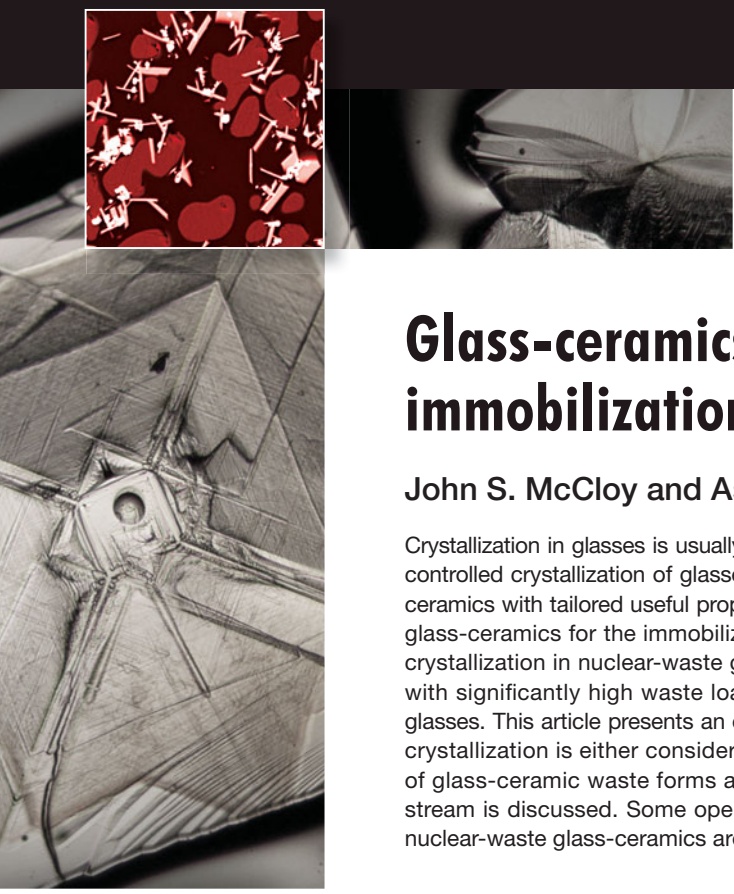


Glass-ceramics for nuclear-waste immobilization

John S. McCloy and Ashutosh Goel

Crystallization in glasses is usually considered to be a problem in the glass industry. However, controlled crystallization of glasses is an important prerequisite in the development of glass-ceramics with tailored useful properties. Similar boundary conditions apply when considering glass-ceramics for the immobilization of nuclear waste via vitrification. While uncontrolled crystallization in nuclear-waste glasses is problematic, chemically durable glass-ceramics with significantly high waste loadings can be produced with controlled crystallization of glasses. This article presents an overview of various aspects of nuclear-waste glasses where crystallization is either considered to be advantageous or problematic. The classification of glass-ceramic waste forms and strategies to design glass-ceramics for a given waste stream is discussed. Some open and relevant problems faced by researchers developing nuclear-waste glass-ceramics are also offered.

Introduction

Radionuclides and radiation are constituents of the Earth and play important roles in natural processes. Ever since Becquerel discovered natural radioactivity in 1896, radioactive materials have been utilized for society's benefit in science, medicine, industry, and defense. However, using naturally occurring and artificially created radioactive materials leads to waste products, many of which contain significant levels of radionuclides. In particular, the radioactive wastes generated during production of nuclear weapons have high chemical complexity, as they are the result of multiple chemical processes and contain a range of fission products. These so-called "legacy" wastes, as well as those created during used nuclear-fuel reprocessing, constitute the bulk of "high-level waste" (HLW) as defined by the International Atomic Energy Agency (IAEA).[1] Other nuclear-waste sources include medical treatments, oil and gas exploration, research reactors, nuclear facility decommissioning activities, and accidental releases requiring cleanup activities (e.g., the Fukushima Daiichi disaster in recent years).[2]

HLW is typically heat generating, due to extensive radioactive decay, and is the most hazardous, but the lowest volume of nuclear waste. Lower radioactivity classes such as low-level/low-activity wastes (LLWs/LAWs) and intermediate-level wastes (ILWs) generally have higher volumes and different disposal regulations. Classification of these wastes and regulations about their disposition depend on many factors, including the quantities and half-lives ($t_{1/2}$) of the various radioisotopes, types of radiation generated, and origination of the material.[1] The intent of radioactive waste management is to immobilize wastes in suitable matrices (known as waste forms) such that any release is controlled below thresholds set by local and international regulations protecting humankind and the environment. Depending on the applicable regulations, immobilized wastes are intended to be stored in various ways, including landfill disposal, shallow burial, or deep geologic repository, with risk and economics being the primary driving requirements. Since long-term stability of the waste form is desirable, chemically durable materials with high resistance to radiation damage are considered for waste forms.

Various material types have been considered as matrices for immobilization of specific radioactive wastes, including glasses, ceramics, cements, bitumen (hydrocarbon, also known as asphalt), and metals. However, the use of glasses, crystalline ceramics, and glass-ceramics for immobilization of HLW and for many other wastes has garnered the maximum support among scientists.[3–5] Glass is widely considered to be the benchmark material for long-term immobilization of complex mixed radioactive wastes, while single-phase ceramics may have advantages when considering highly uniform separated wastes such as actinides (An).[6]

Glass-ceramics used for immobilization of nuclear waste were first proposed in 1976 by researchers at the

John S. McCloy, School of Mechanical and Materials Engineering, Washington State University, USA; john.mccloy@wsu.edu
Ashutosh Goel, Department of Materials Science and Engineering, Rutgers, The State University of New Jersey, USA; ag1179@soe.rutgers.edu
doi:10.1557/mrs.2017.8

© 2017 Materials Research Society

https://doi.org/10.1557/mrs.2017.8 Published online by Cambridge University Press

Hahn-Meitner-Institute Berlin[7] as a potential means to improve the mechanical properties of nuclear-waste glasses and their thermal stability in the presence of decay heat. In these original studies, deliberate devitrification (i.e., crystallization) of borosilicate-based glasses was designed to yield one or more major crystalline phases that would incorporate some of the waste components (details discussed further). However, it is important to note that despite extensive research and development, glass-ceramics have not yet been used in any broad scale in actual nuclear-waste immobilization efforts. Current renewed interest in glass-ceramic waste forms is due to present requirements to treat "difficult" waste streams that are poorly suited for borosilicate glass and too complex for single-phase ceramic-waste forms. In this article, a brief typology of nuclear-waste glass-ceramics is given, according to either the microstructure of the product or synthesis process, an overview of the main relevant glass-ceramic families is offered, and some open science questions are discussed.

