Applications of Cementitious Materials within the DOE Complex - 17548

Devon McClane*, Elizabeth Hoffman*, Amy Ramsey*
*Savannah River National Laboratory, Aiken SC, 29803

ABSTRACT

Cementitious materials are used in a variety of ways for the containment, treatment and disposal of waste. This document explores some of these applications and provides a review of how cementitious materials have been used across the Department of Energy (DOE) complex. The intent is to highlight cementitious waste formulations, installations, experimental work, and modeling efforts supported by a variety of DOE programs. Further focus is provided regarding how/where cementitious materials are used for: waste stream treatment, production of containment structures, closure of tanks, in-situ decommissioning of reactors, and environmental restoration.

INTRODUCTION

The Department of Energy (DOE) is tasked with managing the legacy defense wastes that resulted from nuclear materials production and nuclear arms development. Nuclear-waste management encompasses generation, processing (treatment and packaging), storage, transport, and disposal[1]. To date, there are over 100 million gallons of liquid radioactive and chemical mixed wastes within the Department of Energy complex as well as solid waste, debris, and environmental restoration media that require disposal[2].

The ultimate disposal paths for these wastes depend on the source, waste classification, type, concentration, expected lifetime of contaminants present, the type(s) of storage and/or disposal required, as well as the regulations associated with each[3].

The use of cementitious materials is technically mature, with thousands of papers written on the hydration and setting of cement[4-6]. The comprehensive characterization of cementitious materials, relative simplicity of low-temperature processing, and (comparatively) low price tag, is why they are a popular means for disposal of low level (LLW), intermediate, and secondary wastes. Only the Hanford Site plans to vitrify low-activity waste (LAW).

In addition to highlighting how the DOE has used/uses cementitious materials for treating/disposing of waste, this paper also provides a broad-based review of the implementations, experimental work/research, and modeling efforts performed within the DOE complex with/on these materials, and is intended to serve as a directory on where more information pertaining to how cementitious materials have been utilized to serve the DOE mission can be found. Implementations include: processing, immobilizing, isolating and housing of LLW, intermediate, and secondary solid and liquid wastes.

IMPLEMENTATIONS

Waste Treatment

Cementitious materials are often selected for treating a wide variety of low level waste that typically contains the following contaminants: Ce, Cs, Hg, I, Sr, Tc, Th, transuranic (TRU), and those categorized under the Resource Conservation and Recovery Act (RCRA)[2, 7].

The primary objective of a cementitious waste form is to solidify/stabilize the waste to prohibit environmental exposure. This is typically done by encapsulating and/or sorbing the contaminants in the cementitious matrix. Several formulations for incorporating/immobilizing waste have been studied[3, 8-15], and similar dry-blend compositions are currently in use at both Savannah River Site (SRS) (45 wt% slag cement, 45 wt% Class F fly ash, and 10 wt% Type I/II Portland cement) and Hanford (47 wt% blast furnace slag, 45 wt% Class F fly ash, and 8 wt% Type I/II Portland cement)[12]. Once these dry-blends have been mixed with the liquid waste, they are pumped into disposal units. An example of how this final waste form is stored is shown in Figure 1.

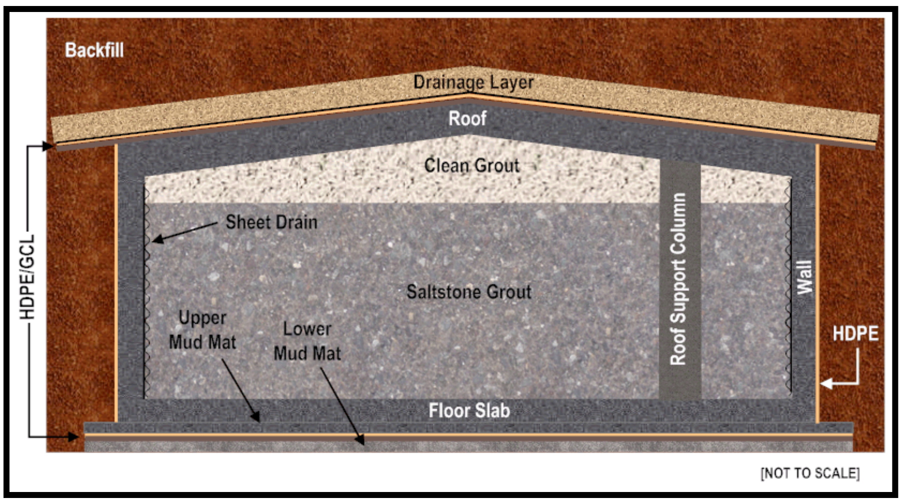

Figure 1: Containment Structure for Saltstone Disposal[16]

