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OTHER FEATURES

Opportunities for US-Russian collaboration on the safe disposal of nuclear waste

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ABSTRACT

The United States and Russia both possess large quantities of nuclear waste, generated during the production of nuclear energy and nuclear weapons. To ensure that this radioactive material remains safely sequestered for tens of thousands of years or more, both countries plan to bury it in deep geologic repositories. However, US and Russian repository design strategies are highly distinct. For example, Russia plans to dilute waste in aluminophosphate glass, package waste in stainless steel containers, and bury waste in hard, crystalline granite gneiss rock. The US approach includes the use of borosilicate glass, multi-component superalloy containers, and porous volcanic tuff or highly-plastic bedded salt. The relative efficacies of these design choices remain uncertain. This represents a unique opportunity for applied, comparative study of various natural and engineered barriers to the release of radioactive materials. US-Russian collaboration and sharing of data on repository performance could provide a better technical basis for the long-term immobilization of nuclear waste.

KEYWORDS

Nuclear waste; geologic repositories; nuclear fuel cycle; US-Russia relations

Russia and the United States share a common legacy of nuclear waste production and a common need to safely and effectively manage this waste. Both have operated nuclear reactors for more than six decades. Today, nuclear energy accounts for roughly 20 percent of electricity generation in both the United States and Russia (US Energy Information Administration 2020; International Atomic Energy Agency 2020). This nuclear energy is unavoidably accompanied by the production of vast quantities of nuclear wastes. The United States possesses approximately 80,000 metric tons of civilian high-level radioactive waste; Russia possesses about 24,000 metric tons (Laverov et al. 2016; Nuclear Energy Institute 2019). Much of this is in the form of spent fuel composed largely of uranium, as well as transmutation productions (e.g. plutonium, neptunium, and americium) and fission products (e.g. cesium, strontium, and iodine) produced during the irradiation of fuel (Bruno and Ewing 2006). Low level wastes resulting from nuclear energy generation, including contaminated clothing or equipment exposed to neutron irradiation, constitute another nuclear waste stream (Yim and Simonson 2000).

Alongside these civilian inventories, Russia and the United States possess the vast majority of the world's weapons plutonium and highly enriched uranium – fissile materials from which nuclear weapons are constructed (International Panel on Fissile Materials 2015). Much of this material has been declared excess to military needs and must be disposed of. Furthermore, the past production of these fissile material stockpiles and of nuclear arsenals has yielded large quantities of radionuclide-contaminated wastes. This totals 340,000 metric tons of material in the United States, and likely similar quantities in Russia (US Department of Energy 1997).

These diverse nuclear waste inventories necessitate the disposal of large quantities of radioactive material. In both nations, nuclear wastes are currently stored primarily in temporary, above-ground storage facilities. To be sure, a portion of this material might be diverted to other purposes, as with Russian plans to recycle plutonium from spent fuel and weapons stockpiles for use in mixed-oxide (MOX) fuel (Diakov 2013). But plutonium recycling generates its own wastes, and many components of fuel cycle waste streams – fission products, for example – cannot be recycled in this manner (Krall and Macfarlane 2018). Thus, both nations face the common challenge of establishing a safe, effective, long-term means of nuclear waste disposal.

Both nations have identified deep geologic disposal, in which waste is packaged and buried in a subsurface geologic repository, as their preferred means of nuclear waste management (Laverov et al. 2016; Swift and Bonano 2016; Ewing, Whittleston, and Yardley 2016). This approach is attractive because the local geology can serve as a barrier to the release of radiotoxic material to the surface, where it could pose a serious and persistent threat to public health. But transport of radioactive material through these geologic media remains possible, due to factors such as rock porosity and groundwater

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flow (Ryan and Kipp 1997). So both nations plan to use multi-barrier systems, in which the geologic barrier is complemented with multiple, layered, engineered barriers to radionuclide release (Ewing, Whittleston, and Yardley 2016). The latter include metallic containers in which wastes are packaged, as well as durable oxide solids into which radionuclides are diluted (Figure 1).

