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Mining for the Bomb: The Vulnerability of Buried Plutonium to Clandestine Recovery

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ABSTRACT
Efforts by the United States and Russia to bilaterally reduce their weapons plutonium stockpiles are currently stalled following a U.S. decision to dilute and bury excess plutonium in a geologic repository. Russia has derided this approach as impermanent and easily reversible. Conversely, many analysts contend that the recovery of buried plutonium would require large-scale mining operations, rendering it observable and preventable. Here, we show that the use of advanced mining techniques overlooked in prior analysis (namely, salt solution mining and in situ leaching) would enable the rapid, clandestine recovery of buried plutonium. Burial would therefore yield a novel plutonium geologic resource. We attribute the persistence of international technical controversy over the permanence of plutonium burial to state-level divergence in U.S. and Russian technological framings of plutonium and geologic repositories—distinct socially constructed understandings of the meanings, uses, and risks of these technologies.

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Introduction

Fissile material—capable of sustaining a nuclear chain reaction—is the central ingredient of nuclear weaponry. Two materials are commonly used for this purpose: isotopically enriched mined uranium and plutonium produced via the irradiation of uranium in a nuclear reactor. Globally, there exist vast stockpiles of both materials, a legacy of rampant weapons production during the Cold War.[1] These stockpiles, held primarily by the United States and Russia, are sufficient for the production of over one hundred thousand nuclear weapons.[2]

The existence of these large inventories, far in excess of what states have judged necessary for military purposes, poses a grave threat to global security.[3] First, they are attractive targets for theft or diversion by aspiring nuclear proliferators. The production of fissile material is typically the greatest technical hurdle to nuclear weapon development, making

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preexisting stocks an attractive potential source.[4] Second, these stockpiles limit the permanence of arms control measures achieved to date. Under bilateral agreements the United States and Russia have removed thousands of nuclear warheads and delivery vehicles from deployment. Yet, even if these weapons are dismantled, the rapid reconstitution of nuclear forces remains possible so long as the corresponding fissile material remains stockpiled.[5]

These risks can be mitigated by means of stockpile reductions. Irreversible disposal or destruction of fissile material renders it less vulnerable to theft or diversion. Reductions also bring down numerical limits on the number of nuclear weapons a state could produce without the need for the relatively difficult, costly, and observable production of new fissile material.[6] Recognizing the value of stockpile reductions, the United States and Russia have cooperatively eliminated hundreds of tonnes of highly enriched uranium via dilution in natural, unenriched uranium.[7] Yet, to date, plutonium stockpiles remain undiminished.[8]

In 2000, the United States and Russia signed the Plutonium Management and Disposition Agreement (PMDA), obliging each to eliminate thirty-four metric tonnes of weapons plutonium by converting it to nuclear fuel and irradiating it in nuclear reactors. But in 2016, facing escalating costs, the United States announced plans to instead bury this plutonium in a geologic repository, asserting that this method would be as permanent and irreversible as irradiation.[9] Russia, however, argued that buried plutonium could be easily recovered and reused; it soon thereafter suspended its commitment to the PMDA. Thus ended what Congress had deemed "one of the most important nonproliferation initiatives undertaken between the United States and Russia."[10]

Many analysts contend that the vulnerability of mining activities to detection and observation obviates any meaningful risk of the recovery and reuse of plutonium buried in a geologic repository.[11] According to this line of reasoning, any breach of U.S. obligations to refrain from recovery would be immediately evident to Russia due to the massive signatures (visual, seismic, etc.) associated with conventional mining techniques, allowing Russia to respond quickly and proportionately.[12] While some Russian analysts disagree, they proffer no specific analysis of the mining methods that might be used or their vulnerability to detection.[13]

In the wake of this controversy, crucial questions remain unresolved. Is the Russian objection valid? Does the risk of plutonium recovery pose a substantial risk to international security? Why has discord arisen over seemingly objective technical assessments?

Much of the literature on the interface between science, technology, and security deals with uncertainty over the security implications of emerging technologies.[14] Yet the questions posed here arise instead from state-level distinctions in the ways technical communities process information, define problems, and assess the risks posed by existing, well-established technologies. Theoretical treatment of these topics is lacking.