Classification of waste forms considered as glass-ceramics

Classification by the product

In materials science, glass-ceramics are defined as materials with ≥10 vol% crystal phase obtained by controlled crystallization.[5,8] Normally, this involves bulk nucleation of crystals, as surface crystallization is not considered to be controlled. However, in the nuclear-waste-form community, several types of product materials have been described as "glass-ceramics" or a similar moniker, so a brief review is warranted.

The US National Research Council (NRC) has classified waste forms[2,9] based on the inclusion mechanism of radioactive elements (see **Figure 1**). In general, the immobilization of radionuclides can be considered as due to incorporation, encapsulation, or both. Chemical incorporation occurs at the atomic scale, while encapsulation involves embedding or physical sequestration. The following typology has been modified from the NRC classification.

In the first type of glass-ceramic, a small fraction (a few vol%) of crystals form that do not incorporate radionuclides, thus the radioactive component is only incorporated in the glass. The formation of crystals here is generally undesirable,[10,11] but may or may not affect long-term performance of the system. For example, in Hanford HLW glasses, the formation of Fe-Cr-Mn spinels is acceptable, while the formation of nepheline ($NaAlSiO_4$) crystals is detrimental to performance.[11,12] In the second type of glass-ceramic, at least one radionuclide is targeted for containment in a crystalline phase, using a tailored waste stream and crystal chemistry considerations to select an appropriate host phase. The partitioning between glass and ceramic phase may not be complete, but the goal is to incorporate the radionuclide into a durable crystalline phase (e.g., zirconolite [$CaZrTi_2O_7$]),[13] which is surrounded by (encapsulated in) a durable glassy phase (e.g., alumino-boro-silicate), thus providing double containment. The main technical issue in this case lies with the effective partitioning of the radionuclide into the crystalline phase. The third glass-ceramic material type is one in which a crystalline phase is initially produced containing the waste and radionuclides. This phase, usually in the form of a high-surface-area powder, is then consolidated, often with a glass binder, producing a "glass-bonded" material (or "glass-composite material"),[14] where the glass provides further encapsulation of the radionuclides that are present in durable crystalline phases. One example of this scheme is a composite based on a borosilicate or lead silicate glass matrix with crystals of pyrochlore (e.g., $(Ca, Ln, An)_2(Ti, Hf, Zr)_2O_7$, where Ln indicates lanthanide elements).[15] However, details of the interface interactions between the glass binder and crystals vary considerably with the system in question and must be carefully studied to ensure long-term waste form performance, particularly in terms of radiation stability and chemical durability in the presence of water.

Classification by the process

Some researchers classify "glass-ceramics" by the process by which the crystallization is obtained (see **Figure 2**). Traditionally, glass-ceramics for other applications are produced by quenching a glass, nucleating at an elevated temperature, and then growing crystals at a higher temperature. This scenario with separate nucleation (I) and growth (u) steps gives the greatest control over crystallization, but requires a reheat step that may not be desirable for nuclear facilities, although scenarios of this kind have been proposed for glass-ceramics

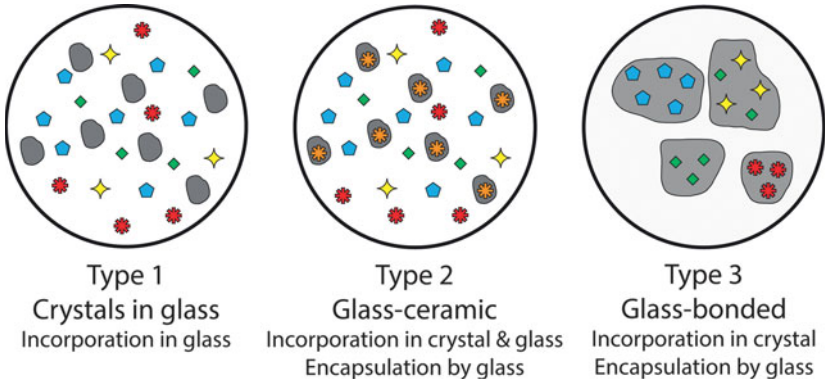


Figure 1. Illustration of radionuclide incorporation and definition of various materials considered as glass-ceramics. In Type 1, crystals (gray) form in glass but radionuclides (colored symbols) are not in crystals but in glass (white). In Type 2, crystals form in glass, some radionuclides are in these crystals (orange in gray) while some are in the glass (other colored symbols), and the glass forms an additional barrier around the crystals. In Type 3, most or all of the radionuclides are incorporated into the crystalline structure of one or more phases (gray grains containing colored symbols), and the surrounding glass (white) serves to connect and further protect these crystals.[2,9] Note: Different symbols denote radionuclides such as Cs, Sr, Tc, U, and Pu, and are schematic only.

https://doi.org/10.1557/mrs.2017.8 Published online by Cambridge University Press

