Bulletin of the Atomic Scientists

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/rbul20

Sociotechnical risks posed by the geologic disposal of weapons plutonium

Cameron L. Tracy

To cite this article: Cameron L. Tracy (2025) Sociotechnical risks posed by the geologic disposal of weapons plutonium, Bulletin of the Atomic Scientists, 81:1, 36-42, DOI: 10.1080/00963402.2024.2441045

To link to this article: https://doi.org/10.1080/00963402.2024.2441045

Published online: 13 Jan 2025.

BULLETIN OF THE ATOMIC SCIENTISTS
2025, VOL. 81, NO. 1, 36–42
https://doi.org/10.1080/00963402.2024.2441045

Sociotechnical risks posed by the geologic disposal of weapons plutonium

Cameron L. Tracy

ABSTRACT
The United States possesses a large stockpile of excess weapons plutonium. Following a failed attempt to bilaterally dispose of this material under an arms control agreement with Russia, the United States now plans to bury it at the Waste Isolation Pilot Plant (WIPP), a geologic repository in southeastern New Mexico. This is a new mission for WIPP, which was originally designed to store radioactive wastes from nuclear weapons production, not excess weapons plutonium. It raises questions about whether this repository can safely contain weapons plutonium for the thousands of years it remains a threat to the environment, secure weapons plutonium from illicit extraction and weaponization, and do all of this in a cost-effective manner.

KEYWORDS
Weapons plutonium; geologic repository; nuclear waste disposal; Waste Isolation Pilot Plant; arms control

The United States has a plutonium problem. This heavy metal, rarely found in nature but produced by nuclear reactors, is a primary ingredient of nuclear weaponry. A modern thermonuclear weapon, containing just a few kilograms of this material, could level much of a metropolitan area. During the Cold War, the United States and the Soviet Union produced enough plutonium to make tens of thousands of nuclear weapons (IPFM 2015). Both the United States and Russia, which inherited the Soviet nuclear weapons enterprise, have since declared large portions of their stockpiles to be excess: unnecessary for purposes of national defense. But after decades of effort and billions of dollars spent trying to dispose of this material, their weapons plutonium stockpiles remain undiminished (von Hippel and Takubo 2020).

The United States currently plans to bury about one third of this stockpile in the Waste Isolation Pilot Plant (WIPP), a geologic repository mined 650 meters below the surface of southeastern New Mexico's Delaware Basin (NASEM 2020). Preparation to dispose of this material is well underway, but key questions about this approach remain unresolved. Will the repository safely contain this radiotoxic material over the thousands of years for which it presents a threat to the environment? Can the repository be effectively secured against attempts to illicitly recover weaponizable material? Can all of this be accomplished on a realistic schedule and budget?

None of these questions have easy answers, in part because they are inherently sociotechnical, posing complex challenges that are simultaneously scientific, technological, political, economic, and social in nature (Bijker and Law 1994). Given sufficient effort, funding, and good fortune, the United States may arrive at a workable solution to its plutonium problem. But until questions of safety, security, and cost are addressed, and the associated risks are weighed, agreement on just what it means for a geological plutonium repository to "work" is likely to remain out of reach.

How did we get here?

After the fall of the Soviet Union in 1991, US and Russian concerns about the risks posed by large plutonium stockpiles came to overshadow the prior focus on nuclear arms racing. US discourse emphasized the risk of nuclear proliferation if the newborn Russian state were to lose control over its stockpile, but also recognized that the oversize US stockpile was costly to maintain and secure (Perkovich 1993). In addition, plutonium stockpiling limited the permanence of the bilateral nuclear arms reductions achieved by the US and Soviets in recent decades, as the removal of weapons from deployment could be quickly reversed so long as their plutonium remained available (Cliff, Elbahtimy, and Persbo 2011).

Recognizing these risks, the US National Academy of Science and its Russian counterpart met in 1992 to discuss the issue (NASEM 1994). This agenda eventually rose to the highest levels of government, serving as a centerpiece of discussion between Presidents Bill Clinton and Boris Yeltsin over the next few years. By 2000, the United States and Russia had negotiated and signed the Plutonium Management and Disposition Agreement (PMDA), pledging to reciprocally dispose of 34 metric tons of excess weapons plutonium.