A table illustrating the magnitude of cementitious materials used for the treatment of waste at the Savannah River Site (SRS) Saltstone Disposal Facility (SDF) is shown below.

Table I FY2016 Saltstone Processing Summary[17]

	Saltstone Disposal Unit 5A	Saltstone Disposal Unit 5B	Total in SDF during FY2016
FY2016 Volume of Salt Waste Disposed (L)	~5.2 x 10^6	~4.7 x 10^5	~5.7 x 10^6
FY2016 Volume of Saltstone Emplaced (L)	~9.1 x 10^6	~8.7 x 10^5	~10 x 10^6
FY2016 Curies Disposed (Bq)	~3.1 x 10^{14}	~1.6 x 10^{13}	~3.2 x 10^{14}

Much of the recent experimental work has largely concentrated on waste forms, with particular focus typically on one of three distinct areas; 1) increasing/maximizing the waste loading in cementitious waste forms[18-22], 2) improving the retention of waste form contaminants such as Tc, I, and Hg[12, 23-26], and 3) elucidating how waste forms/containment structures change with time under a variety of environments in an attempt to supplement modeling efforts on long term performance[16, 27-38]. Other research efforts have focused on providing an alternative material, such as Ceramicrete™ (chemically bonded phosphate ceramics) and DuraLith (aluminosilicate geopolymer), to ordinary cements and alkali-activated cements (i.e. slag containing cements) for treating radioactive and hazardous wastes[5, 23, 39, 40].

Containment Structures

Cementitious materials are also used for a variety of structural applications for containing and/or isolating waste. Some of these include vaults (such as the E-Area low level waste vaults at SRS)[41, 42], secondary containment for tanks, basins (such as the waste encapsulation storage facility basin at Hanford)[43, 44], and disposal units[45]. Construction of a 184 foot long (~56 meter) by 83 foot (~25 meter) wide basin, made with Type K cement, located in Oak Ridge, Tennessee is shown in Figure 2.

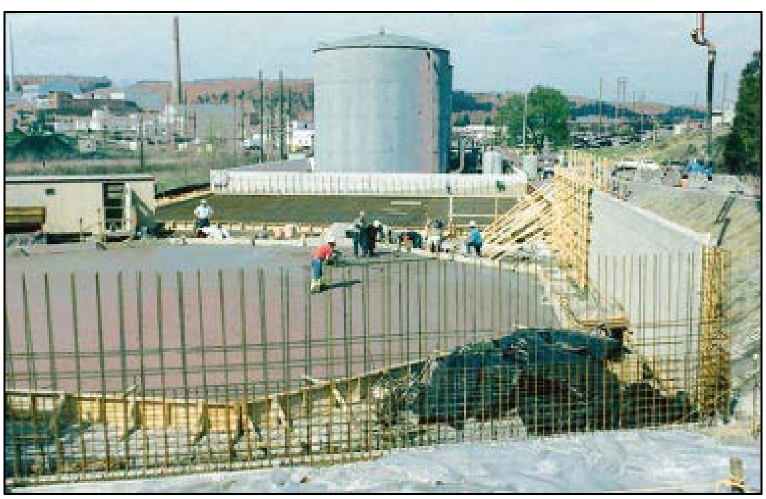

Figure 2: Construction of Concrete Basin at Oak Ridge[43]

A few of the disposal units present at SRS are shown in Figure 3a. For perspective the disposal units labeled SDU 2, 3 and 5 are 150 feet (~46 meters) in diameter and 22 feet (~7 meters) high with a capacity of approximately 2.9 million gallons (~11 million liters). The new generation unit labeled SDU 6 is 375 feet (~114 meters) in diameter and 44 feet (~13 meters) high with a capacity of over 32 million gallons (~121 million liters), the inside of which is shown in Figure 3b.