Here, we address the coupled technical and social facets of the plutonium burial controversy. We argue that prior assessments of the feasibility and observability of plutonium recovery suffer from an unsuitably narrow conception of the applicable mining techniques, considering only highly visible, conventional methods. We contend that the use of advanced extraction techniques would facilitate clandestine recovery and reuse of buried fissile material, posing a threat to global nuclear security. Finally, we employ a concept of national technological frames, adapted from literature on the sociology of technology, to show how distinct social characteristics of U.S. and Russian technical communities came to be embedded in their respective assessments of plutonium burial, triggering and sustaining the controversy that scuttled cooperative stockpile reduction efforts.

This article proceeds in four sections. First, we survey the history of bilateral U.S.–Russian plutonium reduction efforts and the role that concepts of irreversibility played in shaping them. We then address technical dimensions of the issue, outlining a method—combined salt solution mining and in situ leaching—by which buried plutonium could be clandestinely recovered for later reincorporation into a nuclear arsenal.[15] We subsequently analyze the source of U.S.–Russian disagreement over the technical basis for plutonium stockpile reduction, attributing it to distinctions in national nuclear cultures and technological framings. We conclude with a summary of the findings and discussion of both technical and policy steps that might facilitate the development of more robust, internationally credible stockpile reduction strategies.

The history of bilateral plutonium stockpile reductions

The early 1990s saw the United States and the Soviet Union (subsequently the Russian Federation) engage in a flurry of bilateral arms control.[16] Following the 1991 success of the START I negotiations, which produced stringent limitations on the deployment of nuclear warhead delivery systems, attention turned to the stockpiles of fissile materials from which nuclear warheads are made. Presidents Clinton and Yeltsin promoted the reduction of these stockpiles as a means of ensuring the “transparency and irreversibility” of arms limitations, such that nuclear arsenals could not be rapidly expanded were bilateral relations to sour.[17]

The PMDA was a key part of these efforts. Its genesis can be traced to a 1992 meeting of the U.S. National Academy of Sciences (NAS) and the

Russian Academy of Sciences regarding prospects for cooperative plutonium stockpile management.[18] The Clinton administration subsequently tasked the NAS with an in-depth study of this topic, published in 1994.[19] Presidents Clinton and Yeltsin directly discussed reductions at the 1996 Moscow Nuclear Safety and Security Summit and the 1997 Helsinki Summit; statements from both pressed for the elimination of excess fissile material as a means of precluding nuclear rearmament.[20] The PMDA was subsequently negotiated and signed in 2000.

Discord over the means of elimination

The means by which plutonium would be disposed of proved a point of contention before, during, and after negotiation of the PMDA. The precise method used governs the irreversibility of stockpile reduction—and thus its efficacy as an arms control measure—as well as the costs of those reductions. Since bilateral reciprocity was key to the reduction endeavor, an elimination method agreeable to both parties was necessary.

The United States was concerned mainly with the possibility that non-state actors, such as terrorist groups, might acquire fissile material. As such, it focused primarily on the role of radiation barriers that might complicate plutonium recovery and reuse.[21] Acknowledging the vast quantities of civilian spent nuclear fuel that exist worldwide and the weapons-usable plutonium contained therein, the NAS was guided by a “spent fuel standard” under which military plutonium was to be rendered no more amenable to weapons use than that contained in nuclear fuel discharged from civilian reactors.[22] The plutonium in spent fuel is protected from weaponization by its intimate dilution in a highly radioactive blend of non-fissile materials. Extensive reprocessing of the fuel would be necessary to extract this plutonium, a process that is difficult, costly, and vulnerable to detection.[23] This barrier to weaponization can be mimicked, in the case of stockpiled weapons plutonium, by its incorporation in a highly radioactive matrix.

The 1994 NAS report, which shaped the U.S. approach to PMDA negotiations, recommended two means of establishing a radiation barrier to use: irradiation and immobilization.[24] The first approach entails mixing plutonium with uranium dioxide, the most common commercial nuclear fuel, and irradiating the mixture in a nuclear reactor. The resulting spent fuel would be highly radioactive and would contain reactor-grade plutonium which, due to its altered isotopic composition, may be somewhat less amenable to weaponization.[25] The second method, immobilization, entails mixing plutonium with highly radioactive wastes left over from legacy weapons programs.