Despite these broad similarities, the Russian and US waste management strategies differ in several key respects. The geologic settings of their repositories, the metals used for waste packaging, and the materials in which waste are to be immobilized all differ (Laverov et al. 2016). In many cases, these distinctions reflect technical uncertainties regarding the effects of design choices on repository performance. While these uncertainties make waste management and repository design more challenging, they also present opportunities for cooperation and collaboration between Russia and the United States. As these two nations execute their distinct waste management plans, they might treat their operating repositories as "underground laboratories" – large-scale experiments in geologic disposal of nuclear waste that provide a basis for comparative study. The sharing of operational experience and repository performance data between Russia and the United states could help to resolve many technical uncertainties, and would yield a stronger technical basis for nuclear waste management.

Unfortunately, collaboration between Russia and the United States on nuclear waste management is lacking. Political tensions have impeded this style of bilateral research and development activity. However, there exists a strong precedent for cooperation in this area. Consider, for example, Russia's development of its geologic repository, in which it has consistently based its design on the results of "research done internationally in the existing underground laboratories" (Polyakov et al. 2014). Current planning states that a key step in the design process is "submitting a long-term safety case to international experts" (Nikitin 2018). Similarly, the design of a planned US repository was guided by "a joint peer review panel composed of top international experts assembled by the International Atomic Energy Agency and the Organization for Economic Cooperation and Development's Nuclear Energy Agency," although this panel regrettably failed to include Russian experts (US Senate Committee on Environment and Public Works Majority Staff 2006; OECD Nuclear Energy Agency and International Atomic Energy Agency 2002).

Here, we survey the key differences between the Russian and US nuclear waste disposal strategies, identifying specific areas in which collaboration and data sharing could help to resolve important scientific and technical uncertainties. In keeping with the multi-barrier design of Russian and US repositories, we consider three of these barriers in turn, starting with the geologic setting of the repository, proceeding to the containers in which wastes are packaged, and concluding with analysis of the waste form material.

The US repositories: Yucca Mountain and the Waste Isolation Pilot Plant

The most apparent barrier to the release of radionuclides from a geologic repository to the surface is the rock into which the repository is mined. The local

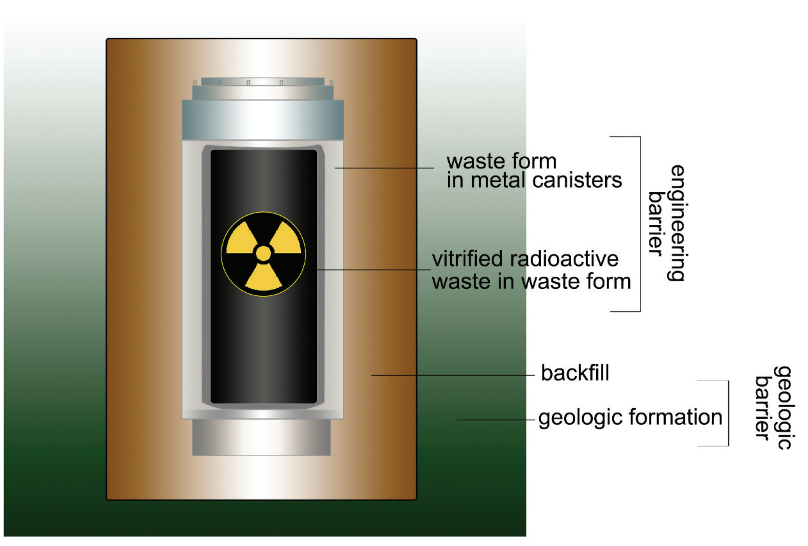

Figure 1. Illustration of a multi-barrier system, in which engineering barriers and geologic barriers act in tandem to prevent or slow radionuclide release.

geology and geochemistry determine the efficacy of this geologic barrier; different settings can have distinct hydrological characteristics and rock types, for example, which influence radionuclide transport properties. The geologic settings selected for operating and planned repositories in Russia and the United States are highly distinct. The United States has opted for disposal of wastes in "soft" rocks – tuff and salt – while Russia has chosen "hard" crystalline granite gneisses (Laverov et al. 2016; Swift and Bonano 2016; Metlay 2016).