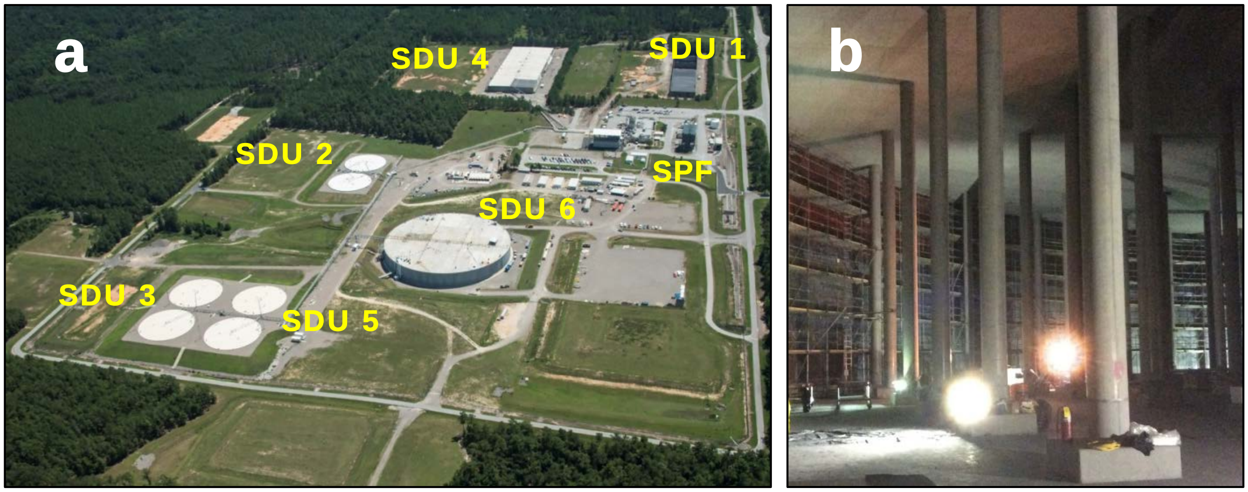

Figure 3: (a) Aerial View of Saltstone Disposal Units (SDUs) at SRS, (b) Inside View of SDU 6

Of particular interest, is how these containment structures withstand time due to interaction with the environment and radiation exposure. Because of this interest, these structural containments are monitored and their performance is assessed[46].

Tank Closure

There are over 330 tanks within the DOE complex that require closure. Closure refers to the process of filling an emptied waste tank with cementitious fill material to ensure the tank does not collapse, and that no incidental release of remaining contaminants occurs[4, 47]. Modest progress has been made to date. The Savannah River Site (SRS) has successfully closed Tanks 17-F, 20-F, 18-F, 19-F, 5-F, 6-F, 16-H, and 12-H [47-50]. The Idaho Nuclear Technology and Engineering Center (INTEC) has closed four 110 m^3 and seven 1100 m^3 tanks at the Tank Farm Facility (TFF)[51]. Additionally, West Valley has pre-treated[52] and evaporated the liquid from tanks 8D-1, 8D-2, 8D-3, and 8D-4[53] as they work towards completing closure of their tanks.

Some of the challenges of tank closure include the presence of residual waste, or “heels”, and also interior tank artifact equipment (such as cooling coils and air lift circulators) that must also be considered[54]. Because of these challenges, strategic cleaning[51] and pour strategies have been implemented to incorporate waste that could not safely be removed; an example of this pour strategy is shown in Figure 4.

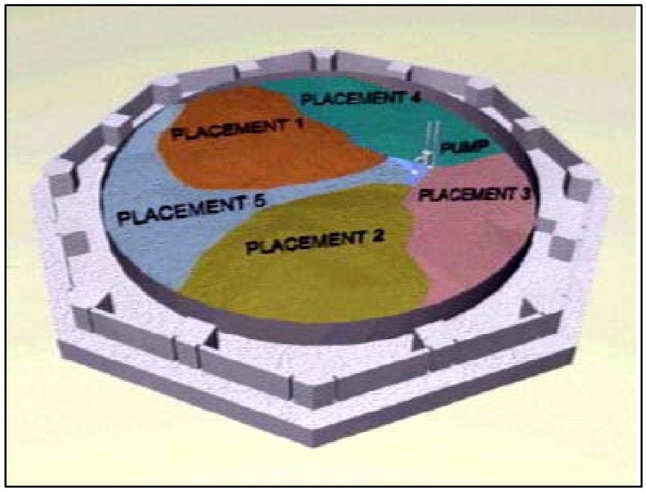

Figure 4: Sequential Grout Placement During Tank Closure at the Idaho National Laboratory[54]