CONTACT Cameron L. Tracy cltracy@stanford.edu

Negotiation of this landmark agreement gave rise to one of the earliest sociotechnical controversies over plutonium disposal: disagreement on how it should be effectively disposed of. US analyses concluded that dilution of this metal by mixing with another, non-weaponizable material would do little, since "plutonium in weapons-useful quantities could be recovered from any of the forms in the disposition program," requiring only modest expenditure and technical skill (Hinton et al. 1996). Disposing of plutonium underground could help to secure it from theft, but it would remain "recoverable by the state that emplaced it, providing a plutonium mine with substantially more plutonium in each ton of rock than there is gold in some mines that are profitably mined today" (NASEM 1994). Meanwhile, Russian negotiators insisted that any means of disposal that failed to change the isotopic composition of the material—that is, which did not involve exposure to irradiation that would induce nuclear reactions in the weapons plutonium—was "just another form of storage" (Bunn 2007). Facing these constraints, both sides agreed to a primary disposal method that was complex and difficult, but jointly seen as effective: conversion of weapons plutonium to nuclear fuel and irradiation in nuclear power plants.

Despite this diplomatic achievement, progress on bilateral plutonium stockpile reduction was short-lived. Construction began on the US facility that would convert this material to nuclear fuel in 2007, but in less than a decade, cost estimates grew from initial projections of a few billion dollars to over one-hundred billion (Hart et al. 2015). In 2016, the Obama administration unilaterally pivoted from the irradiation approach mandated by the plutonium disposal agreement with Russia to a new plan: burial in WIPP. Russia balked at this shift. In an April 2016 speech in St. Petersburg, Russia's president, Vladimir Putin, accused the United States of seeking to "preserve what is known as the breakout potential," disposing of plutonium in name only while ensuring that it could be "retrieved, reprocessed, and converted into weapons-grade plutonium again." Citing this, alongside a broad array of other grievances related to steadily worsening US-Russian relations amid the Russo-Ukrainian War, Russia suspended its commitment to the bilateral plutonium disposal agreement later that year.

A new mission for WIPP

In one sense, the unraveling of the bilateral agreement presented an opportunity for the plutonium disposal mission in the United States. No longer bound by international diplomacy and arms control processes, the disposal program could proceed as the United States saw fit. At the same time, this represented a setback, as the program lost the momentum and political leverage that came with carrying out what one congressional report had deemed "one of the most important nonproliferation initiatives undertaken between the United States and Russia" (US House of Representatives 2001). Regardless, sociotechnical challenges remained, though now largely localized to a patch of desert in southeastern New Mexico.

WIPP is mined into the underground salt formations left behind when the Delaware Sea—once covering portions of southern New Mexico and western Texas—drained hundreds of millions of years ago (Keller, Hills, and Djeddi 1980). Congress established the facility as a pilot project, a "research and development facility to demonstrate the safe disposal of radioactive wastes resulting from the defense activities and programs" (US Congress 1979). WIPP was originally designed to store wastes made up of clothing, gloves, lab equipment, and other detritus contaminated with heavy, radioactive elements like plutonium, which was sitting at nuclear weapons production sites scattered across the United States. Following decades of site characterization, repository design, and construction—alongside $2.5 billion in funding—WIPP accepted its first shipment of this material in 1999 (Feder 1999).

WIPP's mission now extends far beyond its original role as a demonstration project. As the sole US site for the disposal of actinide wastes (referring to the class of heavy, radioactive elements including uranium and plutonium), it is now slated as the permanent disposal site for the 34 metric tons of excess weapons plutonium covered by the now defunct US-Russia plutonium disposal agreement. This is a major shift from WIPP's original design basis, and has introduced new sociotechnical challenges to the safe, secure, and effective operation of the repository—and, therefore, to the plutonium stockpile reduction mission to which it is now intimately tied. What started as a pilot program to aid in the clean-up of contaminated Cold War weapons production facilities is now both a potential solution to the long-standing problem of excess weapons plutonium disposal, and a potential threat to both the environment and to global nuclear security. Whether this one-of-a-kind experiment on the long-term safety, security, and risk of the geologic disposal of nuclear materials is ultimately judged a success or failure will depend on its ability to meet several complex challenges.

Challenge 1: isolating radioactive material from the biosphere

WIPP's central role is to isolate potentially dangerous materials deep underground, preventing the leakage of radioactive material to the surface or to groundwater flows. Designed to store about 12 metric tons of plutonium, it is now slated to contain nearly four times that inventory (Tracy, Dustin, and Ewing 2016). Of course, more radioactive material means greater potential for its release.