For nearly four decades, the United States planned, designed, and began initial construction of a large repository for spent nuclear fuel. This facility is located under Yucca Mountain in Nye County, Nevada, about 160 kilometers northwest of Las Vegas. Yucca Mountain formed several million years ago following a series of volcanic eruptions and is composed primarily of volcanic tuff, which includes compacted ash and rock fragments that settled following the eruptions (Price and Bauer 1985). The main rock units consist of a magmatic upper zonation featuring an upper crystal-rich member and a lower crystal-poor member with an interbedded thin transition zone. The repository is to be excavated in the voluminous crystal-poor member, at a depth of about 180 meters below the mountain's crest (Keefer, Whitney, and Buesch 2007).

This setting offers several advantages. First, the facility is located in an arid region characterized by closed hydrologic basins (Swift and Bonano 2016). This inhibits the long-range transport of radionuclides through groundwater flows. Second, it is placed far from major population centers, minimizing the potential public health effects of near-field radionuclide release and transport. Finally, the site does not contain significant quantities of economically valuable natural resources, so it is unlikely to be inadvertently disturbed by mining activity in the far future, after institutional controls have ceased to prevent such activity (Keefer, Whitney, and Buesch 2007).

But these advantages are balanced by several challenges unique to the site, arising primarily from its geologic characteristics (Ewing and Macfarlane 2002). First, tuff is a highly porous rock, having formed from the compaction of loose ash and other fragmentary rock. Typical porosities are in the range of 10 percent to 40 percent, and this porosity commonly retains water (Long and Ewing 2004). Therefore, the repository setting cannot be considered dry, despite the arid climate. Second, the repository site exhibits oxidizing geochemical conditions. Many important radionuclides – particularly actinide elements like uranium and plutonium – have been shown to become highly mobile in oxidizing environments (Maher, Bargar, and Brown 2013). This mobility is further enhanced by the formation of colloids in groundwater (Novikov et al. 2006). Third, Yucca Mountain is an area of high seismic activity (Swift and Bonano 2016). Over 600 seismic events of magnitude greater than 2.5 on the Richter scale were recorded within a 50 mile radius of the mountain between 1976 and 1992 (State of Nevada 1999). This introduces a substantial threat to the long-term structural integrity of the repository.

In addition to the Yucca Mountain repository, the United States currently operates the Waste Isolation Pilot Plant (WIPP). Located in southeastern New Mexico, approximately 42 kilometers east of the city of Carlsbad, WIPP is the world's only currently-operating geologic repository for nuclear waste. Unlike Yucca Mountain, which is meant to store spent fuel and other high-level wastes, WIPP stores transuranic waste, mainly contaminated clothing, equipment, and debris from legacy weapon production activities (Nelson 2011).

WIPP is mined 650 meters below ground in bedded salt. This is a low porosity, low permeability material due to its plastic nature, which allows it to rapidly flow to close unfilled cavities (Chan, Bodner, and Munson 1998). The setting is seismically stable and exhibits relatively low water concentrations (Butcher 1993; Powers et al. 1978). Furthermore, salt possesses high thermal conductivity, enabling the fast dissipation of heat generated by radioactive wastes (Bauer and Urquhart 2016). But this setting is also characterized by the presence of pressurized brine pockets underlying the repository. Were these punctured, release of the pressurized brine could carry radionuclides to nearby groundwater flows (Tracy, Dustin, and Ewing 2016). In addition, these salt deposits can be collocated with valuable geologic resources, including natural gas and potash, increasing the likelihood of inadvertent intrusion into the repository by future mining activities (US Department of Energy 1993).