As identified by Langton et al., cementitious materials used for filling tanks at the Hanford Site must be self-leveling and pumpable, have a low viscosity, set in the order of weeks to months, have minimal bleed water, be resistant to solids segregation, have a low heat of hydration, be capable of irreversibly sorbing/stabilizing contaminants of interest, be resistant to leaching for 500 to 1000 years, and be capable of flowing through soils[2]. Many of these criteria are required throughout the DOE complex[55]. Figure 5 below shows the emptied out Tank 18 (at SRS) which previously held more than 1 million gallons (~ 4 million liters) of waste, being filled.

Figure 5: SRS Tank 18 Being Filled with Cementitious Material

In-situ Decommissioning

In-situ decommissioning has been used throughout the DOE complex for isolating the radioactive and hazardous components of a facility such that it is left in a safe state[56-60], and is predominantly adopted when it has been evaluated to be safer and more cost effective than complete demolition, removal and transport[61]. In this process, a cementitious material is used to selectively fill areas of the reactor facility, permanently entombing and stabilizing residual contaminants and debris below grade[62].

In-situ decommissioning requires a cementitious mix that can be easily pumped, is sufficiently flowable to reach remote locations, is self-leveling, can incorporate additives to counteract set-times, and exhibits long term stability[61]. An illustration of this process that was successfully utilized for decommissioning of the P-Reactor at the Savannah River Site (SRS) is shown in Figure 6.

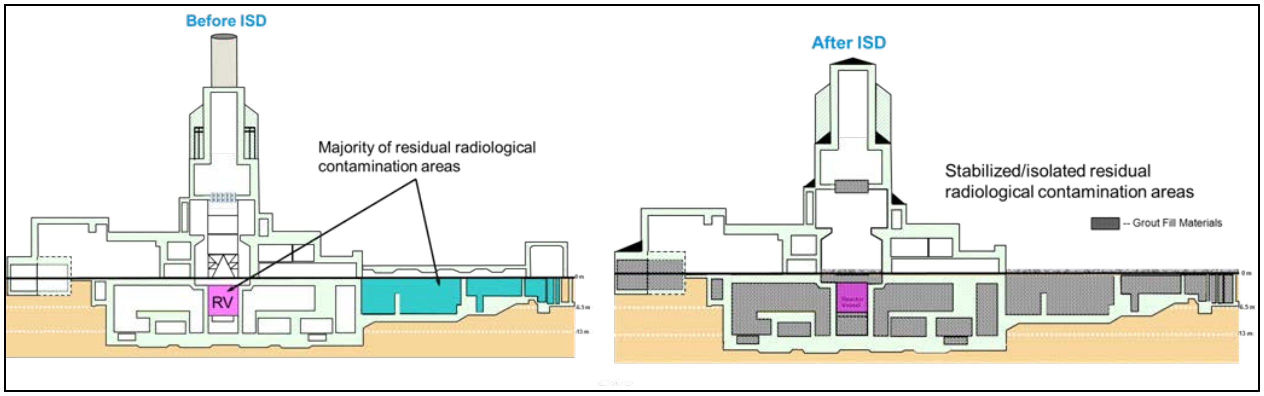

Figure 6: Illustration of In-Situ Decommissioning of P-Reactor at SRS[63]

Environmental Restoration

Environmental restoration refers to the process of remediating hazardous wastes to restore damaged or degraded ecosystems. Examples of this include seepage basins[64, 65], and curtains[66-68]. One example of a grout curtain can be seen at SRS, where deep soil mixing with a low permeable grout was utilized to form a barrier to minimize contaminant migration to groundwater)[67, 68]. This installation, shown in Figure 7, covered a linear distance of 1400 feet (~427 meters) and depths of 70 feet (~21 meters).