In both cases the resulting radioactive, plutonium-bearing material would be buried in a geologic repository. Yet it is the radiation barrier, rather than burial, upon which the U.S. approach relied. In the 1990s the United States specifically rejected dilution in non-radioactive material as a means of plutonium elimination based on its determination that, absent a radiation barrier, "the resources required for the recovery of a significant quantity of plutonium are … relatively modest."[26] Alternatives such as the vaporization of plutonium via underground nuclear detonations were also discarded on the grounds that, absent a radiation barrier, "the material would be recoverable by the state that emplaced it, providing a plutonium mine" to the possessor.[27]

In contrast to the U.S. position, Russia placed little stock in extrinsic barriers to recovery such as dilution or radioactivity. Negotiators consistently derided these methods as "just another form of storage" that would leave plutonium vulnerable to retrieval were the United States to renege on its commitments.[28] They instead favored methods that would alter the intrinsic isotopic composition of plutonium, such as irradiation. This intrinsic alteration of the material is considered by Russia to be "more attractive from the irreversibility point of view" because it "makes plutonium less usable for nuclear weapons."[29] While irradiation of plutonium would achieve isotopic adulteration, simple mixing with preexisting stocks of radioactive material and burial, the U.S. "immobilization" strategy, would not.

Failure of the PMDA

Ultimately, a compromise was reached. The PMDA established irradiation as the primary means of elimination but allowed the United States to immobilize a small portion of plutonium too impure for use as reactor fuel.[30] Still, stockpile reductions did not proceed smoothly. Shortly after signing of the PMDA, the costs of plutonium elimination came to overshadow the goal of bilateral nuclear risk reduction in U.S. policy. In 2002 the United States abandoned its immobilization program due to cost concerns.[31] The irradiation track was similarly troubled. That same year, the U.S. Department of Energy (DOE) projected a cost of roughly \$5–8 billion (in 2021 dollars) for construction and operation of a facility where plutonium could be converted into nuclear fuel.[32] By 2014 these cost projections had ballooned to roughly \$23–32 billion (in 2021 dollars).[33]

The U.S. commitment to its PMDA obligations withered in the face of these cost projections. The DOE commissioned assessments of alternative disposal methods, which recommended substitution of irradiation with an alternative approach: dilution of the plutonium in a non-radioactive material and burial in a geologic repository.[34] In 2016, the DOE formally announced a unilateral pivot to this "dilute and dispose" strategy.[35]

Under this approach plutonium is destined for the Waste Isolation Pilot Plant (WIPP), the world's only operating geologic repository.[36] Located 650 meters below ground in the bedded salt of southeastern New Mexico's Salado Formation, WIPP was originally designed to contain legacy wastes from nuclear weapons activities such as lab coats, gloves, and other refuse contaminated with transuranic, radioactive material. The addition of excess weapons plutonium to the material already emplaced in or destined for the repository would leave it with an eventual inventory of roughly fifty metric tonnes of plutonium—several times the roughly ten metric tonnes it was originally designed to contain.[37]

Disposal of weapons plutonium at WIPP would establish three potential barriers to its recovery. First, plutonium would be diluted in "stardust," a non-radioactive material of classified composition.[38] Second, the mixture would be sealed in steel containers. Finally, these packages would be buried in the repository. Without having completed any detailed assessment of the security of plutonium buried in WIPP, the DOE has argued that these barriers to recovery and illicit use are broadly comparable to those associated with irradiation.[39] In 2016, a State Department official went so far as to argue that this method could be substituted without any renegotiation of the PMDA.[40] A number of American nonproliferation experts and former officials posited an uncomplicated substitution of irradiation with any "reasonable alternative."[41] Moscow disagreed; Russian analysts maintained that:

> Deviation from one of the basic provisions of the Agreement would hardly find a positive response from Russian experts who always asserted that a real weapon grade plutonium disposition is possible only through its irradiation … other approaches proposed by Americans do not exclude the possibility of a premeditated withdrawal of weapon grade plutonium from the place of its storage and its repeated use in weapons.[42]

An official of the Russian Ministry of Foreign Affairs stated in 2016 that the idea of plutonium dilution and burial had been "discarded as not irreversible."[43] That same year, President Putin voiced concern that plutonium disposed of by this method "can be retrieved, reprocessed and converted into weapons-grade plutonium again."[44] In October 2016 he issued a Presidential Decree suspending Russia's commitment to the PMDA citing, among other grievances, "the inability of the United States of America to ensure the fulfillment of its obligations on the disposition of surplus weapons-grade plutonium."[45] In short, Russia argued that U.S. assurances of the permanence of the geologic disposal strategy were non-credible, and suggested that the United States might plan to later renege on its PMDA commitments.