To forecast the risk of release, every five years the US Department of Energy, which operates WIPP, performs a repository performance assessment and submits the results to the US Environmental Protection Agency (EPA 2022). This performance assessment uses computational models to estimate the likelihood and extent of releases of radioactive material from WIPP over a 10,000-year period. Federal law defines this performance assessment as "an analysis that identifies the processes and events that might affect the disposal system, examines the effects of these processes and events on the performance of the disposal system, and estimates the cumulative releases of radionuclides … caused by all significant processes and events" (Code of Federal Regulations 1985). However, predicting the future is challenging, even when legally mandated.

Consider, for instance, one of the key repository failure modes: borehole intrusion. WIPP is located is the Permian Basin, which is currently the most prolific oil-producing region in the United States (EIA 2024). High levels of drilling in the area, including immediately adjacent to the repository site, present a significant risk that a borehole might one day pierce the repository, allowing groundwater to flow through it and transport radioactive material to the surface (Tracy, Dustin, and Ewing 2016). To estimate the magnitude of this risk over the next 10 millennia, the Department of Energy feeds into its performance assessment model a historical average drilling rate in the region over the last 100 years (EPA 2022). There is a clear problem with this methodology: Drilling in the region was virtually nonexistent prior to 1960 and rose exponentially following a boom in the early 1990s. In its original performance assessment from 1996, the Department of Energy extrapolated its 100-year average, predicting 46.8 boreholes per square kilometer in the vicinity of WIPP over the next 10,000 years. Were it to now revise this prediction using a 10-year historical average the estimate would be 15 times higher (DOE 2024). This is not to argue that a shorter time window is superior. Rather, since drilling rates do not vary regularly over decades, an attempt to forecast them over the next 10 millennia constitutes a poor basis for risk analysis.

Still, Department of Energy analysts have argued that the drilling rate they predict is, in fact, irrelevant: "as the drill rate per square kilometer increases, so do the frequencies of boreholes intersecting the repository, but the net result is a continuing large margin in terms of demonstrating regulatory compliance" (Van Luik, Patterson, and Kirkes 2015). Assuming that regulatory compliance corresponds with repository safety, this speaks to a high level of confidence in the failsafe mechanisms designed to prevent radioactive material release even in the event of borehole intrusion into the repository. Chief among these is the addition of large sacks of magnesium oxide powder that sit atop the barrels of waste emplaced in WIPP. This powder is intended to chemically react with groundwater flows that might make their way into the repository, greatly reducing the environmental mobility of plutonium and other radioactive materials in those flows (Krumhansl et al. 1999).

To be sure, this chemical failsafe might work as intended. But adding complexity to nuclear systems, even in the name of safety, often has deleterious effects. Consider, for instance, the experimental Fermi 1 nuclear reactor built near Detroit in the 1950s. Late in the design process, concern that the reactor's nuclear fuel could overheat and melt through the containment vessel prompted engineers to add to the design heat-resistant metal plates that would catch melted fuel before it could damage the reactor. Ironically, the reactor suffered a meltdown in 1966 after one of those plates detached, blocking the flow of coolant through the reactor and causing the exact type of accident they were meant to mitigate (Fuller 1975). Since then, a body of work on "normal accident theory" has developed in order to explain why the design of complex safety systems can in fact make accidents more likely: "We load our complex systems with safety devices in the form of buffers, redundancies, circuit breakers, alarms, bells, and whistles … In complex and tightly coupled systems, however, these redundant safety devices are not independent: The alarm rattles the bell; the bell shatters the whistle; the whistle explodes; and suddenly the whole system collapses" (Perrow 2011).

In fact, these dynamics have already been observed at WIPP. In 2014, one of the waste drums emplaced in the repository exploded, releasing radioactive material that made its way to the surface. It was later determined that this accident was caused by the addition of new materials to the repository meant to enhance safety (DOE 2015). An earlier safety review process led to a directive that, when packaging certain liquid wastes for disposal at WIPP, absorbent materials should be added to the drums to absorb that liquid. The subsequent mixing of plutonium-contaminated nitrate salts with a wheat-based kitty litter later resulted in a predictable (although, at the time, unpredicted) chemical reaction between the two, causing the drum in which they were packaged to burst. When considering the behavior of magnesium oxide in the complex geochemical environment of a repository pierced by a borehole and infiltrated by groundwater, this should be taken as a cautionary tale.