Figure 7: F-Area Seepage Basin Grout Wall During (Left) and After (Right) Installation at SRS.

SRS has also investigated permeable active amendment concrete (PAAC) to allow for insitu remediation of contaminants and provide an alternative to capping[69].

CONCLUSIONS

To date cementitious materials have been used in a variety of ways for the containment, treatment and disposal of large quantities of waste within the DOE complex. Applications range from incorporating liquid waste constituents into a cementitious-based matrix, and containing/isolating waste materials; to decommissioning facilities, closing tanks, capping contaminated soils and encompassing waste constituents for long term disposal. Significant work has been done to identify the processing/performance parameters required for specific applications, and many research/modeling efforts have been focused on methods to increase waste loading and predicting and improving long term material performance.

REFERENCES

1. M.-S. Yim and K. Linga Murty, "Materials Issues in Nuclear-Waste Management," *JOM*, 52, 9 (2000).

2. C. A. Langton, R. D. Spence and J. Barton, "State of the Art Report on High-Level Waste Tank Closure (U)," WSRC-TR-2001-00359, Revision 0, Westinghouse Savannah River Company, Aiken, SC (2001).

3. C. A. Langton, "Cementitious Waste Form Design and Evaluation," SRNL-TR-2015-00307, Revision 0, Savannah River National Laboratory, (2016).

4. R. T. Pabalan, F. P. Glasser, D. A. Pickett, G. R. Walter, S. Biswas, M. R. Juckett, L. M. Sabido and J. L. Myers, "Review of Literature and Assessment of Factors Relevant to Performance of Grouted Systems for Radioactive Waste Disposal," CNWRA 2009-001, (2009).

5. J. T. Case, H. C. Johnson, T. M. Broun, J. A. Roach and P. C. Suggs, "Independent Analysis of Alternatives for Disposition of the Idaho Calcined High-Level Waste Inventory Volume 1 - Summary Report," U.S. DOE-EM, (2016).

6. G. Kwong, "Cementitious Materials in Safety Cases for Radioactive Waste: Role, Evolution and Interactions," NEA/RWM/R(2012)3/REV, Nuclear Energy Agency (2012).

7. A. B. Gould, "Waste Management Final Environmental Impact Statement Volume I," DOE/EIS-0217, Savannah River Site Aiken, South Carolina (1995).

8. V. Maio, R. K. Biyani, R. D. Spence, G. Loomis, G. Smith and A. Wagh, "Testing of Low-Temperature Stabilization Alternatives for Salt Containing Mixed Wastes-Approach and Results to Date," ORNL/CP-98259, (1998).

9. "Stabilization of High Salt Waste Using a Cementitious Process," DOE/EM-0500, Oak Ridge National Laboratory, Oak Ridge, Tennessee (1999).

10. J. E. Kessler, G. C. Rogers, L. R. Dole and M. T. Morgan, "Formitlation and Durability of Tailored Cementitious Hosts Applied to Tru Waste Generated at the Rocky Flats Plant," Oak Ridge National Laboratory, Oak Ridge, Tennessee (1982).

11. M. N. Baker and H. M. Houston, "Cement Encapsulation of Low-Level Waste Liquids Final Report," DOE/NE/44139-84, West Valley Nuclear Servieces Co., Inc., West Valley, New York (1999).

12. R. Serne and J. W. Jr., "Data Package for Secondary Waste Form Down-Selection - Cast Stone," PNNL-20706, Pacific Northwest National Laboratory, Richland, Washington (2011).

13. M. M. Reigel, B. R. Pickenheim and W. E. Daniel, "Process Formulations and Curing Conditions That Affect Saltstone Properties," SRNL-STI-2012-00558, Savannah River National Laboratory, Aiken, SC (2012).

14. M. H. Layton, *Evaluation of the Use of Grade 120 Slag Cement in Tank Closure Grout Versus Performance Assessment Assumptions*, (2015). Found at: <http://pbadupws.nrc.gov/docs/ML1605/ML16057A491.pdf>

15. P. A. Spooner, G. E. Hunt, V. E. Hodge and P. M. Wagner, "Compatibility of Grouts with Hazardous Wastes," JRB Associates, Inc., McLean, Virginia (1984).