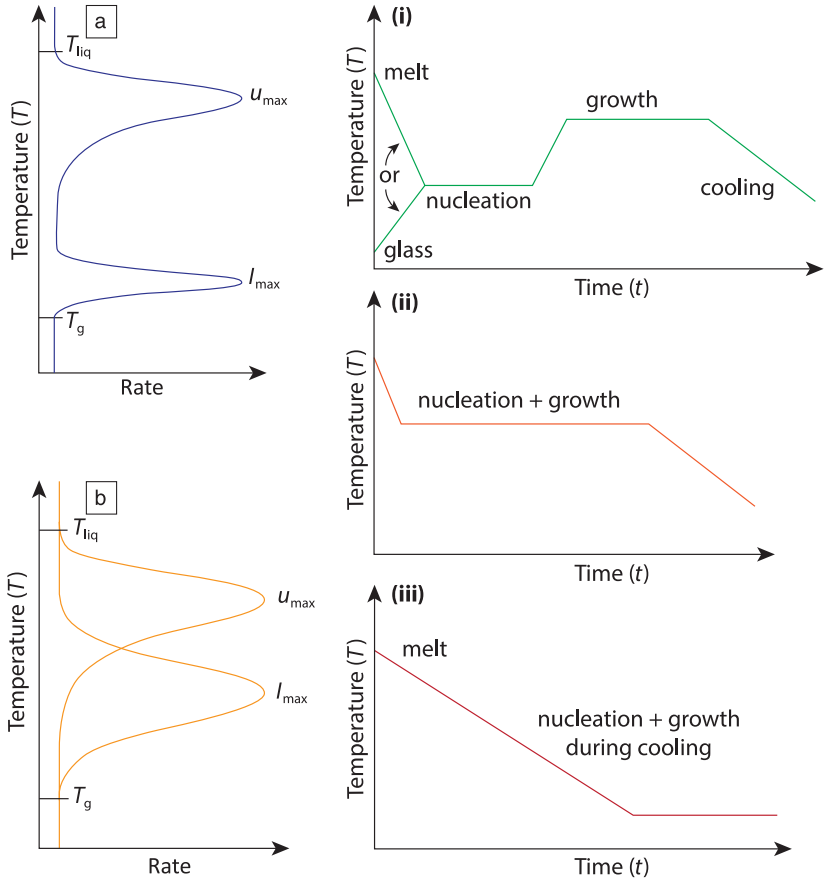


Figure 2. Illustration of the possible thermal treatments used for nuclear glass-ceramics with (a) widely separated maximum nucleation rate (I_{max}) and growth rate (u_{max}) temperatures or (b) closely overlapping nucleation and growth temperature dependencies. Processing of type (a) systems only allows (i) separate nucleation and growth, while systems of type (b) can be processed by either (i), (ii) simultaneous isothermal nucleation and growth, or (iii) nucleation and growth on controlled cooling.[2,5] Note: T_{liq}, liquidus temperature; T_g, glass-transition temperature.

based on celsian ($BaAl_2Si_2O_8$), fresnoite ($BaTiSi_2O_8$), sphene ($CaTiSiO_5$), basalt, and zirconolite.[4,5,16,17] A potentially more desirable approach for nuclear-waste glass-ceramics occurs when the nucleation and crystallization maximum rates overlap substantially in temperature, so crystals can form by either holding at high temperature or by cooling continuously. This approach has been considered for nuclear glass-ceramics based on diopside ($CaMgSi_2O_6$), basaltic phases like augite [$(Ca, Mg, Fe)Si_2O_6$], zirconolite, apatite [$(Na, Ca, Ln)_{10}(SiO_4)_6O_2$ or $(Ca, Ln)_{10}(PO_4)_6O_2$], and powellite ($CaMoO_4$).[4,18] Systems with nucleation and growth maximum temperatures that are well separated cannot be made by the continuous cool method. Those systems with overlapping *I-u* curves can be grown using separate nucleation and growth steps, a single nucleation plus growth step, or continuous cool, depending on the overlap (see Figure 2). In glass-ceramic systems where more than one crystal phase forms, details of the crystal nucleation and growth process can be quite complicated and difficult to untangle.

Glass-ceramic families studied for nuclear-waste management

Many different glass-ceramic systems have been considered for immobilization of nuclear waste, as alluded to earlier. The wide variety of crystalline phases examined is due to the compositional complexity of wastes and the fission product spectrum, as well as various chemical processing steps, resulting in the consideration of many more phases than would be typically needed in a glass-ceramic used for mechanical or optical applications.

Arguably, the best-studied nuclear glass-ceramic system, at least for immobilization of An- or Ln-rich wastes, is zirconolite (see **Figure 3**).[19,20] Single-phase zirconolite glass-ceramics have been produced by nucleation and growth methods, and surface versus bulk crystallization was assessed as a function of nucleation temperature in order to ensure control of crystal phase, size, density, and location in the glass-ceramic, thus optimizing target radionuclide immobilization.[5] Major alternative phases to zirconolite for An immobilization include apatite, perovskite [$(Ca, Sr, Ba, An, Ln)TiO_3$], and pyrochlore. It has been shown that apatite better concentrates Ln^{3+} than zirconolite due to stoichiometric considerations, but zirconolite has better long-term stability in the presence of radiation.[5] Crystal chemistry can influence site preferences through the ionic radius of the substituting ion, such that zirconolite prefers smaller Ln^{3+} and An^{4+} while the Ca site in perovskite prefers larger Ln^{3+} (Nd, Ce) and An^{3+}.[21] Finally, pyrochlore glass-ceramics appear to be less sensitive to processing oxidation/reduction conditions and can potentially increase the waste loading of An.[22]

In addition to An, other important radionuclides require immobilization. Prominent among these are the high-yield, highly radioactive (beta and gamma decays), medium-lived fission products of the alkali and alkaline-earth type, primarily as ^{137}Cs ($t_{1/2}$ = 30.23 y) and ^{90}Sr ($t_{1/2}$ = 28.9 y). These radionuclides can be in a mixed-waste stream or separated. Durable crystalline phases typically considered include pollucite ($CsAlSi_2O_6$) and hollandite [$(Ba, Cs)Al_2Ti_2O_6$] for Cs, and celsian, scheelite [$(Ba, Sr)MoO_4$], and perovskite for Sr (and Ba).[16]

