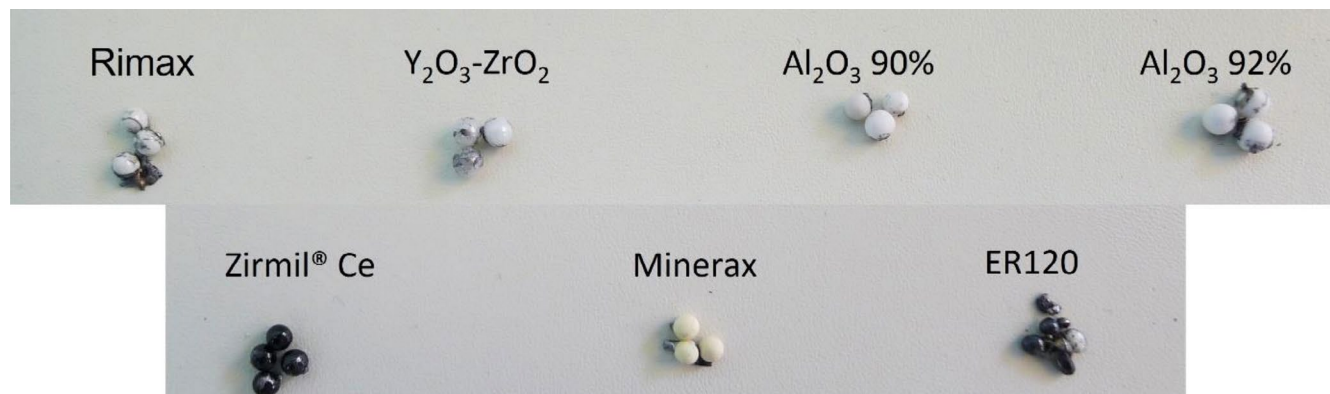


FIGURE 2 | Photo of beads after 1000 h exposure to Pb at 650°C .

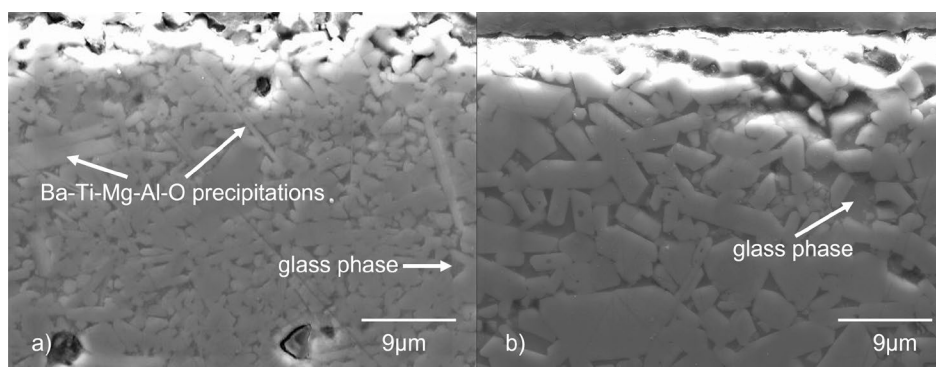


FIGURE 3 | SEM (SE) cross section photos of the Al_2O_3 samples: (a) Al_2O_3 90% (b) Al_2O_3 92%.

TABLE 3 | Chemical composition in wt.% of Al_2O_3 90% and 92% measured by EDS.

	O	Al	Na	Mg	Si	Ca	Ti	Ba
Al_2O_3 90%	50	44.8	—	1.2	1.8	1.9	0.1	0.2
Al_2O_3 92%	50.5	45.5	0.2	0.8	2.3	0.8	—	—

(Figure 3b). The chemical composition of the samples measured by EDS is depicted in Table 3. Based on the cross-section images, the surfaces of both Al_2O_3 90% and 92% beads appear rather rough. Some pores are visible within the beads, with a higher number of pores found in the alumina 90% bead.

The alumina beads contain the typical impurities like silicon, calcium, magnesium, and sodium oxides, the latter not being detectable by EDS in Al_2O_3 90%. These oxide impurities melt during the sintering process, forming a glassy matrix along the Al_2O_3 grain boundaries which is known as inter-granular glassy phase [39]. This phase is visible as a dark gray area in both SEM photos. This glass phase matrix contains Si, Ca, Mg, and in the case of Al_2O_3 92%, small amounts of Na. The main difference between the two ceramics is that Al_2O_3 90% additionally contains Ti and Ba. Ti and Ba, together with Al, Mg, O, and small amounts of the other components, form platelet-shaped crystals appearing as needles in the cross sections.

3.1.2 | Al_2O_3 90% After Pb Exposure

After the exposure to 650°C and 750°C, all Al_2O_3 90% specimens show a slight reaction in some regions on the surface (see bright area in Figure 4a). Figure 4b presents a cross section SEM image of such a region along with the corresponding EDS elemental mapping, highlighting liquid Pb penetration between the outermost Al_2O_3 grains, where the glass phase containing Si, Ca, and Mg is located. Neither the Ba and Ti enriched platelet-shaped oxide nor the Al_2O_3 grains show any corrosion attack. The maximum Pb penetration depth along the glass phase is approximately 4 μm after 1000 h at 750°C and 2–3 μm after 1000 h at 650°C, and even after the extended exposure period of 5000 h no increase in corrosion depth is measurable. Anyway, a systematic time or temperature dependence of the liquid metal attack could not be observed. In

some spots Pb filled surface defects can be observed, similar to how it is shown in Figure 5b for Al_2O_3 92%.

3.1.3 | Al_2O_3 92% After Pb Exposure

The 92% sample exhibits the same corrosion mechanism as the 90% beads: Pb penetrates between the Al_2O_3 grains and along the glass phase rich in Si, Ca, Mg, and Na. A corrosion depth of 3–5 μm is observed after 1000 h at 750°C (Figure 5a). Similar to the Al_2O_3 90%, no time or temperature dependence of the penetration depth could be determined for alumina 92%. In several spots where surface defects such as grooves are visible, liquid lead has penetrated these defects, reaching much higher depth up to around 10 μm (Figure 5b).

3.2 | Minerax: Alumina Zirconia Ceramic Composite

3.2.1 | As-Delivered

Minerax consists mainly of three basic oxides based on a combination of alumina (Al_2O_3), zirconia (ZrO_2), and silica (SiO_2). It is used for the high energy milling of mineral ores due to its high wear resistance. The delivered ceramic has a lot of pores, a high surface roughness, and some defects like cracks close to the surface, see Figure 6a. The chemical composition of the beads as measured by EDS is depicted in Table 4.

A ZrO_2 and a zirconia silicate phase (cf. Figure 6b bright phases) are distributed in the Al_2O_3 matrix. Both contain Y_2O_3 according to the EDS. Their grains are not homogeneously distributed; they can also be locally enriched. The Al_2O_3 matrix consists, in addition to Al and O, of the typical alumina impurities Mg, Na, and Ca. Ca shows an inhomogeneous distribution, while there are no local enrichments of Na or Mg detectable.