The Russian repository: Yeniseisky

Russia is constructing its Yeniseisky repository four kilometers from the city of Zheleznogorsk in the Krasnoyarskiy region of Siberia. This repository will house both high-level wastes and intermediate-level wastes with long-lived radionuclides (Laverov et al. 2016). In contrast to the geologic settings chosen for the two US repositories – tuff and salt – the Yeniseisky repository is mined into crystalline Archean granite gneisses. These strong, structurally rigid rocks differ from the "soft rock" settings characteristic of the US repositories (Ewing and Park 2021). Furthermore, the repository is located below the water table, in contrast to the setting of the Yucca Mountain repository (Laverov et al. 2016). Combined with the presence of sulfides in the surrounding rock, this yields reducing conditions (the opposite of oxidizing conditions) that minimize the environmental mobility of many important radionuclides (Tsang, Neretnieks, and Tsang 2015).

As with the US repositories, there are several challenges associated with this setting. First, the site is bounded by large faults and is subject to regular seismic activity (Kochkin and Petrov 2015). Recorded earthquake events reach up to magnitude 8 on the Richter scale, which poses a threat to the integrity of the repository (Laverov et al. 2016; Kochkin and Petrov 2015). Second, the site is located in a several hundred meter thick permafrost zone. The associated rock fractures can enable groundwater flow near the repository (Laverov et al. 2016). Climatic changes could alter these conditions, making it more difficult to predict the long-term state of the repository's geologic setting.

A comparison: "Hard" versus "soft" rock

Clearly, the geologic settings of the Russian and US repositories are highly distinct, with each offering particular advantages and disadvantages. These distinctions are summarized in Table 1. Which setting is superior, in terms of the ability of the geologic barrier to restrict the release of radionuclides to the environment, remains an open question. However, these distinctions in repository design offer a unique opportunity for comparative study. Once the repositories are operational, sharing of data on their performance, including the results of environmental monitoring to track the rates of radionuclide release and transport, could serve as a valuable input into future repository design.

Waste packaging: US and Russian waste container designs

The containers in which nuclear wastes are packaged serve as barriers between the waste form and its geologic environment. These typically take the form of cylindrical, metallic casks or drums a few hundred liters in volume (Yim and Murty 2000). To effectively separate radionuclides from the environment, these containers must maintain their integrity for long timescales, even under exposure to mechanical stresses from the surrounding geologic media (possibly exacerbated by seismic activity) and corrosion by groundwater (possibly enhanced by chemicals present in the repository). As with their choices in repository geologic setting, the Russian and US waste disposal strategies diverge when it comes to waste container design.

The United States has selected two distinct containers for use at the Yucca Mountain and WIPP repositories. For high-level wastes at Yucca Mountain, an advanced, multi-component waste container was designed, consisting of a stainless steel interior (austenitic 316 steel) surrounded by a nickel-based superalloy exterior (US Department of Energy 2002). The superalloy possesses corrosion resistance superior to that of the steel and was selected to enhance the long-term stability of the containers in Yucca Mountain's oxidizing geochemical conditions. In the repository design, these advanced containers would be further covered by titanium drip shields to protect them from water that might fall from the ceilings of the repository shafts (US Department of Energy 2002).

For WIPP, the US makes use of a simpler double-walled container design, typically consisting of a stainless steel flanged pipe within a larger stainless steel drum (Reedlunn and Bean 2019). Similar containers composed of stainless or carbon steels are planned for use by Russia at the Yeniseisky repository. A total container wall thicknesses of 15 millimeters is planned (Laverov et al. 2016).

Table 1. Waste packaging: US and Russian waste container designs.