16. G. P. Flach, C. A. Langton, H. H. Burns, F. G. Smith, D. S. Kosson, K. G. Brown, E. Samson, J. C. L. Meeussen, P. Seignette and H. A. v. d. Sloot,

"Cementitious Barriers Partnership Fy2014 End-Year Report," CBP-TR-2015-009, Rev. 0, (2015).

17. L. A. Wooten, "Determination of the SDF Inventory through 9/30/2016," SRR-CWDA-2016-00111, Savannah River Remediation LLC, Aiken, SC (2016).

18. R. D. Spence and C. Shi, *Stabilization and Solidification of Hazardous, Radioactive, and Mixed Wastes*, CRC Pess, Boca Raton, FL (2005).

19. R. D. Spence and A. J. Mattus, "Laboratory Stabilization/Solidification of Tank Sludges: Maximizing Sludge Loading," *Journal of Environmental Management*, 70, 3 (2004).

20. K. M. Fox, A. D. Cozzi, E. K. Hanson and K. A. Hill, "Low Temperature Waste Form Process Intensification: FY2015 Progress Report," SRNL-STI-2015-00448, Savannah River National Laboratory, Aiken, SC (2015).

21. D. L. McClane, A. D. Cozzi, K. A. Hill and E. K. Hansen, "Low Temperature Waste Form Process Intensification: FY16 Progress Report," SRNL-STI-2016-00565, Revision 0, Savannah River National Laboratory, Aiken, SC (2016).

22. K. M. Fox, K. A. Roberts and T. B. Edwards, "Cast Stone Formulation at Higher Sodium Concentrations," SRNL-STI-2013-00499, Revision 2, Savannah River National Laboratory, Aiken, SC (2014).

23. E. Pierce, R. Serne, W. Um, S. Mattigod, J. Icenhower, N. Qafoku, J. JH Westsik and R. Scheele, "Review of Potential Candidate Stabilization Technologies for Liquid and Solid Secondary Waste Streams," PNNL-19122, Pacific Northwest National Laboratory, (2010).

24. P. M. Almond, D. B. Stefanko and C. A. Langton, "Effect of Oxidation on Chromium Leaching and Redox Capacity of Slag-Containing Waste Forms," CBP-TR-2013-02, Rev. 0, Savannah River National Laboratory, Aiken, SC (2013).

25. C. A. Langton, "Tc Oxidation in Slag-Based Sodium Salt Waste Forms Exposed to Water and Moist Hanford Soil," CBP-TR-2014-005, Rev. 0, Savannah River National Laboratory, Aiken, SC (2014).

26. R. Spence, "Mass: Mercury Amalgamation Stabilization/Solidification," Found at: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.595.6879&rep=rep1&type=pdf>

27. C. A. Langton and D. M. Missimer, "X-Ray Diffraction of Slag-Based Sodium Salt Waste Forms," SRNL-STI-2014-00397, Revision 1, Savannah River National Laboratory, Aiken, SC (2014).

28. J. P. Petti, D. Naus, A. Sagues, R. E. Weyers, B. A. Erler and N. S. Berke, "Nuclear Containment Steel Liner Corrosion Workshop: Final Summary and Recommendation Report," SAND2010-8718, Sandia National Laboratory, Albuquerque, New Mexico (2011).

29. S. Sarkar, D. S. Kosson, S. Mahadevan, H. Meeussen, H. v. d. Sloot, K. G. Brown, G. Flach and C. Langton, "Effects of Various Factors on Durability Prediction of Nuclear Waste Containment Structures - 11546," *WM Symposia*, Phoenix, AZ, (2011).

30. S. Sarkar, S. Mahadevan, J. C. L. Meeussen, H. v. d. Sloot, K. Brown and D. S. Kosson, "Probabilistic Durability Analysis of Cementitious Materials under Combined Sulfate Attack and Calcium Leaching – 10149," *WM Symposia*, Phoenix, AZ, (2010).

31. W. P. Kubilius and C. Bagwell, "Method Development for Studying Gas Transport through Porous Cementitious Materials," CBP-TR-2015-011, (2015).