Prior assessment of recovery risks

To be sure, myriad factors contributed to the dissolution of the PMDA, which coincided with a general degradation of U.S.–Russian relations. But ostensibly technical matters remain at the heart of the controversy: whether the recovery of plutonium buried in WIPP is feasible and, if so, the ease of preventing recovery. A substantial body of literature has addressed this topic. Most reached the same conclusion: attempted recovery, while possible, would be obvious to international observers, rendering the associated risk insubstantial.

The earliest discussion of recovery from a geologic repository took place under the auspices of the International Atomic Energy Agency (IAEA), due to its policy that nonmilitary fissile material remain under safeguards until rendered unusable for weapon activities or practicably irrecoverable.[46] A 1979 report, prepared by the U.S. delegation to an IAEA working group, concluded that "mining operations of the type required to recover buried waste from a repository … would be difficult to conceal."[47] This overt observability was attributed to the need for large-scale excavation in order to access buried materials. Use of conventional mining techniques, drilling and blasting of vast quarries or large tunnel systems, would yield immense signatures: large-scale surface disturbances, massive industrial equipment, and intense seismic signals. Assuming the presence of these signatures, even modest monitoring in the form of seismic sensing, satellite imagery, and intermittent on-site inspection could reliably preclude clandestine recovery.[48]

Similar conclusions appear in IAEA reports spanning the next several decades.[49] Analyses from academia, non-governmental organizations, and the U.S. National Laboratories echo these findings.[50] By the time of the U.S. pivot from plutonium irradiation to burial there had emerged a broad consensus that the risk of recovery was negligible, as attempts "will be readily detectable if reasonable safeguards are applied at the repository sites."[51] Perhaps the sole counterpoint to this view in the prior literature is the work of Swahn, who drew attention to the tension between retrievability and security, and Peterson, who has argued that certain novel mining techniques, such as laser melting of rock and cutting with high pressure water jets, might reduce the signatures of excavation.[52]

Methods for the clandestine extraction of buried plutonium

Most prior work on the recovery of weapons material from a geologic repository focused on a narrowly conceived range of conventional mining techniques. Even the work of Peterson, demonstrating the threat that the interminable march of technological progress poses to the irreversibility of disposal, remains controversial given its reliance on largely unproven technologies.[53] Puzzlingly, this extensive prior work overlooked the methods by which salt (the geologic setting of WIPP) and actinide-bearing ores (an analogue for diluted plutonium) are commonly mined.

As observed by Garwin in an early assessment of the interplay between emerging technologies and nuclear security, "military capability may be increased as much by old as by new technology."[54] In this vein, we assess the technologies available for plutonium recovery and outline a low-profile mining approach combining two common and well-established—yet previously overlooked—techniques: salt solution mining and in situ leaching. Together these could facilitate the clandestine extraction of plutonium from WIPP, undercutting the supposed permanence and irreversibility of this disposal method.

Recovery techniques: salt solution mining and in situ leaching

To facilitate the clandestine extraction of plutonium from a repository, bypassing countermeasures like seismic and satellite monitoring, a mining method must fulfill two criteria. First, it must enable access to subsurface plutonium-bearing solids with minimal excavation. The removal of large quantities of rock, as required by quarrying or tunneling, produces the most observable signatures of mining. Second, plutonium must be extracted from the "ores" in which it is contained before it is transported to the surface. In this way the need to transport large volumes of solid material, and thus the need for large access shafts, might be obviated. Both criteria are fulfilled by the substitution of conventional solid-state mining techniques with a liquid-state approach since liquids can be pumped to and from the plutonium-bearing materials through a single, narrow borehole. Figure 1 illustrates a potential means by which two such methods, salt solution mining and in situ leaching, might be used to recover plutonium from WIPP.

Access to plutonium buried in a salt medium can be achieved via salt solution mining.[55] This technique begins with the drilling of a narrow borehole from the surface to the deposit of interest, followed by the insertion of an annular pipe into the resulting shaft. Water is then injected down the center of the pipe and into the deposit. The resulting salt-saturated brine is pumped up the pipe annulus and back to the surface, where it can be disposed of on- or off-site. The dissolution of salt into the injected water yields an underground cavern. Subsequent pumping of water down the annulus and up the center of the pipe allows for controlled, horizontal expansion of this cavern. At WIPP this would allow for access to a