The immobilization of ^{137}Cs and ^{90}Sr is even more challenging in molybdenum-rich wastes that are produced from used nuclear-fuel reprocessing streams such as the UMo-MoSnAl fuel from gas-graphite reactors[23] or the mixed-lanthanide-transition-metal waste stream proposed for US aqueous-fuel reprocessing.[18] Both of these waste streams are not suitable for a glass-only waste form, as they contain significant quantities

https://doi.org/10.1557/mrs.2017.8 Published online by Cambridge University Press

of the highly radioactive and decay heat producing Cs and Sr as well as high Mo content, above that which would be soluble in borosilicate glasses.[24] This waste is currently planned to be mixed with an alumino-boro-silicate, but on cooling, a liquid–liquid phase separation occurs followed by crystallization of molybdate phases and subsequent additional liquid–liquid phase separation (see **Figure 4**).[25,26] The composition of the starting melt (waste plus additives) strongly affects the cooled phase composition, since each consecutive phase separation or crystallization changes the composition of the residual melt, thus effecting phase evolution at lower temperatures.[5,27,28] For instance, if a large concentration of alkali (Na, Cs) is present, undesirable water-soluble alkali molybdates result. If more alkaline earth elements (Ca, Sr, Ba) are present, durable alkaline-earth molybdates like powellite will form, often with multiple compositions. Additionally, changes in starting composition involving other components, such as B, P, and Zr, affect the distribution and availability of Na for crystallization. Therefore, a detailed understanding of thermochemistry of these glass compositions is required to ensure the formation of desired crystalline phase assemblage.

One last example of the types of glass-ceramic used for nuclear applications are those for halide (Hd) ions (see Figure 3). Typically, Hd elements, of which fission product radioactive ^{129}I is one, have low solubility in silicate glasses,[4,29] though they can have higher solubilities in other glass systems such as phosphate[30] and tellurite.[31] Particular waste streams high in chlorides, such as contaminated molten salt utilized in reprocessing used metallic nuclear fuel (electrochemical or pyrochemical process), do not lend themselves to borosilicate glass waste forms. The current approach for these wastes is to produce a sodalite ($Na_8Al_6Si_6O_{24}Cl_2$) mineral powder and bond it together using a sodium borosilicate glass.[29,32,33]

Open and relevant problems for nuclear-waste glass-ceramics

While the chemistry of nuclear wastes and the development of respective waste forms are country-specific, the fundamental science governing the design and development of these waste forms is the same globally. For example, the chemical composition of Mo-rich wastes is different for the United States, France, the United Kingdom, and Japan, but the scientific challenges faced by researchers in the development of glass and glass-ceramic waste forms for their immobilization are common. One such problem is the complex interaction between multiple liquid–liquid phase separations (both droplet-in-matrix and spinodal) in glass melts. The order in which these events occur affects the ultimate partitioning of elements in the final crystalline phases through effects on the residual melt compositions after phase separation and crystallization events. A testimony to this statement is the sequence of phase

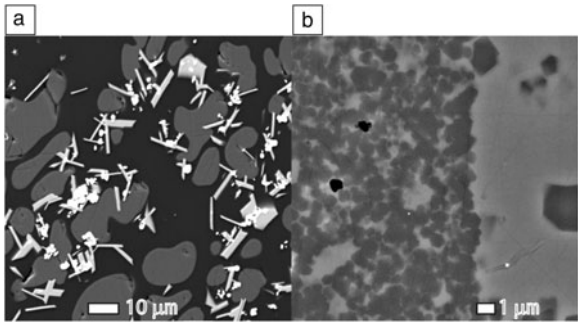


Figure 3. Microstructures of example nuclear glass-ceramics, including (a) zirconolite ($CaZrTi_2O_7$) and (b) sodalite ($Na_8Al_6Si_6O_{24}Cl_2$). In (a) PuO_2 contaminated CaF_2 slags from the Sellafield nuclear site (UK) were targeted for immobilization; dark phase is the glass matrix, gray island-type structures are the CaF_2, white needle-shaped crystals are zirconolite, and white spherical shapes are excess ZrO_2.[19] Courtesy of E. Maddrell, National Nuclear Laboratory. In (b), the glass-bonded sodalite was made from 26 wt% glass and 74 wt% salt-occluded zeolite. Dark gray crystals are sodalite and light gray is glass.[20] Courtesy B. Riley, Pacific Northwest National Laboratory.

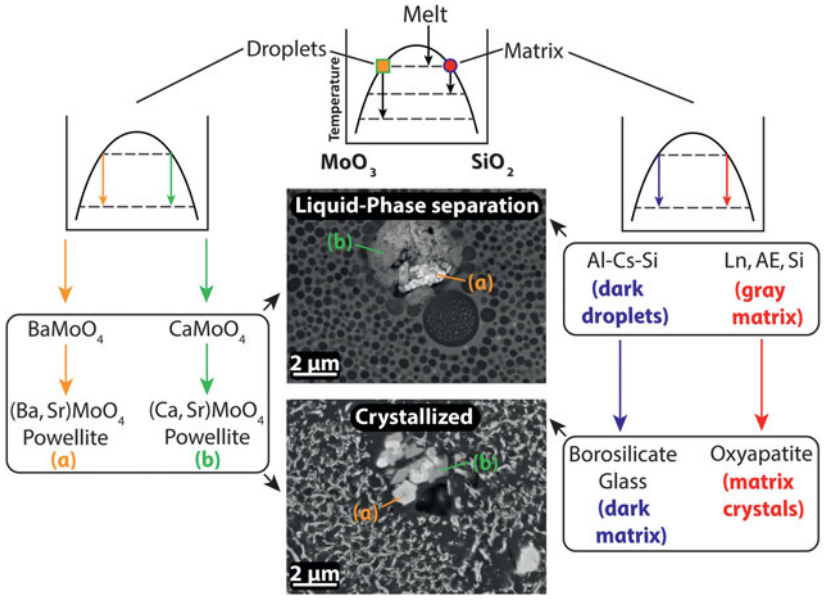


Figure 4. Complex phase separation and crystallization in powellite [(Ca, Ba, Sr)MoO_4]/oxyapatite [(Na, Ca, Ln)$_{10}(SiO_4)_6O_2$] system.[25] At high enough temperatures, the MoO_3- and SiO_2-rich melts are miscible (above the dome), but as temperatures drop (dashed lines), phase separation occurs of the droplet–matrix type. In other similar diagrams, *y*-axis is temperature, *x*-axis is composition, dashed lines indicate fixed temperatures, and region under the curve is the immiscibility region. (Left) Droplets rich in Mo further separate into (a) Ba-rich and (b) Sr-rich phases that crystallize as powellite with different compositions. (Right) The silica-rich matrix phase separates as a new droplet–new matrix. This new droplet phase is enriched in Al and Cs and becomes a residual borosilicate glass on full cooling. The new matrix phase is enriched in lanthanides (Ln) and alkaline earths (AEs) and on full cooling, transforms to oxyapatite crystals.