32. J. R. Harbour, "Summary of Grout Development and Testing for Single Shell Tank Closure at Hanford," WSRC-TR-2005-00195, Savannah River National Laboratory, Aiken, SC (2005).

33. *Research Information Letter, “Assessing the Performance of Cement Based Materials as Engineered Barriers for Isolating Radioactive Waste”*, Found at: <http://www.nrc.gov/docs/ML0608/ML060800524.pdf>

34. R. Pabalan and D. Pickett, "Cementitious Materials for Waste Treatment, Disposal, Remediation, and Decommissioning Workshop; Leachxs Training Seminar," (2006).

35. C. A. Langton, D. S. Kosson, A. C. Garrabrants and K. G. Brown, "Reference Cases for Use in the Cementitious Barriers Partnership Project - 9446," *WM Symposia*, Phoenix AZ, (2009).

36. F. P. Glasser, D. Macphee, M. Atkins and R. W. M. R. Programme, *Immobilization of Radwaste in Cement Based Matrices: Cement/Slag Chemistry Studies*, Department of the Environment Radioactive Waste Management Research Programme, (1988).

37. "The Behaviours of Cementitious Materials in Long Term Storage and Disposal of Radioactive Waste Results of a Coordinated Research Project," IAEA-TECDOC-1701, International Atomic Energy Agency, Vienna (2013).

38. C. A. Langton and D. S. Kosson, "Review of Mechanistic Understanding and Modeling and Uncertainty Analysis Methods for Predicting Cementitious Barrier Performance," CBP-TR-2009-002, (2009).

39. A. S. Wagh and D. Singh, "Stabilization Using Phosphate Bonded Ceramics," DOE/EM-0486, Argonne National Laboratories-East, Chicago, Illinois (1999).

40. W. Gong, W. Lutze and I. Pegg, "Duralith Alkali-Aluminosilicate Geopolymer Waste Form Testing for Hanford Secondary Waste," VSL-10R2140-1, Rev. 1, Vitreous State Laboratory, Washington, DC (2011).

41. *Low Level Waste Management, Disposal and Shipping at the Savannah River Site*, (2002). Found at: <http://www.srs.gov/general/news/factsheets/llwmds.pdf>

42. E. Wilhite, "E-Area Low-Level Waste Facility DOE 435.1 Performance Assessment," WSRC-STI-2007-00306, Revision 0, Washington Savannah River Company LLC, Aiken, SC (2008).

43. J. W. BAKER, *Using Type K Cement in Waste-Containment Structures*, (1998). Found at: <http://www.concreteconstruction.net/how-to/repair/using-type-k-cement-in-waste-containment-structures_o>

44. D. Millikin and G. Tyree, *Waste Encapsulation and Storage Facility*, (2016). Found at: <http://chprc.hanford.gov/files.cfm/WESF_Factsheet.pdf>

45. "Technical Evaluation Report for the Revised Performance Assessment for the Saltstone Disposal Facility at the Savannah River Site, South Carolina," U.S. Nuclear Regulatory Commission Office Of Federal And State Materials And Environmental Management Programs, Washington, DC (2012).

46. C. A. Langton and D. S. Kosson, "Overview of the U.S. Department of Energy and Nuclear Regulatory Commission Performance Assessment Approaches," CBP-TR-2009-001, (2009).

47. C. A. Langton, D. B. Stefanko, H. H. Burns, J. Waymer, W. B. Mhyre, J. E. Herbert and J. C. J. Jr., "Cementitious Grout for Closing Srs High Level Waste Tanks - #12315," *WM Symposia*, Phoenix, AZ, (2012).

48. *Radioactive Liquid Waste: Operational Closure of Tanks*, (2016). Found at: <http://www.srs.gov/general/news/factsheets/srr_tank_closure.pdf>

49. J. Petersen and D. Campbell, *Grouting Complete for Closure of 7th Srs Waste Tank*, (2015). Found at: <http://www.srs.gov/general/news/releases/nr15_srr-tank-16-grouting-completed.pdf>

50. C. R. H. Jr., L. T. Ling and J. L. Newman, "A Successful Innovative Approach to High Level Radioactive Waste Tank Closure at DOE's Savannah River Site," *WM Symposia*, (1998).