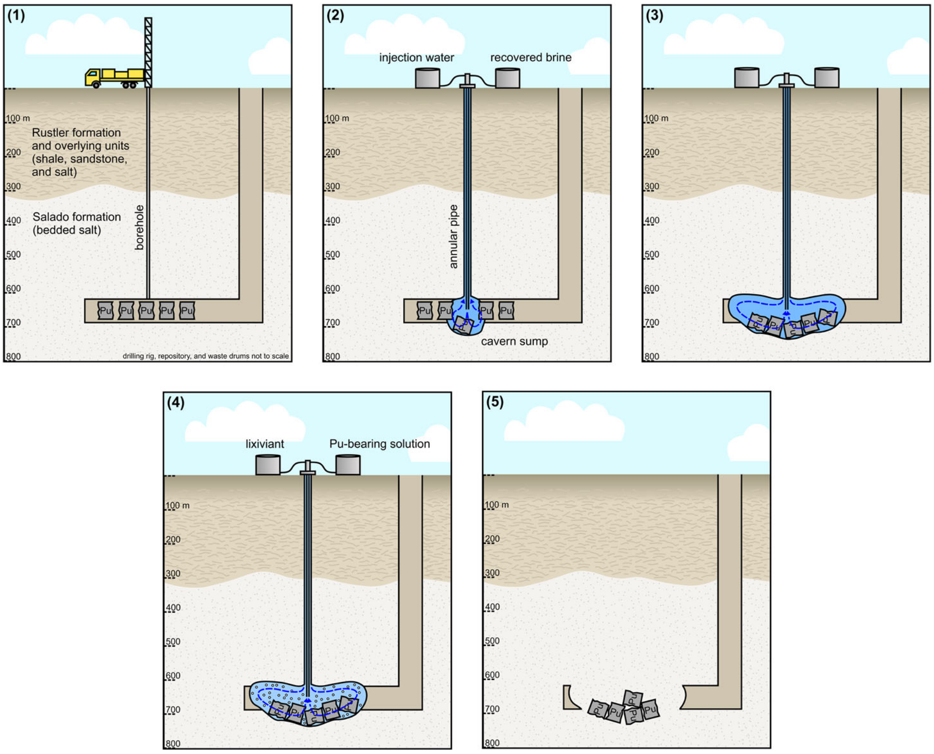

Figure 1. The application of salt solution mining and in situ leaching to plutonium recovery from WIPP. (1) A borehole is drilled into the repository using a mobile drilling rig. (2) An annular pipe is inserted into the borehole. Water is pumped down and up the pipe, forming a cavern. (3) The cavern is expanded horizontally through controlled pumping of water. (4) Lixiviant is pumped into the cavern, where it leaches plutonium into solution. The solution is then pumped back to the surface. (5) All surface equipment is removed. The borehole naturally seals itself via salt flow.

large portion of the repository, containing a substantial amount of plutonium-bearing material, from a single borehole.

Salt solution mining is a well-established technique, first developed over two millennia ago and practiced continually since then.[56] Cavern depths greater than one kilometer (well below the 650 meter depth of WIPP) were achieved as early as the 19th century.[57] Today, this mining method is widely practiced, constituting the primary source of U.S. salt production.[58]

After plutonium-bearing solids have been accessed, in situ leaching offers a means of extracting this fissile metal from the solid waste form.[59] This hydrometallurgical technique was developed to extract uranium from low-concentration, natural deposits. The chemical similarity of uranium and plutonium, both light actinide elements with variable oxidation states, renders the method applicable to either.[60]

In situ leaching begins with the injection of a lixiviant fluid—a liquid chemically engineered to leach a specific metal out of an ore—into the deposit of interest. Leaching of uranium is commonly carried out using chemicals that increase the oxidation state of this element or form chemical complexes of uranium with carbonate ligands; both methods enhance the mobility of the actinide in the geochemical environment. Plutonium, which exhibits similar relationships between oxidation state, complexation, and environmental solubility/mobility, is likely to be comparably sensitive to this means of leaching.[61] For example, the addition of carbonates or bicarbonates, common ingredients in commercial lixiviants, has been shown to increase the solubility of plutonium in water by several orders of magnitude.[62] After leaching, the solution can then be pumped back to the surface and transported offsite for extraction of the actinide metal.[63]

Like salt solution mining, in situ leaching is a common, well-established technique. First developed in the 1950s, it is now the primary means of uranium mining worldwide.[64] Typical depths in industrial operations range from 10–750 meters, inclusive of WIPP's 650 meter depth.[65]

Minimizing the signatures of illicit recovery

The key question is not whether plutonium buried in WIPP could be extracted—it surely could by rudimentary methods like quarrying—but whether this could be accomplished in a clandestine manner, denying adversaries the chance to respond and potentially upsetting the nuclear strategic balance. The plutonium recovery method outlined here differs from those considered in prior assessments (quarrying, tunnel boring, etc.) in that it is designed to minimize the observable signatures of mining.[66]