https://doi.org/10.1557/mrs.2017.8 Published online by Cambridge University Press

separation and crystallization in Ln^{3+} containing Mo-rich borosilicate glasses, as shown in Figure 4. While Nd^{3+} is known to suppress the phase separation of the Mo-rich phase in these glasses, the partitioning of Nd^{3+} in the glass matrix results in premature crystallization of Nd-containing oxyapatite, leading to uncontrolled phase separation of the Mo-rich phase.[34,35] Therefore, it is crucial to understand the thermodynamics and kinetics of phase separation and crystallization in nuclear-waste glasses in order to design glass-ceramics with desired crystalline phase assemblage.

The other major problem with design and development of nuclear-waste glasses/glass-ceramics is their compositional complexity. In general, a nuclear-waste glass-ceramic comprises ≥30 elements, including all types of metals and their oxides (alkali, alkaline earth, multivalent transition metals, noble metals, Ln, An), oxide glass-formers and intermediates (Si, B, P, Al), and Hd elements. Therefore, even if the phase-separated interfaces themselves play little role in nucleation,[36] the compositional complexity of a nuclear-waste glass-ceramic makes the mapping of nucleation and growth of different phases difficult. While inducing volume nucleation in these glass-ceramics is generally not a limiting factor—as undissolved noble metals, TiO_2, and ZrO_2 in the glass melts act as nucleation agents—it is important to understand the distributions of elements in crystalline phases, their size and morphology, and the chemistry of the residual glassy phase, in order to design durable glass-ceramic waste forms. Therefore, traditional methods of performing nucleation and growth studies from quenched glasses may not be completely relevant to potentially inhomogeneous production-scale glass-ceramic systems, which are produced in large ingots and thus cool with differing thermal profiles in different locations.[25] High-temperature *in situ* characterization techniques, such as x-ray or neutron ultrasmall to wide-angle scattering, are difficult to perform, but they are needed to show temperature-dependent phase evolution.[37,38]

It is known from optical glass-ceramics with nanoparticles that some crystal growth can be self-limiting due to composition-related viscosity and topology changes at the interface.[39] This interfacial viscosity increase is effective for limiting crystal growth in nonstoichiometric systems where the growing crystal depletes the residual glass of elements that lower the viscosity at the melt/crystal interface (e.g., F). However, when the growing crystal produces a lower viscosity at the growing interface, such as nepheline growing in a borosilicate nuclear-waste glass-ceramic,[40] crystal growth is uninhibited and undesirably large crystals may grow unimpeded. Since every nuclear glass-ceramic is a nonstoichiometric system, more studies on crystallization and interface effects are needed, such that compositions can be designed to control growth rates, particularly for continuously cooled waste forms.

Finally, due consideration needs to be given to the chemical durability of nuclear-waste glass-ceramics. During final geological disposal, the intrusion of groundwater through a repository is the most likely mechanism by which radionuclides may be removed from the glass-ceramic waste forms once the canister containing the glass-ceramic degrades (likely ~10^3 years at most). Radionuclides may then be carried to the biosphere unless the waste forms are stable in the presence of water over geological time scales (10^3 to 10^9 years).[41,42] The performance of a glass-ceramic waste form in a geological repository is dictated by its crystalline phase assemblage and the chemical composition of the residual glassy phase, as well as local geochemical conditions.[23,43] Therefore, a fundamental understanding of the compositional dependence of crystallization behavior and its impact on the durability of the final waste form is essential.[44]

Summary

In this review, an introduction to glass-ceramics as nuclear-waste forms is offered. The different types of glass-ceramics studied as waste forms are described and contrasted, based on their microstructures and processing methods. A summary of some of the most important glass-ceramic families for nuclear-waste immobilization is presented, along with important fundamental insights offered by some of these studies. Finally, selected ongoing research directions are described showing some ties to new knowledge from traditional glass-ceramics, in the hopes that other researchers can contribute to the understanding of complex glass-ceramics for nuclear-waste immobilization.

Glass-ceramics have not been implemented on any widespread scale in actual nuclear-waste immobilization efforts to date due to the acceptability of borosilicate glass for most efforts. However, there is renewed interest in glass-ceramic waste forms for treating problematic wastes containing high fractions of poorly soluble components, high contents of radioactive decay heat-generating materials, wastes from new reactor types, and higher waste loading scenarios than could be accommodated by borosilicate glass. Rather than being seen as problematic, crystallization can be beneficial for immobilization of nuclear waste and long-term thermal and chemical stability of nuclear-waste forms, while the benefits of processing materials as glasses has always been one of the central advantages to glass-ceramic technology for all applications.

Acknowledgments

The authors gratefully acknowledge research funding from the US Department of Energy, offices of Nuclear Energy (Nuclear Energy University Program) and Environmental Management (Office of River Protection), Contract Nos. DE-EM0002904, DE-EM0003207, DE-NE0008431, and DE-NE0008257. We also thank E. Maddrell, J. Marra, and J. Crum for assistance with the manuscript and especially B. Riley for assistance with the figures.