3.2.2 | Minerax After Pb Exposure

After extraction, large areas of the sample surface are covered with Pb, most probably due to the high surface roughness. However, after cleaning the beads from adherent Pb, isolated areas are visible where Pb has reacted with the sample surface,

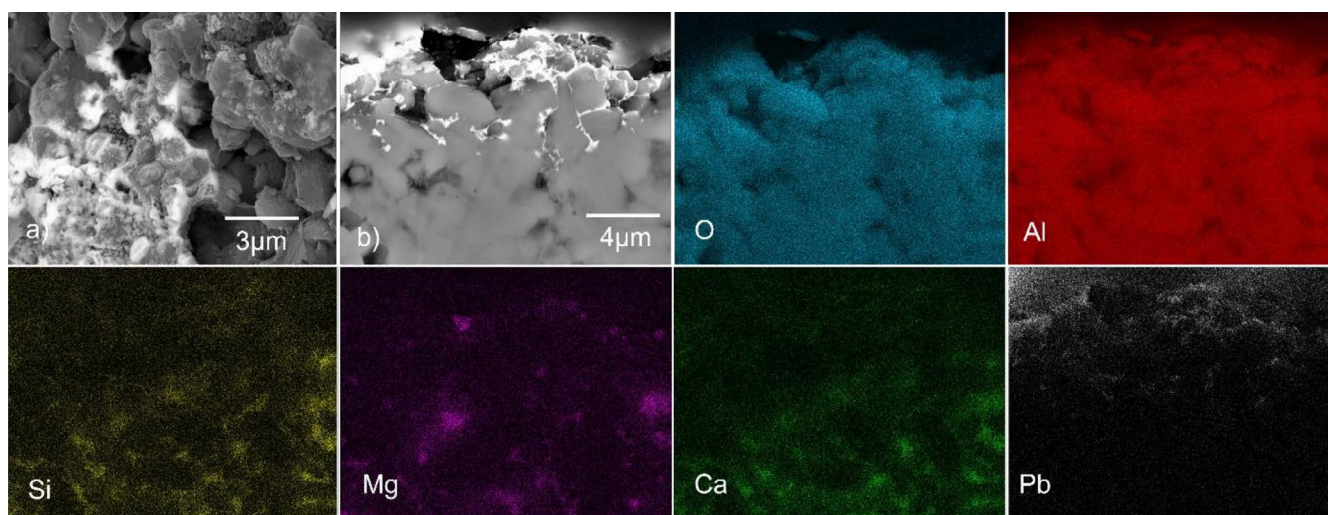


FIGURE 4 | Al_2O_3 90% after 1000h exposure to Pb at 750°C. (a) surface reaction with Pb, (b) penetrated Pb close to the surfaces including corresponding EDS elemental mapping photos.

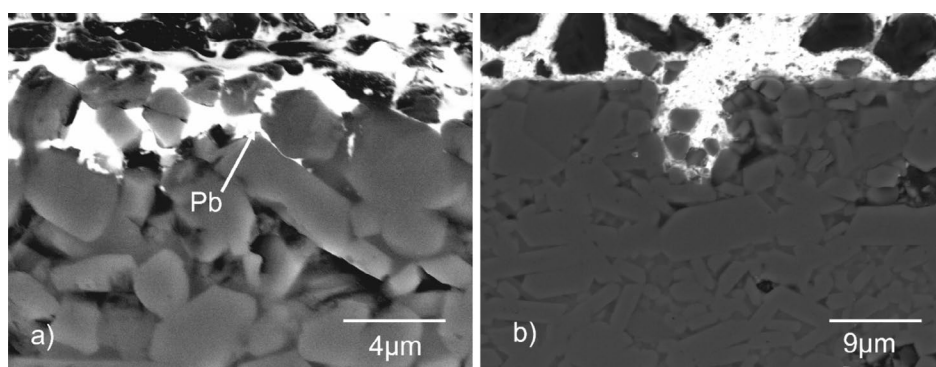


FIGURE 5 | Al_2O_3 92% after 1000h exposure to Pb (a) at 750°C showing penetration of Pb along the Al_2O_3 grains into the material. (b) at 650°C showing local Pb penetration at a surface defect. The black large particles in the lead above the samples are SiO_2 from grinding.

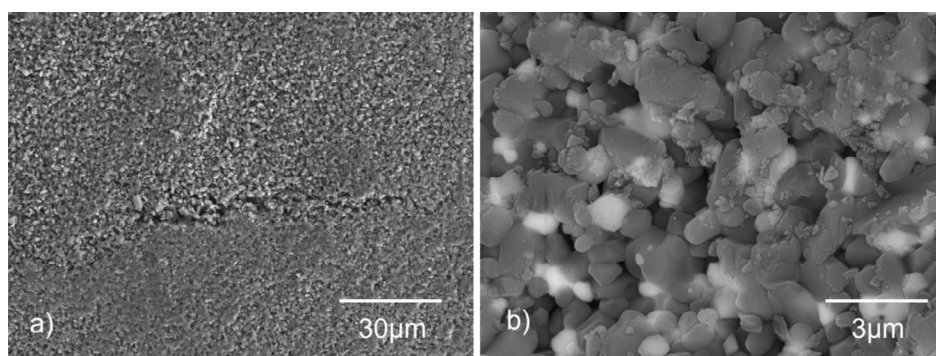


FIGURE 6 | Surface SEM (BSE) images of as-delivered Minerax at different magnifications.

TABLE 4 | Chemical composition in wt.% of the alumina zirconia composite Minerax.

O	Al	Zr	Na	Mg	Si	Ca	Y
50.1	44.8	8.4	0.1	0.20	3.4	0.4	1.1

but it is not possible to measure by EDS what the Pb has reacted with. Figure 7 shows the typical appearance at 650°C. Penetration of Pb is only locally visible close to the surface in the first 1–2 μm along grain boundaries and in pores and surface defects like gaps/

cracks that were already observed on the original samples; see Figure 8a.

Additionally, isolated areas with larger breakaways without Pb inclusions like in Figure 8b can be observed at some beads. Most probably this breakage occurred after Pb exposure during cooling to room temperature and was caused by a defect in the material. The black spots within the adherent Pb are silica particles from the abrasive paper, which were incorporated into the rather soft Pb during cross-section preparation.

A similar corrosion behavior like the one at 650°C is observed at 750°C. Pb has penetrated into the materials only close to the surface (Figure 8c) and in places where cracks and pores exist.

3.3 | ZrO₂ Stabilized With Y₂O₃ or CeO₂

3.3.1 | As-Delivered

Both yttria (Y₂O₃-ZrO₂) and ceria (Zirmil Ce) stabilized zirconia beads are high density milling media. The chemical composition of the materials is depicted in Table 5. Both materials exhibit elevations and small depressions at the surface, which have the same chemical composition as the base material. Additionally, small black spots are visible, which are Al₂O₃ precipitations, see Figure 9. They can be found in the whole material. In contrast to the more or less round Al₂O₃ precipitations of Y₂O₃-ZrO₂ (Figure 9c), Zirmil Ce shows elongated

Al-oxides (Figure 9d). Zirmil Ce exhibits defects at the surface (Figure 9b,d).