None of this is to say that WIPP cannot operate safely. However, its ability to do so with the current plutonium inventory is uncertain, as uncertainties in long-term local drilling rates and repository chemistry demonstrate. A fourfold increase in WIPP's plutonium inventory will only add to this safety challenge.

Challenge 2: ensuring that buried plutonium remains buried

Recall the Russian argument that plutonium burial is merely a temporary, easily reversible means of disposal. While Russian perspectives matter less following the downfall of the bilateral plutonium disposal agreement, ensuring the permanence of disposal remains of the utmost importance. To date, the acquisition of weapons plutonium has posed the most costly and technologically challenging barrier to nuclear weapons production (OTA 1993). A world in which weapons plutonium could be mined like any other geologic resource would be one in which nuclear weapons were more readily attainable. Given plutonium's long half-life, this proliferation risk would persist for many millennia.

Most prior work on this issue has concluded that mining a geologic repository to recover weapons-usable material would be slow and highly observable, leaving ample time to stop those attempting it (IAEA 1988; Lyman and Feiveson 1998; Mongiello, Finch, and Baldwin 2013). This analysis assumes the use of conventional mining technique like quarrying, which requires the excavation of vast quantities of rock and produces large visual and seismic signatures. There is a problem with this assumption: this is not how salt (the geologic setting of WIPP) or actinides (the class of chemical elements that includes plutonium) are typically mined.

The use of two alternative techniques that were overlooked in the prior literature, salt-solution mining and in situ leaching, would allow rapid access to buried plutonium with minimal excavation (Tracy and Ewing 2022). Salt solution mining involves drilling of a single, narrow borehole into a salt deposit and pumping water down that borehole, then back to the surface, forming an underground cavern. This technique is currently the primary means of salt mining in the United States and is regularly performed at depths greater than that of WIPP (Warren 2016). In situ leaching involves pumping of a fluid designed to react with actinide elements into an underground ore body where it mobilizes those actinides, then back to the surface where they can be extracted from the fluid. Developed in the 1950s, in situ leaching is now the primary method of uranium extraction worldwide, uranium being an actinide element that is geochemically similar to plutonium (Seredkin, Zabolotsky, and Jeffress 2016).

Applied to WIPP, these techniques could provide access to large quantities of weapons plutonium via only a single borehole just tens of centimeters in diameter (Tracy and Ewing 2022). Plutonium might then be extracted in a matter of days. Afterwards, plastic flow of salt would seal the borehole, removing evidence of the clandestine extraction.

As above, this is not to say that WIPP could not securely prevent any future use of the weapons plutonium disposed of there. To date, however, the risks of recovery have been insufficiently studied, and WIPP's design does little to mitigate these risks. Thus, confidence in the security of weapons plutonium disposed of in WIPP is unwarranted. Most worryingly, much of the work on this issue has sought merely to dismiss the risk of plutonium recovery, rather than to establish a design basis for mitigating that risk.

Challenge 3: managing a complex and costly disposal program

Even if solutions were found for the safety and security challenges detailed above, there would still remain the monumental challenge of implementing those solutions alongside the unprecedented task of burying 34 metric tons of weapons plutonium over half-a-kilometer below ground. Two of the most serious obstacles to successful disposal are the cost and time required. As seen in the earlier US failure to construct a facility for converting this plutonium to nuclear reactor fuel, which presaged the failure of the US-Russia plutonium disposal agreement, financial and management challenges can doom even a technically straightforward program.

These challenges are uniquely substantive for the Department of Energy. Analysis of past projects of similar scope overseen by the part of this agency that manages the weapons plutonium stockpile shows that many were canceled before completion and that "of the few major projects that were successfully completed, all experienced substantial cost growth and schedule slippage" (Hunter et al. 2019). The Government

Accountability Office, a congressional organization that audits and evaluates US government agency performance, regularly cites management and budgetary failings in the Department of Energy's plutonium stockpile programs (GAO 2017).