References

1. W.E. Lee, M.I. Ojovan, C.M. Jantzen, Eds., *Radioactive Waste Management and Contaminated Site Clean-Up: Processes, Technologies and International Experience* (Woodhead Publishing, Oxford, UK, 2013).
2. I.W. Donald, B.L. Metcalfe, R.N.J. Taylor, *J. Mater. Sci.* **32**, 5851 (1997).

https://doi.org/10.1557/mrs.2017.8 Published online by Cambridge University Press

3. M.I. Ojovan, W.E. Lee, *An Introduction to Nuclear Waste Immobilisation* (Elsevier, Amsterdam, The Netherlands, 2005).
4. I.W. Donald, *Waste Immobilization in Glass and Ceramic Based Hosts: Radioactive, Toxic, and Hazardous Wastes* (Wiley, Chichester, UK, 2010).
5. D. Caurant, P. Loiseau, O. Majerus, V. Aubin-Chevaldonnet, I. Bardez, A. Quintas, *Glasses, Glass-Ceramics and Ceramics for Immobilization of Highly Radioactive Nuclear Wastes* (Nova Science, New York, 2009).
6. W.J. Weber, R.C. Ewing, C.R.A. Catlow, T.D. de la Rubia, L.W. Hobbs, C. Kinoshita, H. Matzke, A.T. Motta, M. Nastasi, E.K.H. Salje, E.R. Vance, S.J. Zinkle, *J. Mater. Res.* **13**, 1434 (1998).
7. A.K. De, B. Luckscheiter, W. Lutze, G. Malow, E. Schiewer, *Am. Ceram. Soc. Bull.* **55**, 500 (1976).
8. W. Höland, G.H. Beall, *Glass Ceramic Technology*, 2nd ed. (Wiley, Hoboken, NJ, 2012).
9. National Research Council, Committee on Waste Forms Technology and Performance, *Waste Forms Technology and Performance: Final Report* (National Academy of Sciences, Washington, DC, 2011).
10. M. Ojovan, W. Lee, *Metall. Mater. Trans. A* **42**, 837 (2011).
11. P. Hrma, *J. Non Cryst. Solids* **356**, 3019 (2010).
12. D.S. Kim, D.K. Peeler, P. Hrma, *Ceram. Trans.* **61**, V. Jain, R. Palmer, Eds. (American Ceramic Society, Westerville, OH, 1995), p. 177.
13. P. Loiseau, D. Caurant, N. Baffier, L. Mazerolles, C. Fillet, *J. Nucl. Mater.* **335**, 14 (2004).
14. W.E. Lee, M.I. Ojovan, M.C. Stennett, N.C. Hyatt, *Adv. Appl. Ceram.* **105**, 3 (2006).
15. A.R. Boccaccini, E. Bernardo, L. Blain, D.N. Boccaccini, *J. Nucl. Mater.* **327**, 148 (2004).
16. J.P. Hayward, in *Radioactive Waste Forms for the Future*, W. Lutze, R.C. Ewing, Eds. (North-Holland, Amsterdam, 1988), p. 427.
17. W. Lutze, J. Borchardt, A.K. De, "Characterization of Glass and Glass Ceramic Nuclear Waste Forms," *Mater. Res. Symp. Proc.* **1**, G.J. McCarthy, R.L. Schwoebel, R.W. Potter II, A.M. Friedman, J.G. Moore, H.C. Burkholder, W. Lutze, Eds. (Materials Research Society, Warrendale, PA, 1979), p. 69.
18. J.V. Crum, L. Turo, B. Riley, M. Tang, A. Kossoy, *J. Am. Ceram. Soc.* **95**, 1297 (2012).
19. E. Maddrell, S. Thornber, N.C. Hyatt, *J. Nucl. Mater.* **456**, 461 (2015).
20. W.L. Ebert, C.T. Snyder, B.J. Riley, S.M. Frank, "Designing Advanced Ceramic Waste Forms for Electrochemical Processing Salt Waste" (Report No. FCRD-MRWFD-2016-000038, Argonne National Laboratory, Argonne, IL, 2016).
21. G.R. Lumpkin, *Elements* **2**, 365 (2006).
22. Y. Zhang, Z. Zhang, G. Thorogood, E.R. Vance, *J. Nucl. Mater.* **432**, 545 (2013).
23. O. Pinet, A. Grandjean, P. Frugier, H. Rabiller, S. Poissonnet, *J. Non Cryst. Solids* **352**, 3095 (2006).
24. D. Caurant, O. Majérus, E. Fadel, A. Quintas, C. Gervais, T. Charpentier, D. Neuville, *J. Nucl. Mater.* **396**, 94 (2010).
25. J. Crum, V. Maio, J. McCloy, C. Scott, B. Riley, B. Benefiel, J. Vienna, K. Archibald, C. Rodriguez, V. Rutledge, Z. Zhu, J. Ryan, M. Olszta, *J. Nucl. Mater.* **444**, 481 (2014).
26. S. Schuller, O. Pinet, B. Penelon, *J. Am. Ceram. Soc.* **94**, 447 (2011).
27. S. Schuller, O. Pinet, A. Grandjean, T. Blisson, *J. Non Cryst. Solids* **354**, 296 (2008).
28. M. Magnin, S. Schuller, C. Mercier, J. Trébosc, D. Caurant, O. Majérus, F. Angéli, T. Charpentier, *J. Am. Ceram. Soc.* **94**, 4274 (2011).
29. B.J. Riley, J.V. Crum, J. Matyáš, J.S. McCloy, W.C. Lepry, *J. Am. Ceram. Soc.* **95**, 3115 (2012).
30. T. Lemesle, F.O. Méar, L. Campayo, O. Pinet, B. Revel, L. Montagne, *J. Hazard. Mater.* **264**, 117 (2014).
31. B.J. Riley, B.T. Rieck, J.S. McCloy, J.V. Crum, S.K. Sundaram, J.D. Vienna, *J. Nucl. Mater.* **424**, 29 (2012).
32. K.J. Bateman, C.J. Knight, C.W. Solbrig, "Current Status of Ceramic Waste Form Development" (Report INL/INT-06-11736, Rev. 1, Idaho National Laboratory, Idaho Falls, ID, 2007).
33. E.R. Vance, J. Davis, K. Olufson, I. Chironi, I. Karatchevtseva, I. Farnan, *J. Nucl. Mater.* **420**, 396 (2012).
34. N. Chouard, D. Caurant, O. Majérus, J.L. Dussossoy, A. Ledieu, S. Peuget, R. Baddour-Hadjean, J.P. Pereira-Ramos, *J. Non Cryst. Solids* **357**, 2752 (2011).
35. N. Chouard, D. Caurant, O. Majérus, N. Guezi-Hasni, J.-L. Dussossoy, R. Baddour-Hadjean, J.-P. Pereira-Ramos, *J. Alloys Compd.* **671**, 84 (2016).
36. E.D. Zanotto, *Int. J. Appl. Glass Sci.* **4**, 105 (2013).
37. R. Hill, A. Calver, A. Stamboulis, N. Bubb, *J. Am. Ceram. Soc.* **90**, 763 (2007).
38. C. Fernandez-Martin, G. Bruno, A. Crochet, D. Ovono Ovono, M. Comte, L. Hennet, *J. Am. Ceram. Soc.* **95**, 1304 (2012).
39. C. Bocker, C. Rüssel, I. Avramov, *Chem. Phys.* **406**, 50 (2012).
40. J.S. McCloy, M.J. Schweiger, C.P. Rodriguez, J.D. Vienna, *Int. J. Appl. Glass Sci.* **2**, 201 (2011).
41. P. Trocellier, *Ann. Chimie Sci. Materiaux.* **26**, 113 (2001).
42. S. Gin, A. Abdelouas, L.J. Criscenti, W.L. Ebert, K. Ferrand, T. Geisler, M.T. Harrison, Y. Inagaki, S. Mitsui, K.T. Mueller, J.C. Marra, C.G. Pantano, E.M. Pierce, J.V. Ryan, J.M. Schofield, C.I. Steefel, J.D. Vienna, *Mater. Today* **16**, 243 (2013).
43. H. Li, J.D. Vienna, P. Hrma, D.E. Smith, M.J. Schweiger, *Mater. Res. Soc. Symp. Proc.* **465**, W.J. Gray, I.R. Triay, Eds. (Materials Research Society, Warrendale, PA, 1997), p. 261.
44. J.D. Vienna, J.V. Ryan, S. Gin, Y. Inagaki, *Int. J. Appl. Glass Sci.* **4**, 283 (2013). □