3.3.2 | Y₂O₃-ZrO₂ After Pb Exposure

After exposure, the white shiny surface of the Y₂O₃-ZrO₂ beads is slightly gray. Investigations on uncleaned bead surfaces show the formation of a Pb-Zr-O compound (62–65 at.% O, 21–26 at.% Zr, 5–10 at.% Pb with impurities of Y, Al, and Si-possibly PbZrO₃ [40]) attached to the surface. This is shown exemplarily in Figure 10a for a bead exposed for 5000 h to Pb at 750°C. A clear confirmation of the formation of PbZrO₃ phase would have required an XRD analysis; however, this was not feasible because of the curvature of pebble surface. After cleaning the beads from adherent Pb, the Zr-Pb-O compounds cannot be found anymore, but small Sn particles were detectable at the surface, which are attributed to an impurity of the Pb. Chemical analysis

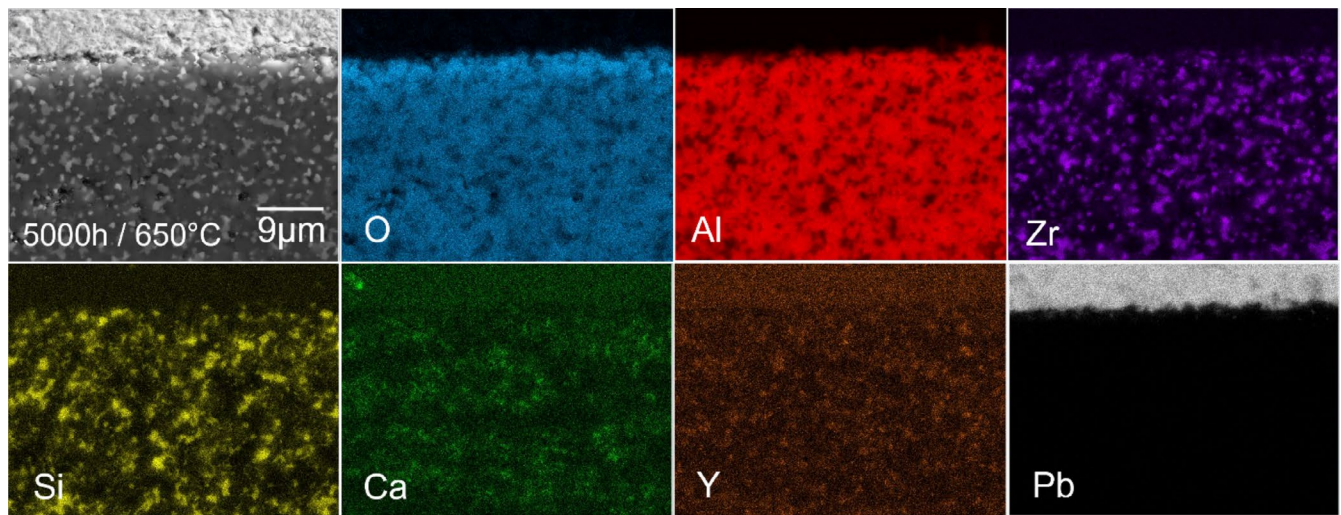


FIGURE 7 | SEM photo of Minerax bead after 5000 h exposure in Pb at 650°C with corresponding element mapping.

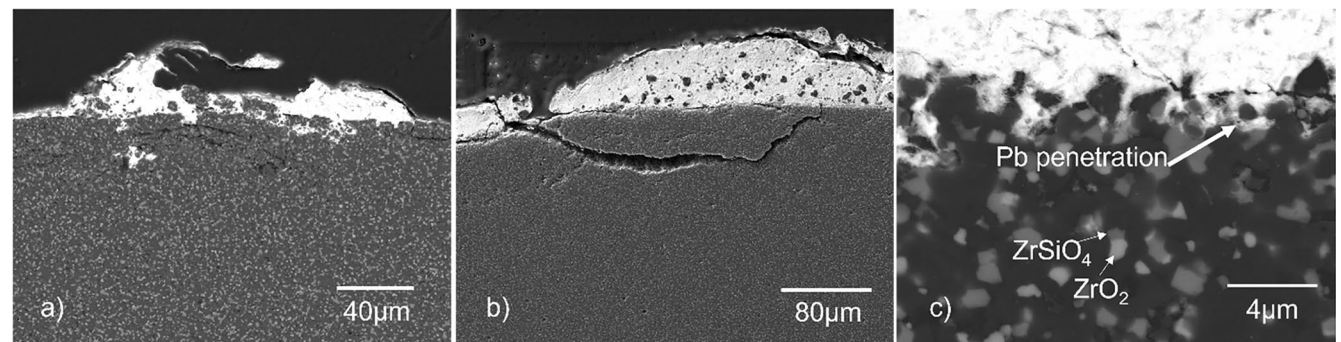


FIGURE 8 | Minerax: (a) after 2000 h exposure in Pb at 650°C showing a Pb filled defect at the surface. (b) after 1000 h of exposure in Pb at 650°C showing a larger breakage at the surface. (c) After 2000 h of exposure in Pb at 750°C exhibiting Pb penetration in the surface region.

TABLE 5 | Chemical composition in wt.% of yttria and ceria stabilized zirconia beads measured by EDS.

	O	Zr	Al	Na	Si	Y	Ce	Mg	Ca
ZrO ₂ -Y ₂ O ₃	29.9	60	1.3	1.3	1.3	6.3	—	—	—
ZrO ₂ -CeO ₂	30.4	52.1	0.5	0.3	0.3	0.77	15.3	0.2	0.2

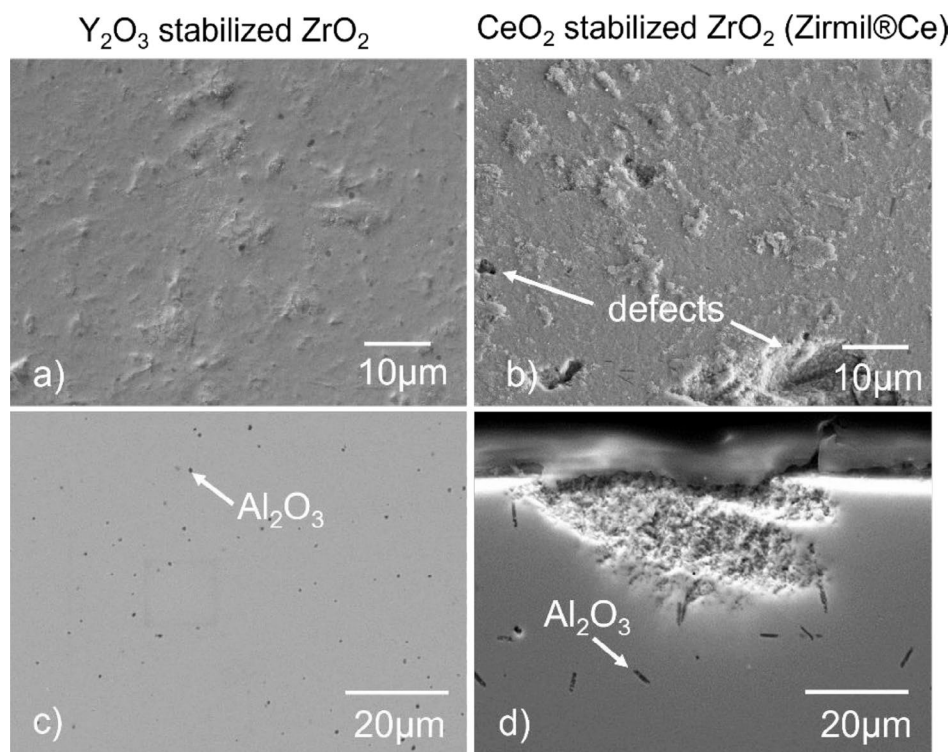


FIGURE 9 | Surface (a, b) and cross-section (c, d) SEM photos of the ZrO_2 samples stabilized with Y_2O_3 (a, c) and with CeO_2 (b, d).