Comparison with similar weapons stockpile reduction programs managed by other agencies highlights the Department of Energy's unique shortcomings in this area. Consider, for instance, the US Army's destruction of its chemical weapons stockpile. Like the plutonium stockpile reduction mission, this effort targeted excess weapons material, required highly complex disposal methods, and ultimately cost roughly $40 billion. Yet unlike the Department of Energy, which abandoned its original plutonium irradiation plans in the face of expanding costs and timelines, the Army showed a remarkable ability to maintain the necessary funding and carry forward the arsenal destruction mission, ultimately finishing in 2023 (Tracy 2023).

Given the Department of Energy's track record, financial and management difficulties should be expected with a project of this size. As the effort grows in cost and complexity, so too does the likelihood that it, like earlier plutonium disposal efforts, could come to be seen as infeasible and a target for cancellation.

Working toward a repository that "works"

The literature on processes of sociotechnical change shows that what it means for a technology to effectively "work" can be subjective and contentious. This is because groups of stakeholders often differ in their interests, and therefore in their recognition of the problems a technology is meant to solve and in their judgment of the proper means of doing so (Pinch and Bijker 1984). For technologies like geologic plutonium repositories, problems of risk come to the forefront: What level of risk is expected, what level is acceptable, and even how risk should be measured. Plutonium disposal presents a means of reducing global nuclear risk by shrinking stockpiles of weapons material—a yet unrealized dream of the post-Cold War world. At the same time, burial of this material at WIPP presents new risks of radioactive contamination of the environment, lower barriers to the production of nuclear weapons, and unsustainable cost overruns.

It remains to be seen how the United States will weigh, address, and perhaps mitigate these risks, as well as how analysts will judge its success. More immediate, however, is the risk to WIPP posed by ongoing mission creep. This one-of-a-kind experiment in radioactive waste isolation, originally designed as a small-scale demonstration project, has performed admirably over two-and-a-half decades. It could, over the years to come, provide much-needed data on the long-term behavior of nuclear waste in the geologic environment. The imposition of a dramatically expanded plutonium inventory and a fundamentally different mission, however, introduces new threats to its continuing success. These range from unanticipated chemical interactions and the geopolitical dynamics of nuclear arms control to the more mundane challenges faced by bureaucratic organizations trying to manage complex, capital-intensive projects.

Another relevant lesson from the literature on sociotechnical change is the process of "closure" by which technological controversies end (Pinch and Bijker 1984). Technologies are typically judged to succeed when relevant communities—designers, consumers, users, and others—reach agreement on their understandings of what it means for a technology to "work." Reaching closure often means doing one thing and doing it well, providing a basis for later refinement and differentiation of the technology. WIPP, with its recent mission creep, is being led in the opposite direction. If the goal is to establish a firm technical basis for nuclear waste disposal, now is the time to get WIPP back on course.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Notes on contributor

Cameron L. Tracy is a research scholar in the Center for International Security and Cooperation at Stanford University and a non-resident fellow in the Goldman School of Public Policy at the University of California, Berkeley. His research analyzes the global security implications of weapons technologies and the communication of technological risks between technical and policy communities.

ORCID

Cameron L. Tracy http://orcid.org/0000-0002-0679-8522

References

Bijker, W. E., and J. Law, eds. 1994. *Shaping Technology/Building Society: Studies in Sociotechnical Change*. Cambridge: MIT Press.

Bunn, M. 2007. “Troubled Disposition: Next Steps in Dealing with Excess Plutonium.” *Arms Control Today* 37. April. https://www.armscontrol.org/act/2007-04/features/troubled-disposition-next-steps-dealing-excess-plutonium.

Cliff, D., H. Elbahtimy, and A. Persbo. 2011. *Irreversibility in Nuclear Disarmament Practical Steps Against Nuclear Rearmament*. Verification Research, Training and Information Centre. https://www.vertic.org/media/assets/Presentations/Irreversibility_Launch_Presentation.pdf.

Code of Federal Regulations. 1985. “Part 191—Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes.” *Federal Register* 50 (182). https://www.ecfr.gov/current/title-40/chapter-I/subchapter-F/part-191.

DOE (Department of Energy). 2015. *Accident Investigation Report: Radiological Release Event at the Waste Isolation Pilot Plant*. February 14, 2014. Department of Energy. https://www.energy.gov/ehss/articles/accident-investigations-february-14-2014-radiological-release-waste-isolation-pilot.

DOE (Department of Energy). 2024. *Waste Isolation Pilot Plant Delaware Basin Monitoring Annual Report*. Department of Energy. https://wipp.energy.gov/Library/RES/LATA_24-100_Enclosure-2023_Delaware_Basin_Monitoring_Annual_Report_FINAL.pdf.