		Yucca Mountain	WIPP	Yeniseisky
Geologic barrier	Rock type	Volcanic tuff	Salt beds	Granite gneiss
	Porosity	High	Low	Low
	Structural strength	Medium	High	High
	Geochemical conditions	Oxidizing	Reducing	Reducing
	Disposal horizon	200 meters above the water table	655 meters below ground	450–525 meters below ground
Engineering barrier	Waste packaging	Stainless steel/nickel-based superalloy	Stainless steel	Stainless or carbon steels
	Waste form	Borosilicate glass, various	Various	Aluminophosphate glass, various
Others	Wastes intended for disposal	Spent nuclear fuel, high level wastes	Transuranic wastes	High level wastes, intermediate level waste with long-lived radionuclides
	Compliance period	100,000 years	10,000 years	10,000 years

The complex, multi-component superalloy container designed for use at Yucca Mountain differs from the simpler stainless steel containers in several respects, most notably in cost. Both the superalloy and the titanium sheets planned for use as drip shields are significantly more costly than stainless steel and are more difficult to work and machine. This use of expensive, high-performance packaging materials to enhance corrosion resistance mirrors the approach of Sweden and Finland, which use costly copper containers in their nuclear waste repository designs (King, Lilja, and Vähänen 2013).

But the question of whether the enhanced corrosion resistance that these containers might provide justifies their higher cost, relative to stainless steel containers, remains unresolved. Russian experts contend that such containers are not worth the expense, arguing that "from the Russian perspective, the use of containers made of expensive [metal] leads to unjustified cost without a significant improvement in safety" (Laverov et al. 2016).

As with their distinctions in geologic setting, these differences in the proposed US and Russian high-level waste containers represents an opportunity for comparative study. Sharing of data on post-emplacement container integrity as a function of time could elucidate the utility, or lack thereof, of the more complex, multi-component containers, relative to simpler stainless steel containers. This would build on a history of multilateral cooperation on nuclear waste container design, such as that which took place under the auspices of the International Atomic Energy Agency (IAEA) in the early 2000s, which included both US and Russian experts (International Atomic Energy Agency 2000).

Materials for waste immobilization

The final barrier to radionuclide release is the material in which radionuclides are diluted, known as a nuclear waste form material. Many such materials have been proposed and studied, including a wide range of durable, crystalline ceramics (Ewing 1999). However, Russian and US waste immobilization carried out to date has focused instead on vitrification of waste – its incorporation in non-crystalline glass materials (Ojovan and Lee 2011).

Vitrification is advantageous in several respects (Ojovan and Lee 2011). Glasses can incorporate a large number of radionuclide elements into a single phase, since these radionuclides need not fit into an ordered, crystalline structure. That allows for the relatively simple vitrification of complex waste streams such as those from spent fuel, which contain a range of actinides and lighter fission products. Glasses exhibit minimal reactivity with the chemical environments typical of repository conditions. Finally, they generally exhibit high radiation tolerance; that is, they are inherently capable of incorporating high degrees of structural disorder of the sort induced by irradiation-induced atomic displacements.

Although both Russian and US waste management strategies make use of vitrification, each nation has selected a distinct glass material, each offering unique benefits and drawbacks. The United States uses borosilicate glasses based on networks of silicon-oxygen (SiO_4) tetrahedra (Manaktala 1992). The addition of small quantities of borate (BO_3) reduces the thermal expansivity of the glass, inhibiting cracking caused by temperature gradients. This can increase the long-term durability of radionuclide-bearing glasses, in which radioactive decay can yield substantial heating.

In contrast, Russia uses sodium aluminophosphate glass based on networks of phosphorus-oxygen (PO_4) tetrahedra. This material can incorporate higher radionuclide concentrations than can borosilicate glasses, serving to reduce the volume of vitrified material necessary to immobilize a given volume of nuclear waste (Day, Ray, and Kim 2004). However, aluminophosphate glasses tend to react with refractory materials commonly used in glass melt processing (Ojovan, Lee, and Kalmykov 2019). This can make the vitrification process quite complex and costly, relative to that of borosilicate glasses.