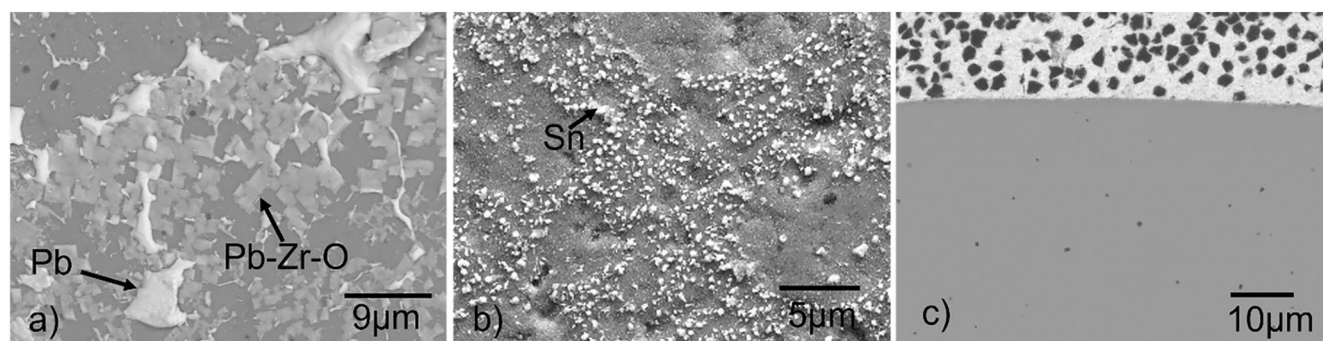


FIGURE 10 | SEM photos of yttria stabilized ZrO_2 beads after 5000 h exposure to 750°C in Pb: (a) uncleaned surface of a bead with Zr-Pb-O compounds, (b) surface after cleaning of adhering Pb showing Sn particles, (c) cross section.

(SPARK-OES) confirmed the presence of very low amounts of Sn (< 0.0001 wt.%) in the as-delivered Pb. However, no influence of the Sn impurity on the corrosion was observed. Based on the distribution of the Sn particles on the samples surface where almost Sn-free circles form, cf. Figure 10b, it can be assumed that the surface was not completely wetted by the Pb. Despite remnants of Pb in the surface depressions of the wetted areas, no corrosion attack is detectable on the surface or in the cross sections of the samples exposed to 650°C and 750°C, respectively, see Figure 10c.

3.3.3 | Zirmil Ce After Pb Exposure

The behavior of the Ce oxide stabilized ZrO_2 (Zirmil Ce) is quite different. After exposure, the beads exhibit a lot of cracks running deep into the material, see Figure 11a, for example. This occurs at both temperatures and for all exposure times. It is concluded that the material is not thermal shock resistant. Pb can

penetrate into larger cracks. Additionally, the liquid metal reacts with Zirmil Ce at the surface and forms very small plate-like crystals (wetted area in Figure 11b). The determination of their chemical composition by SEM/EDS is not clearly attainable. Figure 11b shows a wetted and an unwetted surface. The wetted area is presented by the plate-like crystals, whereas at the border (brighter “line”) Ca and Na are enriched together with Pb. Therefore, it can be assumed that the plate-like crystals result from a reaction of Ca and Na with Pb.

3.4 | Zirconium-Silicate: Rimax and ER120

3.4.1 | As-Delivered

In the Rimax and ER120 beads, the yttria stabilized zirconia phase (bright phase) is embedded in a glassy silica phase (dark gray phase), see Figure 12. While the surface of the Rimax beads (Figure 12a,b) shows a lot of surface defects (small cracks,

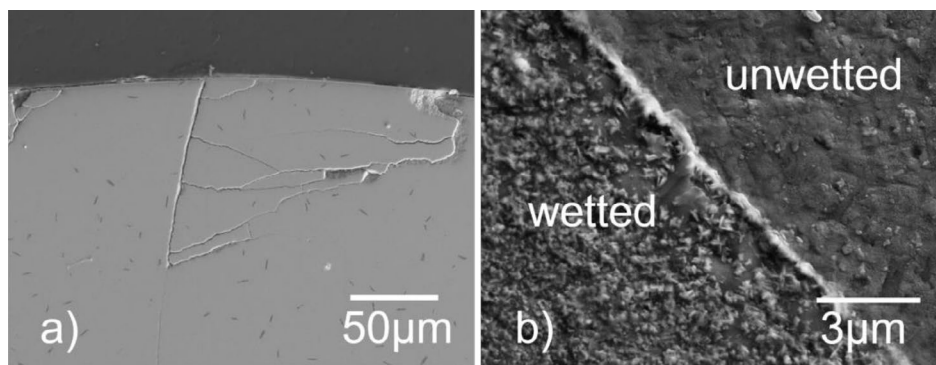


FIGURE 11 | SEM photos of ceria stabilized ZrO_2 beads: (a) cross section of a bead after 2000 h exposure in Pb at 650°C and (b) surface of a bead after 5000 h exposure in Pb at 750°C with a wetted and unwetted area.

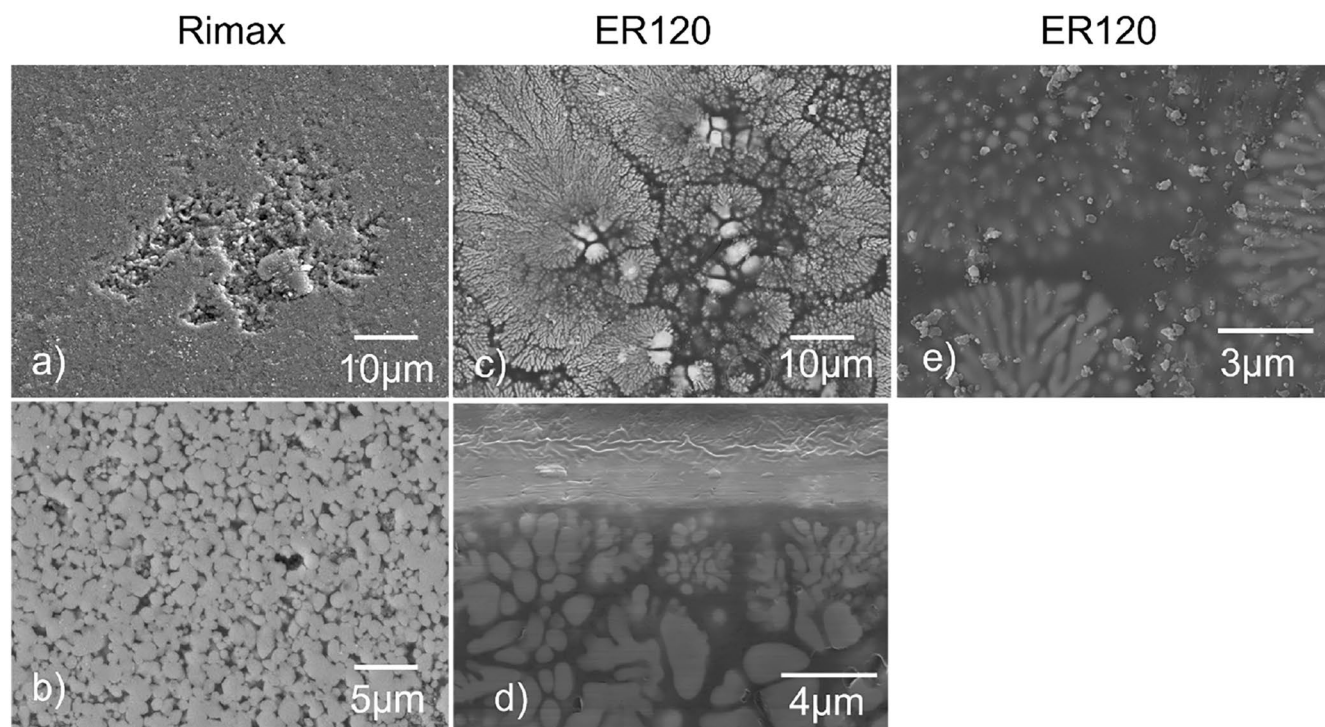


FIGURE 12 | Surface (a, c, e) and cross section (b, d) of Rimax (a, b) and ER120 (c, d, e) as delivered.

indentations...), the ER120 beads (Figure 12c,d) are surrounded by a glass shell, which consists mainly of Si and O with a minor content of Zr (2.5–5.5 at.%) and Al (0–1.9 at.%) according to EDS point measurements. Table 6 contains the average chemical composition data in wt.% measured on the cross section of a bead.