John S. McCloy joined Washington State University in 2013, and is currently the Director of the Materials Science and Engineering PhD program. From 2008 to 2013, he worked at the Pacific Northwest National Laboratory, where he continues as a joint appointee. He received his SB degree in 1996 from the Massachusetts Institute of Technology and PhD degree in 2008 from The University of Arizona, both in materials science and engineering. His current research focuses on the development of glasses and glass-ceramics for nuclear-waste immobilization, as well as the application of new material characterization techniques to study phase evolution on cooling from the melt. McCloy can be reached by phone at 509-335-7796 or by email at john.mccloy@wsu.edu.



Ashutosh Goel joined Rutgers, The State University of New Jersey, as an assistant professor in January 2014. Prior to this, he worked as a senior scientist at Sterlite Technologies Ltd., India, and as a materials scientist at Pacific Northwest National Laboratory. His current research focuses on understanding nucleation and crystallization in nuclear-waste glasses, and chemical durability of glasses. He is an associate editor for the "Glass Science" section of *Frontiers in Materials*. He has authored more than 60 articles and holds two patents. Goel can be reached by phone at 848-445-4512 or by email at ag1179@soe.rutgers.edu.

MRS MATERIALS RESEARCH SOCIETY
Advancing materials. Improving the quality of life.

NOMINATE A COLLEAGUE TODAY

for one of these prestigious awards from the Materials Research Society

- Von Hippel Award
- David Turnbull Lectureship
- MRS Medal
- Materials Theory Award
- The Kavli Foundation Early Career Lectureship in Materials Science

mrs.org/awards

Nomination Deadline—April 1, 2017

https://doi.org/10.1557/mrs.2017.8 Published online by Cambridge University Press

Journal of MATERIALS RESEARCH
FOCUS ISSUE • DECEMBER 2017

Submission Deadline—May 1, 2017



CALL FOR PAPERS

Mechanical properties and microstructure of advanced metallic alloys—in honor of Prof. Hael Mughrabi

Understanding the correlation between the microstructure and the mechanical behavior of materials has always been one of the key challenges in materials science. This is the case in particular for cyclic deformation behavior, creep properties, and high-temperature behavior. Recent years have seen significant progress in these fields through the widespread use of new microscopic techniques such as focused ion beam, high resolution TEM, nanomechanical testing approaches, atom probe microscopy, *in situ* testing, and multiscale simulations.

Contributions by Prof. Hael Mughrabi, who will turn 80 in 2017, have been key to the development of these fields. His seminal contributions in understanding fatigue mechanisms and to the new field of very high cycle fatigue are particularly well-known. The fatigue behavior of ultrafine-grained materials was another focus of his interests. Mughrabi also made significant advances in the field of high-temperature materials, where his work led to an improved understanding of the influence of the lattice misfit and raft formation process. To honor Hael Mughrabi's long lasting contributions in materials research, manuscript submissions are invited particularly in the following fields:

- Cyclic deformation behavior and fatigue mechanisms including the VHCF regime
- Deformation behavior of high-temperature materials, for example, TiAl alloys, Ni and Co-based superalloys and coatings
- Mechanical behavior of nano, ultrafine-grained, and nanolamellar materials

GUEST EDITORS

Mathias Göken, Friedrich-Alexander-University Erlangen-Nürnberg, Germany
Gunther Eggeler, Ruhr University Bochum, Germany
Yuntian Zhu, North Carolina State University, USA
Lei Lu, Institute of Metal Research, CAS, China

MANUSCRIPT SUBMISSION

To be considered for this issue, new and previously unpublished results significant to the development of this field should be presented. The manuscripts must be submitted via the *JMR* electronic submission system by **May 1, 2017.** Manuscripts submitted after this deadline will not be considered for the issue due to time constraints on the review process. **Submission instructions may be found at www.mrs.org/jmr-instructions.** Please select "Focus issue: *Mechanical properties and microstructure of advanced metallic alloys—in honor of Prof. Hael Mughrabi*" as the manuscript type. **Note our manuscript submission minimum length of 6000 words, with a maximum of 6–8 figures.** All manuscripts will be reviewed in a normal but expedited fashion. Papers submitted by the deadline and subsequently accepted will be published in the Focus Issue. Other manuscripts that are acceptable but cannot be included in the issue will be scheduled for publication in a subsequent issue of *JMR*.

jmr@mrs.org
Please contact **jmr@mrs.org** with questions.

https://doi.org/10.1557/mrs.2017.8 Published online by Cambridge University Press

2017 MRS® SPRING MEETING & EXHIBIT

April 17–21, 2017 | Phoenix, Arizona

REGISTER BY MARCH 31 AND SAVE!