A key, unresolved question is apparent: Is the increased waste loading achievable with aluminophosphate glasses worth the added complexity of waste form processing, relative to that of borosilicate glasses? Also, is the performance of one glass type superior to that of the other in terms of radionuclide immobilization (as determined by radionuclide diffusivity, leach rate, etc.)? In one sense, this national divergence in waste-form material selection is the inverse of the previously discussed divergence in waste container design. While the United States has favored complex, costly containers, as opposed to the Russian preference for cheaper stainless steel drums, Russia has opted for more advanced, yet difficult to process, aluminophosphate glass, in contrast to the US preference for simpler borosilicate glass.

As with questions regarding the efficacy of design choices related to repository geologic setting and metallic container materials, comparison of Russian and US waste disposal system operation could help to resolve questions associated with waste glass performance. Comparison of long-term waste form integrity and leach rates, determined via inspection of emplaced wastes, could indicate which waste form best immobilizes radionuclides.

Opportunities for future collaboration

These distinctions between Russian and US approaches to the geologic disposal of nuclear waste – geologic setting, waste container design, and waste form glass material – offer several opportunities for comparative study of the effects of these design choices on repository performance. Data sharing on, for example, radionuclide release rates to nearby groundwater or waste form integrity as a function of time would yield an improved technical basis for nuclear waste management. It would also produce useful quantitative data on radionuclide mobility under various disposal conditions (geochemical conditions, repository chemical inventory, etc.), providing improved inputs for mathematical modeling of long-term repository performance, as is critical to repository safety and risk analysis. In this concept, operating Russian and US repositories could serve as vast underground laboratories. Waste emplacement would constitute a long-term, international experiment, serving to elucidate the specific repository characteristics and combinations of characteristics that best sequester nuclear wastes from the environment over geologic timescales.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Bauer, S., and A. Urquhart. 2016. "Thermal and Physical Properties of Reconsolidated Crushed Rock Salt as a Function of Porosity and Temperature." *Acta Geotechnica* 11: 913. doi:10.1007/s11440-015-0414-8.

Bruno, J., and R. C. Ewing. 2006. "Spent Nuclear Fuel." *Elements* 2: 343. doi:10.2113/gselements.2.6.343.

Butcher, B. M. 1993. "The Advantages of a Salt/Bentonite Backfill for Waste Isolation Pilot Plant Disposal Rooms." *MRS Proceedings* 333: 911. doi:10.1557/PROC-333-911.

Chan, K. S., S. R. Bodner, and D. E. Munson. 1998. "Recovery and Healing of Damage in WIPP Salt." *International Journal of Damage Mechanics* 7: 143. doi:10.1177/105678959800700204.

Day, D. E., and C-W. Kim. 2004. "Iron Phosphate Glasses: An Alternative for Vitrifying Certain Nuclear Wastes." Rolla, MO: Graduate Center for Materials Research, University of Missouri-Rolla. doi:10.2172/839298.

Diakov, A. 2013. "Status and Prospects for Russia's Fuel Cycle." *Science & Global Security* 21: 167. doi:10.1080/08929882.2013.837333.

Ewing, R. C. 1999. "Nuclear Waste Forms for Actinides." *Proceedings of the National Academy of Sciences* 96: 3432. doi:10.1073/pnas.96.7.3432.

Ewing, R. C., and A. Macfarlane. 2002. "Yucca Mountain." *Science* 296: 659. doi:10.1126/science.1071886.

Ewing, R. C., and S. Park. 2021. "The Concept of Geological Disposal of Highly Radioactive Nuclear Waste." *Refence Module in Earth Systems and Environmental Sciences*. doi:10.1016/B978-0-12-819725-7.00156-2.

Ewing, R. C., R. A. Whittleston, and B. W. D. Yardley. 2016. "Geological Disposal of Nuclear Waste: A Primer." *Elements* 12: 233. doi:10.2113/gselements.12.4.233.