3.4.2 | Rimax After Pb Exposure

After the exposure, the Rimax beads exhibit a significant corrosion attack on the glass phase, see Figure 13. Liquid metal enters between the zirconia grains where the glass phase is located (Figure 13a). This causes a loss of their cohesion, which can lead to detachment of individual grains or grain aggregations. In areas with homogeneous Pb penetration, a slight temperature-dependent corrosion attack is measurable. The corrosion depth is around 2 µm after 5000 h exposure at 650°C, while at 750°C it is around 4–5 µm after 1000 h of exposure. But these homogeneous attacks are rarely observed; more often the

penetration of Pb takes place via cracks or other defects on the surface, which leads to corrosion of the glass phase in deeper areas, Figure 13b,c.

3.4.3 | ER120 After Pb Exposure

The susceptibility of glass to Pb is clearly evident in the ER120 balls. Pb is incorporated into the outer layer of glass, which leads to embrittlement, cracking, and chipping. As an example, a bead that was exposed at 750°C for 5000 h is depicted in Figure 14a,b. Figure 14a shows the cracking of the glass shell and Figure 14b shows the chipping, thereby exposing the underlying zirconia phase. EDS point measurements on the glass shell reveal 0.3–2.8 at.% Pb, 0.8–2.3 at.% Zr, and 0.9–1.6 at.% Al beside the main constituents Si and O. Pb is not only incorporated into the outer glass shell, it also penetrates into the glass matrix; see the element mappings in Figure 14d–g. It is visible that the zirconia is not affected by this attack. The penetration

of the lead is accelerated by the breaking and chipping of the outer glass layer. The deepest attack was found after the longest exposure time of 5000 h; for 650°C it was 12 μm and for 750°C 20 μm . However, a systematic dependence on temperature cannot be found because the penetration depth depends on defects in the outer glass shell. For example, after 1000 h the deepest attack with 6 μm was found on a bead exposed to 650°C, while the deepest attack on a 750°C exposed bead was 3 μm .

4 | Summary and Discussion

Seven ceramics were tested in oxygen depleted Pb at temperatures of 650°C and 750°C for up to 5000 h. It was found that neither a temperature nor a time dependence could be detected in the attack of the liquid metals on the ceramic beads at these two temperatures due to the nonuniform attack, with the exception

of the Rimax beads. The results clearly showed that, when it comes to ceramics, liquid metal attack is not the only factor to consider, as thermal shock resistance is also crucial [41–43]. Table 7 summarizes the results.

The further to the left the ceramics are positioned in the table, the better they performed. Furthermore, the materials were grouped in three categories: + indicates good performance, samples marked with 0 showed minor defects, and – indicates poor performance. The latter are not suitable as heat storage material with Pb as HTF. Zirmil Ce is one of the ceramics that performed worst. The main reason is its poor thermal shock resistance. The cracks after exposure run deep into the material. The slight reaction of the impurities like Ca and Na with the liquid Pb is negligible. The other two materials with poor performance, Rimax and ER120, belong to the group of zirconium silicate (ZrSiO_4) ceramics. These ceramics have excellent thermal shock resistance [44], however, they also have a high amount of a glass silica phase.

TABLE 6 | Chemical composition in wt.% of zirconium-silicate beads measured by EDS.

	O	Zr	Si	Na	Mg	Al	Ca	Fe	Y
Rimax	43	35.2	17.4	0.4	0.6	2.0	0.4	0.1	0.9
ER120	46.4	35.5	16.2	—	—	0.89	—	—	1

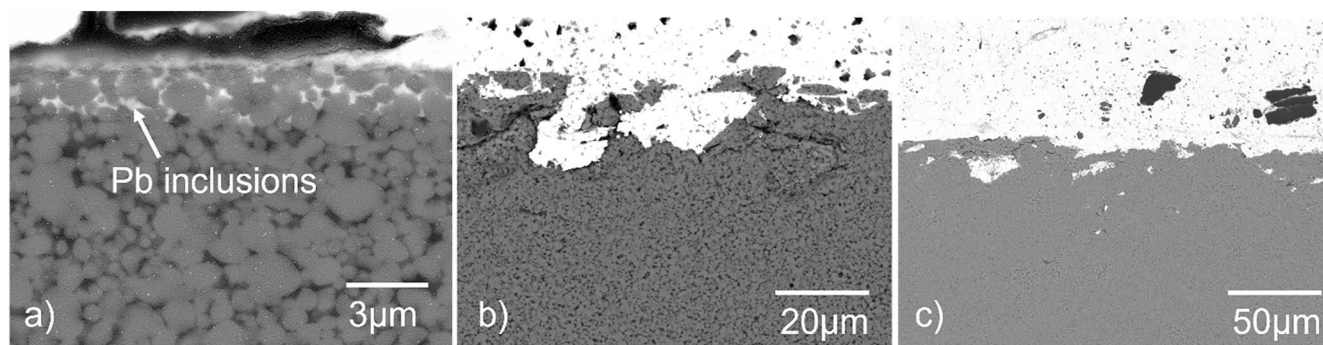


FIGURE 13 | Cross section of Rimax beads (a) after 5000 h at 650°C showing Pb inclusions in the glass phase; (b) and (c) presents Pb penetration in cracks after 2000 h (b) and 5000 h (c) at 750°C.

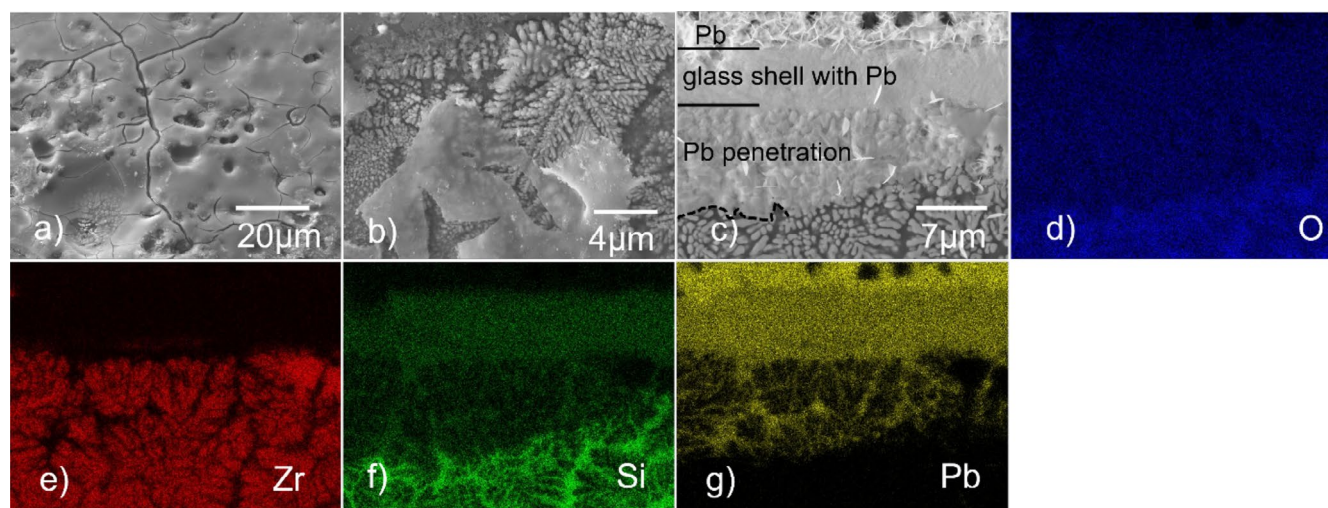


FIGURE 14 | ER120 after 5000 h exposure at 750°C. (a, b) Surface of a bead with cracks and spallation of the outer glass shell, (c) cross section showing severe corrosion attack with penetration of Pb, and (d–g) associated SEM mapping of the element distribution.