51. C. A. Langton and J. R. Cook, "Recent Progress in DOE Waste Tank Closure," *WM Symposium*, Phoenix, AZ, (2008).

52. S. K. Jr. and D. C. Meess, "Thorex Processing and Zeolite Transfer for High-Level Waste Stream Processing Blending," DOE/NE/44139-82, West Valley Nuclear Services Company, Inc., West Valley, New York (1997).

53. B. Bower, *West Valley Demonstration Project Decommissioning Status*, (2014). Found at: <http://www.wv.doe.gov/Document_Index/QPM%20Feburary%202014/2014-02-26%20Decommissioning%20Status.pdf>

54. N. R. Council, *Tank Waste Retrieval, Processing, and on-Site Disposal at Three Department of Energy Sites: Final Report*, The National Academies Press, Washington, DC (2006).

55. T. B. Caldwell, "Tank Closure Reducing Grout (U)," WSRC-TR-97-0102, Westinghouse Savannah River Company, Aiken, SC (1997).

56. A. T. Armstrong, D. A. Arrenholz and J. R. Weidner, "Evaluation of in Situ Grouting for Operable Unit 7-13/14," INEEL/EXT-01-00278, Idaho National Engineering and Environmental Laboratory, (2002).

57. P. Shaw, "Grout Selection Criteria and Recommendation for the Ou 7-13/14 in Situ Grouting Project," EDF-5333, Idaho National Engineering and Environmental Laboratory, (2004).

58. NEI, *Decommissioning Status for Shut Down Us Nuclear Power Reactors*, (2016). Found at: <http://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/Decommissioning-Status-for-Shut-Down-US-Nuclear-Po>

59. D. B. Stefanko and C. A. Langton, "Blended Calcium Aluminate-Calcium Sulfate Cement-Based Grout for P-Reactor Vesselin-Situ Decommissioning (U)," SRNL-STI-2010-00427 Revision 0, Savannah River National Laboratory, Aiken, SC (2011).

60. C. A. Negin, C. S. Urland and A. P. Szilagyi, "In Situ Decommissioning Lessons Learned – 14042," *WM Symposia*, Phoenix, Arizona, (2014).

61. J. Musall, *Srs P and R Reactor Disassembly Basin in Situ Decommissioning*, (2012). Found at: <https://www.dndkm.org/DOEKMDocuments/BestPractices/26-EFCOG%20Best%20Practice%20-%20SRS%20P%20and%20R%20Reactor%20Basins%20ISD%20Final.pdf>

62. *Innovative Solutions for Decommissioning Large Nuclear Facilities*, Found at: <http://srnl.doe.gov/facts/srnl_is002_d_and_d_larg_facilities.pdf>

63. M. Serrato, *Srs Reactor in-Situ Decommissioning and Long Term Monitoring*, (2012),

64. *Savannah River Laboratory Seepage Basins*, (2003). Found at: <http://www.srs.gov/general/news/factsheets/ersrlsb.pdf>

65. "K Basins Sludge Treatment Process Technology Readiness Assessment," RL-F-1325.6, (2007).

66. R. Noyes, *Nuclear Waste Cleanup Technologies and Opportunities*, Elsevier Science, (2013).

67. *Aiken, Sc: Deep Soil Mixing, Groundwater Barrier Extension at the F-Area Seepage Basin*, (2014). Found at: <http://www.geo-solutions.com/soil-barrier-walls-aiken-sc>

68. "Soil and Groundwater Closure Projects Technology Descriptions," WSRC-RP-99-4015, Savannah River Site, Aiken, SC (2007).

69. A. S. Knox, M. H. Paller and K. L. Dixon, "A Permeable Active Amendment Concrete (Paac) for Contaminant Remediation and Erosion Control," SRNL-STI-2012-00356, Savannah River National Laboratory, Aiken, SC (2012).

ACKNOWLEDGEMENTS

Funding by the U.S. Department of Energy Office of Environmental Management under the Cementitious Materials Integrity Program [program number 4262/HQTD1001] is gratefully acknowledged. The authors would also like to thank Kent Rosenberger (SRR, LLC) and Jeffrey Thibault (SRNS, LLC) for providing several of the images shown above.

DISCLAIMER