International Atomic Energy Agency. 2000. "Multi-Purpose Container Technologies for Spent Fuel Management." https://www-pub.iaea.org/MTCD/Publications/PDF/te_1192_prn.pdf

International Atomic Energy Agency. 2020. "Country Nuclear Power Profiles: Russian Federation." www.cnpp.iaea.org/countryprofiles/Russia/Russia.htm

International Panel on Fissile Materials. 2015. "Global Fissile Material Report 2015." http://fissilematerials.org/library/gfmr15.pdf

Keefer, W. R., J. W. Whitney, and D. C. Buesch. 2007. "Geology of the Yucca Mountain Site Area, Southwestern Nevada." In *The Geology and Climatology of Yucca Mountain and Vicinity, Southern Nevada and California*, edited by J. S. Stuckless and R. A. Levich, Geological Society of America. doi:10.1130/2007.1199(03).

King, F., C. Lilja, and M. Vähänen. 2013. "Progress in the Understanding of the Long-Term Corrosion Behaviour of Copper Canisters." *Journal of Nuclear Materials* 438: 228. doi:10.1016/j.jnucmat.2013.02.080.

Kochkin, B. T., and V. A. Petrov. 2015. "Long-Term Prediction for Seismic Hazard for Radioactive Waste Disposal." *Russian Geology and Geophysics* 56: 1074. doi:10.1016/j.rgg.2015.06.008.

Krall, L., and A. Macfarlane. 2018. "Burning Waste or Playing with Fire? Waste Management Considerations for Non-Traditional Reactors." *Bulletin of the Atomic Scientists* 74: 326. doi:10.1080/00963402.2018.1507791.

Laverov, N. P., S. V. Yudintsev, B. T. Kochkin, and V. I. Malkovsky. 2016. "The Russian Strategy of Using Crystalline Rock as a Repository for Nuclear Waste." *Elements* 12: 253. doi:10.2113/gselements.12.4.253.

Long, J. C. S., and R. C. Ewing. 2004. "Yucca Mountain: Earth-Science Issues at a Geologic Repository for High-Level Nuclear Waste." *Annual Review of Earth and Planetary Sciences* 32: 363. doi:10.1146/annurev.earth.32.092203.122444.

Maher, K., J. R. Bargar, and G. E. Brown Jr. 2013. "Environmental Speciation of Actinides." *Inorganic Chemistry* 52: 3510. doi:10.1021/ic301686d.

Manaktala, H. K. 1992. "An Assessment of Borosilicate Glass as a High-Level Waste Form." San Antonio TX: Center for Nuclear Waste Regulatory Analyses. https://www.nrc.gov/docs/ML0336/ML033650021.pdf

Metlay, S. 2016. "Selecting a Site for a Radioactive Waste Repository: A Historical Analysis." *Elements* 12: 269. doi:10.2113/gselements.12.4.269.

Nelson, R. A. 2011. "WIPP Status and Plans – 2011." In *WM2011 Conference*, 11039. http://archive.wmsym.org/2011/papers/11039.pdf

Nikitin, A. 2018. "The Underground Research Laboratory." *Bellona Working Paper*. https://bellona.org/publication/the-underground-research-laboratory

Novikov, A. P., S. N. Kalmykov, S. Utsunomiya, R. C. Ewing, F. Horreard, A. Merkulov, and S. B. Clark, et al. 2006. "Colloid Transport of Plutonium in the Far-Field of the Mayak Production Association, Russia." *Science* 314: 638. doi:10.1126/science.1131307.

Nuclear Energy Institute. 2019. "Safe, Secure Transportation of Used Nuclear Fuel." https://www.nei.org/resources/fact-sheets/safe-secure-transportation-used-nuclear-fuel

OECD Nuclear Energy Agency and International Atomic Energy Agency. 2002. "An International Peer Review of the Yucca Mountain Project TSPA-SR: Total System Performance Assessment for the Site Recommendation (TSPA-SR)." https://www.oecd-nea.org/upload/docs/application/pdf/2019-12/nea3682-yucca.pdf

Ojovan, M. I., and W. E. Lee. 2011. "Glassy Wasteforms for Nuclear Waste Immobilization." *Metallurgical and Materials Transactions A* 42: 837. doi:10.1007/s11661-010-0525-7.