The previous study [33] performed in liquid LBE at 500°C highlighted the inferior behavior of glass beads in those conditions. The ceramic beads with glassy binder phase or outer shell, ER120 and Rimax, exhibited cracking and chipping of the surface most likely due to the solution of Na, Mg, Ca, and Al out of the glass network mainly by Pb. Especially the behavior of the outer glass shell of ER120 is comparable with the behavior of the tested borosilicate glass in [33]. It shows the same severe cracking. Additionally, Pb is incorporated in the shell and in the outer glass matrix. It is known that a glass structure is ideally suited as a sorbent for heavy metals like Pb. Glasses containing lead have a wide field of application, like crystal classes, optical glasses with high refractive index, classes absorbing ionizing radiation, and glasses for low temperature welding of metals [45]. At low contents (below 40 mol% of PbO), Pb²⁺ can act like Ca²⁺ and Na²⁺ as a network modifier. The breaking of the Si–O–Si linkages partially disrupts the glass network, and Pb²⁺ occupy the cavity sites [46–48]. This change in the glass network has an influence on the properties of the glass. Beside the density and the lowering in glass transition temperature, there is also a significant increase in the thermal expansion coefficient [49]. This causes higher internal stresses during rapid thermal cycling, which can cause cracking. Furthermore, it can be assumed that there is a volume increase due to the larger Pb in the glass, which also increases the internal stress. This seems to be the reason for the cracks and chipping.

Interestingly, the Rimax beads from the same batch showed a good behavior in LBE at 500°C for 168 and 672 h and in a TES operated between 180°C and 380°C, with 37 thermal cycles within a year [33]. Here, only a slight reaction with the glass phase was observed. At this lower temperature the reaction of the glass phase seems to be slower. As the temperatures increase, the penetration depth of Pb into the material also increases, as our results show: 650°C for 5000 h around 2 µm, 750°C for 1000 h around 4–5 µm. This makes the Rimax sample the only ceramic for which a clear temperature dependency has been demonstrated.

The alumina samples showed a much better performance compared to Zirmil Ce und zirconium silicate ceramics. But even here, Pb penetrated slightly into the vitreous phase formed during sintering. The Al₂O₃ itself showed no attack. Similar behavior was reported in Ref. [33]. However, the shock resistance should be further investigated through thermal cycling experiments to prevent the beads from crumbling during operation in a packed-bed TES system. A similar slight reaction with Pb was observed for the alumina zirconia composite-based ceramic (Minerax). Most probably, Pb reacts with a Si-containing phase.

The best behavior is presented by the yttria stabilized zirconia Y₂O₃-ZrO₂. Only a slight reaction with Zr was found at the surface of the Y₂O₃-ZrO₂. It seems that it forms a ternary compound with the liquid Pb at high temperatures, most probably PbZrO₃,

TABLE 7 | Summary of the results: + good behavior, 0 defects, – poor behavior (cracks and/or Pb infiltrated).

	Al ₂ O ₃ 90%/ Al ₂ O ₃ 92%/ Y ₂ O ₃ -ZrO ₂	Minerax	Rimax	Zirmil Ce	ER 120
+	0	–	–	–	–

as deduced from EDS. However, this reaction is negligible. To conclude, the material is suitable for high-temperature TES (up to 750°C) with Pb as HTF. Nevertheless, thermal cycling experiments are recommended.

Estimation of the material costs (filler and HTF) showed prices ranging from €59 kWh^{−1} to €2320 kWh^{−1}. The order of increasing price is as follows: Minerax < Al₂O₃ 90% < Rimax < ER120 < Zirmil Ce < Al₂O₃ 92% < Y₂O₃-ZrO₂. Using Minerax and Al₂O₃ 90% as the filler material results in the cheapest kWh price, at €59 and €77, respectively. The advantage is that both materials also exhibited good corrosion behavior in the corrosion tests. However, the supplier's price for Al₂O₃ 92% was significantly higher than that for Al₂O₃ 90%, resulting in a kWh price of €420, which is similar to the price of €413 when Zirmil Ce is used as the filler material. This clearly shows how important it is to compare similar materials, and the effect this can have on costs. Y₂O₃-ZrO₂, the yttria-stabilized zirconia, performed best in the corrosion test but was also the most expensive at 2320 €/kWh. However, the estimated costs are still far from the maximum target investment cost of 15 €/kWh for the overall storage system [30]. Nevertheless, using a more expensive filler material could be advantageous if it is more stable and has a longer service life without blocking the Pb flow.

5 | Conclusion

Seven ceramics were tested as possible filler material for high-temperature packed-bed TES with Pb as HTF and a cost estimation of the material costs (filler and HTF) was done. The tests were performed for up to 5000 h at 650°C and 750°C in liquid Pb. The ceramics used were alumina materials with different purities (90% and 92%), one alumina zirconia composite named Minerax, two zirconia ceramics stabilized with either yttria or ceria (Y₂O₃-ZrO₂/ ZirmilCe), and two zirconium silicates with different compositions (Rimax and ER120). Tests the following conclusions can be drawn from the exposure tests.

The tested Y₂O₃-ZrO₂ shows only negligible reaction with the liquid metal and is a promising filler material. However, this tested material does have a high selling price, which results in a high kWh price (2320,79 €/kWh). A slightly inferior performance is observed for both alumina samples and the zirconia toughened Al₂O₃ (Minerax). Compared to the Y₂O₃-ZrO₂ tested here, the low purchase price makes Minerax and Al₂O₃ 90% very attractive. Zirconium silicates and the tested Ce oxide stabilized ZrO₂ are not suitable for application in Pb.

A temperature dependence of the liquid metal attack could be demonstrated only for the Rimax beads. As was already shown in an earlier study, it appears that the glass content (vitreous phase) is a very important factor in corrosion behavior because Pb easily penetrates into the Si-O phase, influencing its thermal shock behavior and most likely inducing internal stress.

Thermal shock resistance is an important factor for all ceramics. Therefore, all materials proven to be suitable should also be tested under thermal cycling conditions.

Regarding material costs, these range from 59 to 2320 €/kWh (Minerax < Al₂O₃ 90% < Rimax < ER120 < Zirmil Ce < Al₂O₃

92% < $\text{Y}_2\text{O}_3\text{-ZrO}_2$). These are high costs; however, the purchase price fluctuates depending on commodity markets, supplier negotiations, order volumes, production energy costs, and so on. Similarly, a more expensive filling material can offer advantages if it is more stable and has a longer service life.

Acknowledgments

The authors would like to thank the company Saint-Gobain ZirPro for providing the samples Minerax, ZirmilCe, Rimax, and ER120. Open Access funding enabled and organized by Projekt DEAL.