EIA (Energy Information Administration). 2024. *Permian Production Forecast Growth Driven by Well Productivity, Pipeline Capacity*. Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=62884.

EPA (Environmental Protection Agency). 2022. “Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant’s Compliance with the Disposal Regulations: Recertification Decision.” *Federal Register* 87 (85). https://www.federalregister.gov/documents/2022/05/03/2022-09209/criteria-for-the-certification-and-recertification-of-the-waste-isolation-pilot-plants-compliance.

Feder, T. 1999. “DOE Opens WIPP for Nuclear Waste Burial.” *Physics Today* 52 (5): 59–59. May. https://pubs.aip.org/physicstoday/article-abstract/52/5/59/410751/DOE-Opens-WIPP-for-Nuclear-Waste-Burial?redirectedFrom=PDF.

Fuller, J. G. 1975. *We Almost Lost Detroit*. New York: Reader’s Digest Press.

GAO (US Government Accountability Office). 2017. *Plutonium Disposition: Proposed Dilute and Dispose Approach Highlights Need for More Work at the Waste Isolation Pilot Plant*. US Government Accountability Office. https://www.gao.gov/products/gao-17-390.

Hart, M. J., N. F. Brown, M. J. Rokey, H. J. Huslage, J. D. Castron-Bran, N. Y. Lao, R. J. Duphily, et al. 2015. *Plutonium Disposition Study Options Independent Assessment: Phase 2 Report*. Washington: National Nuclear Security Administration. https://www.energy.gov/sites/prod/files/2018/02/f49/Plutonium_Disposition_Phase_2_TOR_082015_FINAL%5B1%5D.pdf.

Hinton, J. P., R. W. Barnard, D. E. Bennett, R. W. Crocker, M. J. Davis, H. J. Groh, E. A. Hakkila, et al. 1996. *Proliferation Vulnerability Red Team Report*. Albuquerque: Sandia National Laboratories. https://fissilematerials.org/library/doe96c.pdf.

Hunter, D. E., R. T. Hutton, M. Breen, P. F. Bronson, W. A. Chambers, G. A. Davis, D. S. Disraelly, et al. 2019. *Independent Assessment of the Two-Site Pit Production Decision: Executive Summary*. Institute for Defense Analyses. https://www.ida.org/-/media/feature/publications/i/in/independent-assessment-of-the-two-site-pit-production-decision-executive-summary/d-10711.ashx.

IAEA (International Atomic Energy Agency). 1988. *Advisory Group Meeting on Safeguards Related to Final Disposal of Nuclear Material in Waste and Spent Fuel*. International Atomic Energy Agency. https://inis.iaea.org/collection/NCLCollectionStore/_Public/19/101/19101685.pdf.

IPFM (International Panel on Fissile Materials). 2015. *Global Fissile Material Report 2015: Nuclear Weapon and Fissile Material Stockpiles and Production*. International Panel on Fissile Materials. https://fissilematerials.org/library/gfmr15.pdf.

Keller, G. R., J. M. Hills, and R. Djeddi. 1980. “A Regional Geological and Geophysical Study of the Delaware Basin, New Mexico and West Texas.” In *New Mexico Geological Society Guidebook, 31st Field Conference, Trans-Pecos Region*, edited by P.W. Dickerson, J.M. Hoffer, and J. F. Callender, 105–111. Socorro: New Mexico Geological Society. https://nmgs.nmt.edu/publications/guidebooks/downloads/31/31_p0105_p0111.pdf.

Krumhansl, J. L., H. W. Papenguth, P. C. Zhang, J. W. Kelly, H. L. Anderson, and J. O. E. Hardesty. 1999. “Behavior of MgO as a CO_2 Scavenger at the Waste Isolation Pilot Plant (WIPP), Carlsbad, New Mexico.” *MRS Online Proceedings Library* 608:155. https://link.springer.com/article/10.1557/PROC-608-155.

Lyman, E. S., and H. A. Feiveson. 1998. “The Proliferation Risks of Plutonium Mines.” *Science and Global Security* 7 (1): 119–128. https://scienceandglobalsecurity.org/archive/sgs07lyman.pdf.

Mongiello, R., R. Finch, and G. Baldwin. 2013. *Safeguards Approaches for Geological Repositories: Status and Gap Analysis*. Albuquerque: Sandia National Laboratories.