The primary advantage of this method, in terms of covertness, is its minimization of excavation and the accompanying signatures of mining. Both salt solution mining and in situ leaching would require only a single, narrow borehole between the surface and the plutonium deposit.[67] A borehole diameter of approximately 30 centimeters would be sufficient, narrow enough to require only a mobile drilling rig mounted on the bed of a semi-trailer truck.[68] This would substantially hinder attempts to detect recovery since the visual, seismic, and thermal signatures of drilling scale with borehole diameter.[69] Furthermore, the geologic setting of WIPP is particularly conducive to covert recovery, as the seismic signatures of drilling in salt are uniquely low.[70] In fact, study of salt-based nuclear waste repositories has consistently shown that "geophysical monitoring would not contribute much to safeguards objectives with salt as host rock."[71]

Even after drilling, this approach minimizes surface equipment and infrastructure. Both salt solution mining and in situ leaching necessitate only small pumps (roughly one cubic meter in volume), tanks for the storage of mining fluids (water, brine, lixiviant, and pregnant solution), and the associated piping.[72] The slight visible signatures of mining using these techniques are illustrated in Figure 2. Advanced satellite imaging systems dedicated to monitoring this site might still detect such activity were it conducted in the open; to further minimize signatures, equipment could be covered, buried, or housed within the buildings that currently overlay a portion of WIPP.[73] In more technologically complex approaches to mining, horizontal directional drilling might be used to access plutonium from portions of the facility not visible to overhead observation. After the extraction of plutonium all equipment could be removed, leaving minimal tailings, surface disturbance, or other evidence of mining activities.[74] Because salt is a highly plastic geologic medium, the borehole would then naturally seal itself.[75]

To further reduce the observability of onsite activities, extraction of plutonium from the recovered solution could be performed at an offsite facility. This is standard practice in commercial in situ leaching, and even industrial-scale operations require only a single truck shipment per day.[76] This would arouse little suspicion among observers as it is well within the normal operating parameters of WIPP. The facility is expected to remain in operation for several decades and typically receives several daily truck shipments.[77]

In addition to minimizing the magnitude of observable mining signatures, a clandestine recovery process must minimize the period over which those signatures are produced. The salt solution mining and in situ leaching operations described above can be carried out quickly, relative to conventional mining techniques. Initial drilling of the access borehole could be

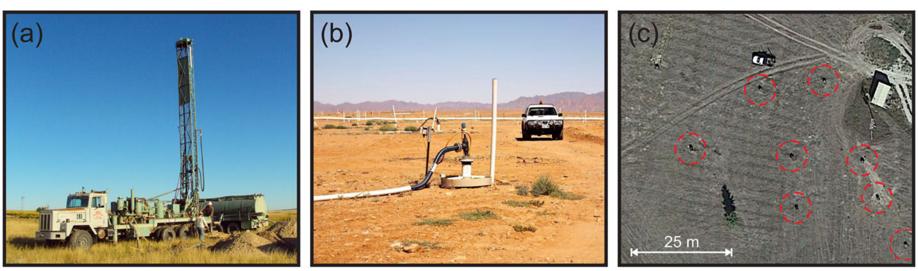

Figure 2. The visible signatures of uranium extraction via in situ leaching. These activities are representative of commercial-scale operations, which produce several hundred tonnes of uranium annually and involve no attempts at concealment. Simple measures like covering of surface equipment would further reduce the observable footprint. **(a)** Truck-mounted, mobile drilling equipment used to install a well at the Crow Butte Uranium Recovery Facility, Crawford, Nebraska, USA. **(b)** A field of small surface pumps that transports lixiviant and uranium-rich solution to and from subsurface resources at the Beverley Uranium Mine, Wooltana, South Australia. A passenger truck provides a scale reference. **(c)** Satellite imagery of surface infrastructure at the Crow Butte Uranium Recovery Facility (Maxar Technologies/Google Earth, 29 September 2013). Pumps, circled in red, are barely visible. A passenger truck near the top of the image provides a scale reference.

completed in a matter of days.[78] Subsequent expansion of a subsurface cavern would require little additional time, as typical salt solution excavation rates are on the order of thousands of cubic meters per day.[79]