Ojovan, M. J., W. E. Lee, and S. N. Kalmykov. 2019. "Immobilisation of Radioactive Wastes in Glass." In *An Introduction to Nuclear Waste Immobilization*, 319. 3rd ed. Amsterdam: Elsevier. doi:10.1016/C2017-0-03752-7

Polyakov, Y. D., A. Y. Porsov, V. P. Beiful, and M.V. Palenov. 2014. "Setting up a Safe Deep Repository for Long-Lived HLW and ILW in Russia: Current State of the Works." In *The Safety Case for Deep Geological Disposal of Radioactive Waste: 2013 State of the Art Symposium Proceedings*, 293. Paris: Organization for Economic Co-operation and Development. https://inis.iaea.org/collection/NCLCollectionStore/_Public/46/027/46027340.pdf?r=1

Powers, D. W., S. J. Lambert, S-E. Shaffer, L. R. Hill, and W. D. Weart. 1978. "Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico." Albuquerque, NM: Sandia National Laboratory Report. doi:10.2172/6441454.

Price, R. H., and S. J. Bauer. 1985. "Analysis of the Elastic and Strength Properties of Yucca Mountain Tuff, Nevada." In *26th U.S. Symposium on Rock Mechanics*, edited by E. Ashworth, 89. Accord, MA: A. A. Balkema.

Reedlunn, B., and J. Bean. 2019. "Simulations of Pipe Overpack Container Compaction at the Waste Isolation Pilot Plant." Albuquerque, NM: Sandia National Laboratories. doi:10.2172/1570309.

Ryan, B. J., and K. L. Kipp Jr. 1997. "Ground-Water Flow and Contaminant Transport of a Radioactive-Materials Processing Site, Wood River Junction, Rhode Island." *U.S. Geological Survey Professional Paper*, 1571. doi:10.3133/pp1571.

State of Nevada. 1999. "Earthquakes Rocking Yucca Mountain Area." http://www.state.nv.us/nucwaste/news/quake/quake1.htm

Swift, P. N., and J. Bonano. 2016. "Geological Disposal of Nuclear Waste in Tuff: Yucca Mountain (USA)." *Elements* 12: 263. doi:10.2113/gselements.12.4.263.

Tracy, C. L., M. K. Dustin, and R. C. Ewing. 2016. "Policy: Reassess New Mexico's Nuclear-Waste Repository." *Nature* 529: 149. doi:10.1038/529149a.

Tsang, C., I. Neretnieks, and Y. Tsang. 2015. "Hydrologic Issues Associated with Nuclear Waste Repositories." *Water Resources Research* 51: 6923. doi:10.1002/2015WR017641.

US Department of Energy. 1993. "Compliance Certification Application for the Waste Isolation Pilot Plant." Appendix IRD, Title 40, CFR Part 191.91-029.

US Department of Energy. 1997. "Linking Legacies: Connecting the Cold War Nuclear Weapons Production Processes to Their Environmental Consequences." Office of Environmental Management.

US Department of Energy. 2002. *Yucca Mountain Science and Engineering Report Technical Information Supporting Site Recommendation Consideration*. North Las Vegas, NV: Office of Civilian Radioactive Waste Management. https://www.energy.gov/sites/prod/files/edg/media/SER.PDF

US Energy Information Administration. 2020. "What is U.S. Electricity Generation by Energy Source?" www.eia.gov/tools/faqs/faq.php?id=427&t=3

US Senate Committee on Environment and Public Works Majority Staff. 2006. "Yucca Mountain: The Most Studied Real Estate on the Planet."

Yim, M., and K. L. Murty. 2000. "Materials Issues in Nuclear-Waste Management." *JOM* 52: 26. doi:10.1007/s11837-000-0183-0.

Yim, M., and S. A. Simonson. 2000. "Performance Assessment Models for Low Level Radioactive Waste Disposal Facilities: A Review." *Progress in Nuclear Energy* 36: 1. doi:10.1016/S0149-1970(99)00015-3.