Funding

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. OECD/NEA, *Handbook on Lead-Bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-Hydraulics and Technologies—2015 Edition* (Nuclear Energy Agency (NEA), 2015), Zugegriffen: 2. Februar 2026. Verfügbar unter: https://www.oecd-neo.org/jcms/pl_14972/handbook-on-lead-bismuth-eutectic-alloy-and-lead-properties-materials-compatibility-thermal-hydraulics-and-technologies-2015-edition?details=true.
2. J. D. Osorio, M. Mehos, L. Imponenti, et al., "Failure Analysis for Molten Salt Thermal Energy Storage Tanks for In-Service CSP Plants, 2024," NREL/TP-5700-89036, 2331241, MainId:89815, März, <https://doi.org/10.2172/2331241>.
3. S. Torras, C. D. Pérez-Segarra, I. Rodríguez, J. Rigola, and A. Oliva, "Parametric Study of Two-Tank TES Systems for CSP Plants," *Energy Procedia* 69 (2015): 1049–1058, <https://doi.org/10.1016/j.egypro.2015.03.206>.
4. F. Klasing and T. Bauer, "Impact of Elevated Wall Temperatures on Nitrate Salt Stability in Thermal Energy Storage," *Energies* 18, no. 23 (2025): 6308, <https://doi.org/10.3390/en18236308>.
5. J. Steinbrecher, A. Bonk, V. A. Sötz, and T. Bauer, "Investigation of Regeneration Mechanisms of Aged Solar Salt," *Materials* 14, no. 19 (2021): 5664, <https://doi.org/10.3390/ma14195664>.
6. A. Bonk and T. Bauer, "Solar Salt—Thermal Property Analysis".
7. A. Bonk, M. Braun, V. A. Sötz, and T. Bauer, "Solar Salt—Pushing an Old Material for Energy Storage to a New Limit," *Applied Energy* 262 (2020): 114535, <https://doi.org/10.1016/j.apenergy.2020.114535>.
8. J. Steinbrecher, A. Hanke, M. Braun, T. Bauer, and A. Bonk, "Stabilization of Solar Salt at 650 °C – Thermodynamics and Practical Implications for Thermal Energy Storage Systems," *Solar Energy Materials and Solar Cells* 258 (2023): 112411, <https://doi.org/10.1016/j.solmat.2023.112411>.
9. J. Steinbrecher, M. Braun, T. Bauer, S. Kunkel, and A. Bonk, "Solar Salt Above 600°C: Impact of Experimental Design on Thermodynamic Stability Results," *Energies* 16, no. 14 (2023): 5241, <https://doi.org/10.3390/en16145241>.
10. K. Niedermeier, M. Lux, A. Purwitasari, et al., "Design of the LIME-LIGHT Test Rig for Component Testing for High-Temperature Thermal Energy Storage With Liquid Metals," *Processes* 11, no. 10 (2023): 2975, <https://doi.org/10.3390/pr1102975>.
11. C. Augustine, D. Kesseli, and C. Turchi, "Technoeconomic Cost Analysis of NREL Concentrating Solar Power Gen3 Liquid Pathway, 2022," gehalten auf der SOLARPACES 2020: 26th International Conference on Concentrating Solar Power and Chemical Energy Systems, Freiburg, Germany, S. 030001, <https://doi.org/10.1063/5.0085836>.
12. M. Imran Khan, F. Asfand, and S. G. Al-Ghamdi, "Progress in Technology Advancements for Next Generation Concentrated Solar Power Using Solid Particle Receivers," *Sustainable Energy Technologies and Assessments* 54 (2022): 102813, <https://doi.org/10.1016/j.seta.2022.102813>.
13. M. N. S. Jagirdar, S. S. Bhogilla, A. Mawire, and H. Niyas, "Recent Advancements in CSP: Evaluating High-Temperature Heat Transfer Fluids, Corrosion Prevention, and Alloy Selection for Enhanced Energy Density," *Solar Compass* 14 (2025): 100118, <https://doi.org/10.1016/j.sol-com.2025.100118>.
14. I. Wolde, J. M. Cardemil, and R. Escobar, "Compatibility Assessment of Thermal Energy Storage Integration Into Industrial Heat Supply and Recovery Systems," *Journal of Cleaner Production* 440 (2024): 140932, <https://doi.org/10.1016/j.jclepro.2024.140932>.
15. K. Niedermeier, "A Perspective on High-Temperature Heat Storage Using Liquid Metal as Heat Transfer Fluid," *Energy Storage* 5, no. 8 (2023): e530, <https://doi.org/10.1002/est2.530>.
16. N. Lorenzin and A. Abánades, "A Review on the Application of Liquid Metals as Heat Transfer Fluid in Concentrated Solar Power Technologies," *International Journal of Hydrogen Energy* 41, no. 17 (2016): 6990–6995, <https://doi.org/10.1016/j.ijhydene.2016.01.030>.
17. G. Alva, Y. Lin, and G. Fang, "An Overview of Thermal Energy Storage Systems," *Energy* 144 (2018): 341–378, <https://doi.org/10.1016/j.energy.2017.12.037>.
18. V. Sobolev, "Thermophysical Properties of Lead and Lead–Bismuth Eutectic," *Journal of Nuclear Materials* 362, no. 2–3 (2007): 235–247, <https://doi.org/10.1016/j.jnucmat.2007.01.144>.
19. K. Niedermeier, F. Müller-Trefzger, and L. Marocco, "Parametric Study of Filler Size and Properties for a Liquid-Metal Thermal Energy Storage," *Applied Thermal Engineering* 212 (2022): 118568, <https://doi.org/10.1016/j.applthermaleng.2022.118568>.
20. A. Weisenburger, A. Heinzel, G. Müller, H. Muscher, and A. Rusanov, "T91 Cladding Tubes With and Without Modified FeCrAlY Coatings Exposed in LBE at Different Flow, Stress and Temperature Conditions," *Journal of Nuclear Materials* 376, no. 3 (2008): 274–281, <https://doi.org/10.1016/j.jnucmat.2008.02.026>.
21. F. Balbaud-Celerier, P. Deloffre, A. Terlain, and A. Rusanov, "Corrosion of Metallic Materials in Flowing Liquid Lead-Bismuth," *Journal de Physique IV, Proceedings* 12, no. 8 (2002): 177–190, <https://doi.org/10.1051/jp4:20020332>.
22. C. L. Griffith, J. Macdonald, C. L. Baxter, J. T. Prabhakar, S. Middleburgh, and W. Villanueva, "Experimental Investigation of Erosion and Corrosion of Aluminized and Non-Aluminized Steels Under High-Velocity Lead Flow," *Nuclear Technology* 212, no. 6 (2026): 1540–1552, <https://doi.org/10.1080/00295450.2025.2583896>.
23. W. Wang, C. Yang, Y. You, and H. Yin, "A Review of Corrosion Behavior of Structural Steel in Liquid Lead–Bismuth Eutectic," *Crystals* 13, no. 6 (2023): 968, <https://doi.org/10.3390/cryst13060968>.
24. E. L. Maia, A. Tsybanov, S. Gavrilov, V. Tsisar, J. Lim, and I. De Graeve, "Oxygen-Enhanced Dissolution Corrosion of Austenitic Stainless Steel 316 L in Static Lead-Bismuth Eutectic at 500°C," *Corrosion Science* 236 (2024): 112224, <https://doi.org/10.1016/j.corsci.2024.112224>.
25. C. Schroer, Z. Voß, O. Wedemeyer, J. Novotny, and J. Konys, "Oxidation of Steel T91 in Flowing Lead–Bismuth Eutectic (LBE) at 550°C,"