After access is achieved, the time required for the leaching of plutonium would depend on myriad factors, including the spatial distribution of plutonium-bearing material in the repository, chemical characteristics of the dilutant material, and the desired quantity of recovered plutonium. Here, comparison with commercial uranium mining operations proves instructive.[80] A typical fluid pump rate for a single well in a commercial operation is roughly 50 cubic meters per day.[81] Typical uranium concentrations in the resulting solution, within a few days of the start of leaching, are on the order of several hundred grams uranium per cubic meter of fluid.[82] Thus, single well uranium recovery rates can be estimated at tens of kilograms per day. Applying conservative assumptions in the plutonium case, a pumping rate of twenty cubic meters of fluid per day and a plutonium concentration of fifty milligrams per liter in the recovered fluid, yields a roughly estimated extraction rate of one kilogram of plutonium per day.[83] A few kilograms of plutonium is sufficient to construct a nuclear weapon.[84] This quantity of plutonium-bearing fluid could be transported within a single tanker truck.

While approximate, this basic analysis suggests that the recovery of plutonium sufficient to make a single weapon could be carried out on the order of days. For comparison, North Korea's Yongbyon plutonium production facility likely generates enough plutonium for a single nuclear weapon in about one year.[85] If faster recovery rates from WIPP were desired, methods akin to those used in commercial leaching operations, such as the installation of multiple injection and recovery wells, could be used. This would involve a tradeoff between recovery rate and observability.

Obstacles to recovery

This analysis demonstrates that a particular combination of mining techniques, unconsidered in most of the prior literature, could enable the clandestine recovery of plutonium buried in WIPP. Several features of WIPP and its geologic setting render it particularly vulnerable to salt solution mining and in situ leaching. But the repository differs from the settings in which both techniques are typically applied in three primary ways: dilution of the actinide material in an engineered waste form, packaging of the actinide-bearing "ore" in stainless steel containers, and the presence of high concentrations of salt during in situ leaching. Each of these distinctions introduces uncertainty to the process and presents technical challenges that might be expected to hinder clandestine plutonium recovery. We now consider these three obstacles in turn.

The DOE intends to dilute plutonium to concentrations below 10% by weight prior to burial.[86] This reduced concentration is, by itself, unlikely to significantly hinder recovery by the methods described above. In situ leaching is routinely used in the recovery of uranium, a closely-related actinide material with similar geochemistry, at concentrations below 0.1%.[87]

Still, chemical properties of the dilutant material could influence the efficacy of plutonium leaching. The DOE plans to use a dilutant known colloquially as "stardust."[88] This refers to a material of classified composition, described as a mixture of "cementing, gelling, thickening, and foaming agents" that make plutonium "more difficult and more complex to recover."[89] This material is added for the express purpose of hindering attempted plutonium extraction.[90] However, the DOE's current confidence in the efficacy of stardust as an obstacle to recovery conflicts with the Department's prior findings. A DOE red team, for instance, concluded that dilution in any engineered material was of only modest utility because, "although there would be some penalties in resources and time required for recovery of plutonium from the more dilute forms, recovery would still be feasible if adequate preparations were made."[91] In formulating the dilution strategy, DOE contractor Kaiser-Hill Co. similarly found that "experienced plutonium chemists have demonstrated they can recover plutonium from any form with the only issue being time and resources necessary to accomplish the end objective."[92]

Thus, while dilution could affect the costs or rate of recovery, the available evidence does not indicate that it would preclude recovery. That said, the classified status of "stardust" prevents any detailed analysis of its possible contributions to the irreversibility of plutonium burial in this work. It also prevents Russia, the party initially concerned about plutonium recovery, from performing the same analysis. Thus, even if some remarkable chemical characteristic of this material rendered plutonium extraction and reuse impossible, there would still exist no technical basis for confidence in this assertion insofar as international actors are concerned.

Next, the containment of diluted plutonium in stainless steel drums could conceivably hinder its recovery by shielding the plutonium-bearing material from lixiviant, thus preventing leaching. The DOE plans to package diluted plutonium in multi-walled, stainless steel containers prior to emplacement in WIPP.[93] The performance of these steel containers as a physical barrier to leaching depends on the extent to which they retain their physical integrity in WIPP's harsh geochemical environment.