NASEM (National Academies of Science, Engineering, and Medicine). 1994. *Management and Disposition of Excess Weapons Plutonium*. Washington: The National Academies Press. https://nap.nationalacademies.org/catalog/2345/management-and-disposition-of-excess-weapons-plutonium.

NASEM (National Academies of Science, Engineering, and Medicine). 2020. *Review of the Department of Energy’s Plans for Disposal of Surplus Plutonium in the Waste Isolation Pilot Plant*. Washington: The National Academies Press. https://nap.nationalacademies.org/catalog/25593/review-of-the-department-of-energys-plans-for-disposal-of-surplus-plutonium-in-the-waste-isolation-pilot-plant.

OTA (US Congress Office of Technology Assessment). 1993. *Technologies Underlying Weapons of Mass Destruction*. Washington: Government Printing Office. https://ota.fas.org/reports/9344.pdf.

Perkovich, G. 1993. “The Plutonium Genie.” *Foreign Affairs* 72 (3): 153. https://www.jstor.org/stable/20045629.

Perrow, C. 2011. *Normal Accidents: Living with High Risk Technologies*. Princeton: Princeton University Press. https://press.princeton.edu/books/paperback/9780691004129/normal-accidents?srsltid=AfmBOooKzny1w4Z4BV2hvQvxFOcnNzNvqEISByMjp0tby77kAeX8nxU5.

Pinch, T. J., and W. E. Bijker. 1984. “The Social Construction of Facts and Artefacts: or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other.”

Social Studies of Science 14 (3): 399–441. https://journals.sagepub.com/doi/10.1177/030631284014003004.

Seredkin, M., A. Zabolotsky, and G. Jeffress. 2016. "In Situ Recovery, an Alternative to Conventional Methods of Mining: Exploration, Resource Estimation, Environmental Issues, Project Evaluation and Economics." *Ore Geology Reviews* 79:500–514. https://www.sciencedirect.com/science/article/abs/pii/S0169136815300937.

Tracy, C. 2023. "Disposal, Destruction and Disarmament: Comparative Analysis of US Chemical Weapon and Weapons Plutonium Stockpile Reductions." *Central European Journal of International & Security Studies* 17 (1): 36–65. https://www.cejiss.org/disposal-destruction-and-disarmament-comparative-analysis-of-us-chemical-weapon-and-weapons-plutonium-stockpile-reductions.

Tracy, C. L., and R. C. Ewing. 2022. "Mining for the Bomb: The Vulnerability of Buried Plutonium to Clandestine Recovery." *Science and Global Security* 30 (3): 131–162. https://www.tandfonline.com/doi/full/10.1080/08929882.2022.2164407.

Tracy, C. L., M. K. Dustin, and R. C. Ewing. 2016. "Reassess New Mexico's Nuclear-Waste Repository." *Nature* 529: 149–151. https://www.nature.com/articles/529149a.

US Congress. 1979. *Public Law 96-164: An Act to Authorize Appropriations for the Department of Energy for National Security Programs for Fiscal Year 1980, and for Other Purposes*. US Congress. https://www.congress.gov/96/statute/STATUTE-93/STATUTE-93-Pg1259.pdf.

US House of Representatives. 2001. *H. Rept. 107-258: Making Appropriations for Energy and Water Development for the Fiscal Year Ending September 30, 2002, and for Other Purposes*. US House of Representatives. https://www.govinfo.gov/content/pkg/CRPT-107hrpt258/html/CRPT-107hrpt258.htm.

Van Luik, A., R. Patterson, and G. Kirkes. 2015. "Influencing Future Exploratory Drilling Rates–A Potential Approach for the Waste Isolation Pilot Plant." Paper presented at the WM2015 Conference, Phoenix, Arizona, March. https://archivedproceedings.econference.io/wmsym/2015/119.html.

von Hippel, F. N., and M. Takubo. 2020. "Global Stocks of Separated Plutonium – Stalled on the Path to Elimination." *Science and Global Security* 28 (3): 171–209. https://scienceandglobalsecurity.org/archive/2020/12/global_stocks_of_separated_plu.html.

Warren, J. K. 2016. *Evaporites: A Geological Compendium: Second Edition*. Springer. https://link.springer.com/book/10.1007/978-3-319-13512-0.