CHARACTERIZATION, THEORY AND MODELING

CM1 Emergent Material Properties and Phase Transitions Under Pressure
CM2 Advanced Numerical Algorithms for Metallic Systems at the Mesoscale in Materials Science
CM3 Computer-Based Modeling and Experiment for the Design of Soft Materials
CM4 *In Situ* Electron Microscopy of Dynamic Materials Phenomena
CM5 Mechanically Coupled Properties, Phenomena and Testing Methods in Small-Scale and Low-Dimensional Systems
CM6 Dislocation Microstructures and Plasticity
CM7 Genomic Approaches to Accelerated Materials Innovation

ELECTRONIC DEVICES AND MATERIALS

ED1 Silicon-Carbide, Diamond and Related Materials for Quantum Technologies
ED2 Materials and Devices for Neuromorphic-Engineering and Brain-Inspired Computing
ED3 Physics, Chemistry and Materials for Beyond Silicon Electronics
ED4 Luminescent Materials for Photon Upconversion
ED5 Photoactive Nanoparticles and Nanostructures
ED6 Nanostructured Quantum-Confined States for Advanced Optoelectronics
ED7 Materials and Device Engineering for Beyond the Roadmap Devices in Logic, Memory and Power
ED8 Development and Integration of Organic and Polymeric Materials for Thin-Film Electronic Devices
ED9 Advanced Interconnects for Logic and Memory Applications—Materials, Processes and Integration
ED10 Material Platforms for Plasmonics and Metamaterials—Novel Approaches Towards Practical Applications
ED11 Phase-Change Materials and Their Applications—Memories, Photonics, Displays and Non-von Neumann Computing
ED12 Quantum Sensing, Metrology and Devices
ED13 Novel Photonic, Electronic and Plasmonic Phenomena in Materials
ED14 Molecular and Colloidal Plasmonics—Synthesis and Applications

ENERGY STORAGE AND CONVERSION

ES1 Perovskite Solar Cells—Towards Commercialization
ES2 High-Capacity Electrode Materials for Rechargeable Energy Storage
ES3 Materials for Multivalent Electrochemical Energy Storage
ES4 Nanogenerators and Piezotronics
ES5 Advances in Materials, Experiments and Modeling for Nuclear Energy
ES6 Mechanics of Energy Storage and Conversion—Batteries, Thermoelectrics and Fuel Cells
ES7 (Photo)electrocatalytic Materials and Integrated Assemblies for Solar Fuels Production—Discovery, Characterization and Performance
ES8 Caloric Materials for Energy-Efficient Applications
ES9 Surfaces, Coatings and Interfaces in Concentrated Solar Energy Applications
ES10 Frontiers in Oxide Interface Spintronics—Magnetoelectrics, Multiferroics and Spin-Orbit Effects
ES11 Advanced and Highly Efficient Photovoltaic Devices
ES12 Soft Magnetic Materials for Next-Generation Power Electronics
ES13 Interfaces and Interphases in Electrochemical Energy Storage and Conversion
ES14 Thin-Film Chalcogenide Semiconductor Photovoltaics

NANOMATERIALS

NM1 Emerging Non-Graphene 2D Materials
NM2 Nanoscale Heat Transport—From Fundamentals to Devices
NM3 Aerogels and Aerogel-Inspired Materials
NM4 Novel Catalytic Materials for Energy and Environment
NM5 Frontiers in Terahertz Materials and Technology
NM6 Mechanical Behavior of Nanostructured Composites
NM7 Semiconductor Nanowires for Energy Applications
NM8 2D Materials—Macroscopic Perfection vs. Emerging Nanoscale Functionality
NM9 High-Performance Metals and Alloys in Extreme Conditions
NM10 Micro/Nano Assembling, Manufacturing and Manipulation for Biomolecular and Cellular Applications

SOFT MATERIALS AND BIOMATERIALS

SM1 Bioelectronics—Materials, Processes and Applications
SM2 Advanced Multifunctional Fibers and Textiles
SM3 Advanced Biomaterials for Neural Interfaces
SM4 A Soft Future—From Electronic Skin to Robotics and Energy Harvesting
SM5 Aqueous Cytomimetic Materials
SM6 Materials in Immunology—From Fundamental Material Design to Translational Applications
SM7 Emerging Membrane Materials for Sustainable Separations
SM8 Advanced Polymers

Meeting Chairs

Christopher J. Bettinger Carnegie Mellon University
Stefan A. Maier Imperial College London
Alfonso H.W. Ngan The University of Hong Kong
W. Jud Ready Georgia Institute of Technology
Eli A. Sutter University of Nebraska–Lincoln

www.mrs.org/spring2017

Don't Miss These Future MRS Meetings!

2017 MRS Fall Meeting & Exhibit
November 26 – December 1, 2017, Boston, Massachusetts

2018 MRS Spring Meeting & Exhibit
April 2 – 6, 2018, Phoenix, Arizona

MRS MATERIALS RESEARCH SOCIETY®
Advancing materials. Improving the quality of life.
506 Keystone Drive • Warrendale, PA 15086-7573
Tel 724.779.3003 • Fax 724.779.8313
info@mrs.org • www.mrs.org

https://doi.org/10.1557/mrs.2017.8 Published online by Cambridge University Press