- Journal of Nuclear Materials* 356, no. 1–3 (2006): 189–197, <https://doi.org/10.1016/j.jnucmat.2006.05.009>.
26. G. Benamati, C. Fazio, H. Piankova, and A. Rusanov, “Temperature Effect on the Corrosion Mechanism of Austenitic and Martensitic Steels in Lead–Bismuth,” *Journal of Nuclear Materials* 301, no. 1 (2002): 23–27, [https://doi.org/10.1016/S0022-3115\(01\)00723-1](https://doi.org/10.1016/S0022-3115(01)00723-1).
 27. A. Purwitasari, C. Oskay, A. Heinzl, R. Fetzer, A. Weisenburger, and G. Müller, “Corrosion of Austenitic Stainless Steels in Liquid pb With 2E-7Wt% Oxygen at 600 and 700°C,” *Corrosion Science* 244 (2025): 112651, <https://doi.org/10.1016/j.corsci.2024.112651>.
 28. P. Dörmstedt, M. Lundberg, and P. Szakálos, “Corrosion Studies of a Low Alloyed Fe–10Cr–4Al Steel Exposed in Liquid pb at Very High Temperatures,” *Journal of Nuclear Materials* 531 (2020): 152022, <https://doi.org/10.1016/j.jnucmat.2020.152022>.
 29. V. Tsisar, Z. Zhou, O. Wedemeyer, A. Skrypnik, J. Konys, and C. Schroer, “High-Temperature Corrosion Behavior of Fe-18Ni-12Cr-2.9Al and Fe-18Ni-12Cr-2.3Al-Nb-C Austenitic Steels Depending on Dissolved Oxygen Concentration in Static Liquid Pb at 700°C,” *High Temperature Corrosion of Materials* 101, no. 3 (2024): 589–602, <https://doi.org/10.1007/s11085-024-10233-2>.
 30. “2012_ESTELA-Strategic Research Agenda 2020–2025_Jan2013_WEB.pdf,” Zugriffen: 26. Februar 2026. [Online]. Verfügbar unter: https://www.estelasolar.org/Docs/2012_ESTELA-Strategic%20Research%20Agenda%202020-2025_Jan2013_WEB.pdf.
 31. M. Zehnder, A. Purwitasari, A. Heinzl, and K. Niedermeier, “Study on Corrosion and Thermal Alteration of Low-Cost Storage Materials for Use in High-Temperature Thermal Energy Storage Systems With Lead as the Heat Transfer Fluid,” *Energy Storage* 7, no. 8 (2025): e70305, <https://doi.org/10.1002/est2.70305>.
 32. E. Garitaonandia, P. Arribalzaga, I. Miguel, and D. Bielsa, “Characterization of the Ratcheting Effect on the Filler Material of a Steel Slag-Based Thermal Energy Storage,” *Energies* 17, no. 7 (2024): 1515, <https://doi.org/10.3390/en17071515>.
 33. F. Müller-Trefzer, A. Heinzl, R. Hesse, A. Weisenburger, T. Wetzel, and K. Niedermeier, “Screening of Filler Material for a Packed-Bed Thermocline Energy Storage Test Facility With Lead–Bismuth Eutectic as the Heat Transfer Fluid,” *Energy Technology* 12, no. 2 (2024): 2300781, <https://doi.org/10.1002/ente.202300781>.
 34. F. Müller-Trefzer, K. Niedermeier, M. Daubner, and T. Wetzel, “Experimental Investigations on the Design of a Dual-Media Thermal Energy Storage With Liquid Metal,” *Applied Thermal Engineering* 213 (2022): 118619, <https://doi.org/10.1016/j.applthermaleng.2022.118619>.
 35. Great Ceramic, “Introduction to Zirconia Toughened Alumina (ZTA) Ceramic,” Verfügbar unter: <https://great-ceramic.com/zirconia-toughened-alumina/>.
 36. T. Tojo, H. Kawaji, T. Atake, T. Mori, and H. Yamamura, “Low Temperature Heat Capacity and Thermodynamic Functions of Ceria-Stabilized Zirconia $\text{Ce}_{0.124}\text{Zr}_{0.876}\text{O}_2$,” *Journal of Chemical & Engineering Data* 48, no. 6 (2003): 1479–1482, <https://doi.org/10.1021/jc034052q>.
 37. westmetal, “Blei Preis,” Zugriffen: 10. Juli 2026. Verfügbar unter: https://www.westmetall.com/de/markdaten.php?action=averages&field=LME_Pb_cash.
 38. G. Mueller, “Study on Pb/Bi Corrosion of Structural and Fuel Cladding Materials for Nuclear Applications, Part 1: Corrosion Investigation of Steels After 800 and 2000h Exposure to Stagnant Liquid Pb/Bi at Elevated Temperatures,” *JNC-TY9400-2002-016*, Juni 2002, Zugriffen: 15. Juli 2026. [Online]. Verfügbar unter: <https://jopss.jaea.go.jp/pdfdata/JNC-TY9400-2002-016.pdf>.
 39. M. Wang, “Effects of Crystallization of Inter-Granular Glassy Phase on the Mechanical Performance of Alumina Ceramics,” *Ceramics International* 49, no. 23 (2023): 39617–39626, <https://doi.org/10.1016/j.ceramint.2023.09.315>.
 40. M. Cancarevic, M. Zinkevich, F. Aldinger, and M. Materials Science International Team, *Phase Diagram of the PbO–ZrO₂ System: Datasheet From MSI Eureka in SpringerMaterials* (MSI, Materials Science International Services GmbH, 2019), Verfügbar unter: https://materials.springer.com/msi/phase-diagram/docs/sm_msi_r_10_011410_01_full_LnkDia2.
 41. Q. Meng, K. Zhang, R. He, and Z. Qu, “A Review of Thermal Shock Behavior of Ceramics: Fundamental Theory, Experimental Methods, and Outlooks,” *International Journal of Applied Ceramic Technology* 21, no. 6 (2024): 3789–3811, <https://doi.org/10.1111/ijac.14846>.
 42. K. Li, D. Wang, H. Chen, and L. Guo, “Normalized Evaluation of Thermal Shock Resistance for Ceramic Materials,” *Journal of Advanced Ceramics* 3, no. 3 (2014): 250–258, <https://doi.org/10.1007/s40145-014-0118-9>.
 43. S. Zeng, D. Zhu, X. Zhang, and J. Liang, “Enhanced Thermal Shock Resistance of Zirconia Ceramics With Multi-Component Rare Earth and Tourmaline Addition,” *Ceramics International* 49, no. 11 (2023): 18689–18698, <https://doi.org/10.1016/j.ceramint.2023.02.246>.
 44. S. Huang, Q. Li, Z. Wang, X. Cheng, and H. Wen, “Effect of Sintering Aids on the Microstructure and Oxidation Behavior of Hot-Pressed Zirconium Silicate Ceramic,” *Ceramics International* 43, no. 1 (2017): 875–879, <https://doi.org/10.1016/j.ceramint.2016.09.152>.
 45. A. Bouquillon and P. Lehuédé, *Lead in Glassy Materials in Cultural Heritage*, 1st ed. (Wiley, 2024), <https://doi.org/10.1002/9781394265411>.
 46. F. Angeli, P. Jollivet, T. Charpentier, M. Fournier, and S. Gin, “Structure and Chemical Durability of Lead Crystal Glass,” *Environmental Science and Technology* 50, no. 21 (2016): 11549–11558, <https://doi.org/10.1021/acs.est.6b02971>.
 47. Z. Chen, W. Ji, X. Xian, S. T. Ng, and C. S. Poon, “Atomic-Scale Mechanisms of pb Immobilization via Waste Glass-Assisted Low Temperature Vittrification Technology,” *Chemical Engineering Journal* 524 (2025): 169116, <https://doi.org/10.1016/j.cej.2025.169116>.
 48. P. W. Wang and L. Zhang, “Structural Role of Lead in Lead Silicate Glasses Derived From XPS Spectra,” *Journal of Non-Crystalline Solids* 194, no. 1–2 (1996): 129–134, [https://doi.org/10.1016/0022-3093\(95\)00471-8](https://doi.org/10.1016/0022-3093(95)00471-8).
 49. P. Sahu and M. A. Sheikh, “Microscopic Structure of Lead-Silicate Glass and Its Correlation With Thermal, Mechanical, and Radiation Shielding Properties,” *Applied Physics A: Materials Science and Processing* 131, no. 11 (2025): 935, <https://doi.org/10.1007/s00339-025-08983-0>.