Two factors—compression and corrosion—pose serious threats to this containment. The plastic nature of salt leads to relatively rapid flow and closure of any cavities excavated within it. As the subsurface rooms in which plutonium is stored shrink, emplaced drums would be subjected to compressive forces, eventually crushing them.[94] This process is expected to begin within about one decade of burial.[95] This mechanical damage to the containment will be accompanied by chemical degradation. The Salado Formation where WIPP is located is home to salt-saturated brine, known to corrode stainless steel.[96] Corrosion-induced perforation of steel drums in WIPP has been observed just a few years after emplacement.[97] In short, packaging of the plutonium-bearing material does not provide long-term containment. It is for precisely this reason that the DOE's safety assessment of WIPP does not consider packaging to substantially contribute to the isolation of plutonium from the environment.[98]

Finally, there is the issue of WIPP's specific geological setting. This salt setting contributes in several ways to the vulnerability of buried plutonium to clandestine recovery. It facilitates the use of salt solution mining to access the repository and shortens the expected lifetime of steel containers that might otherwise isolate buried materials. Yet this setting could also constitute a barrier to recovery if it precludes the application of in situ leaching at the site. This extraction technique is typically performed in sandstone deposits, wherein lixiviant can selectively mobilize actinide elements while minimally affecting the surrounding, relatively insoluble geologic medium.[99] In contrast, salt is highly soluble in water, the primary component of a lixiviant. Uptake of salt into the leaching solution is thus inevitable and it may slow the recovery process. Still, the resulting salinity of the lixiviant is unlikely to pose a significant obstacle to the mobilization of plutonium. Commercial in situ leaching is often performed in the presence of high-salinity groundwater without serious adverse effects on the leaching process.[100] Moreover, experiments have shown that exposure of plutonium-contaminated wastes to brine similar to that present in WIPP's geologic setting results in substantial plutonium uptake.[101] A lixiviant specially designed to promote plutonium leaching would surely perform better than natural brine.

Findings and implications for global nuclear security

This analysis demonstrates a strong technical basis for Russia's objections to plutonium burial. The use of salt solution mining and in situ leaching could facilitate the clandestine recovery of plutonium from WIPP. The observable signatures of recovery would be weak and the necessary surface activity might be disguised as routine repository operations. While obstacles to the use of these methods at WIPP would complicate the recovery process, they are unlikely to render recovery impracticable. Thus, Russian concerns over the permanence of plutonium disposal in a salt repository are reasonable and technically sound.

Due to its inherent reversibility, the disposal of large quantities of weapon plutonium in WIPP would influence the nuclear security landscape in several ways. First, it would create a novel plutonium geologic resource. This would represent an unprecedented route to the acquisition of fissile material, which is commonly the limiting factor governing how quickly a state can expand its nuclear arsenal.[102] Fissile material production has heretofore required either the isotopic enrichment of uranium or its irradiation and chemical separation of the resulting plutonium; both involve the use of complex, costly, and highly observable technologies. The current architecture of nuclear arms control and nonproliferation is built around this hitherto fundamental feature of fissile material acquisition.[103]

A state in possession of a plutonium geologic resource that was vulnerable to mining could extract fissile material from Earth's crust as if it were a mineral commodity, using quick, cheap, and low-profile methods. This would enhance the ability of the possessor to rapidly expand its fissile material inventory, and thus the potential size of its nuclear arsenal. This enhanced production capacity could afford the possessor some measure of strategic advantage over rivals. Fuhrmann and Tkach have shown that "having the capacity to build nuclear weapons … may bolster deterrence" since states with high production capacity "could build nuclear bombs relatively quickly if their security environment deteriorates."[104] The immediate effects of this capability on the global strategic balance would likely be small, given that the United States possesses a large inventory of readily available excess weapons plutonium. Yet any change to this balance might be notable to those concerned with nuclear parity, including Russian analysts.

In addition to its influence on the nuclear balance, the creation of a plutonium geologic resource might impede prospects for future nuclear arms control efforts. Its utility for fissile material production would call into question the credibility of U.S. stockpile reductions and would undercut the reciprocal nature of the PMDA. In effect, burial of plutonium in WIPP would place a portion of the U.S. stockpile in limbo, such that the stockpile's precise size would depend on one's confidence that the United States would refrain from future recovery. This indeterminacy would pose a serious obstacle for any future arms control efforts addressing fissile material stockpiles, since complex verification measures would be necessary to ensure that ostensibly disposed of plutonium remained so.

Finally, the existence of a plutonium geologic resource would impair long-term prospects for nuclear disarmament by establishing a new floor on the extent to which the possessor state could disarm. The cost and time necessary to acquire fissile material would be a primary barrier to rearmament in a hypothetical disarmed world. Construction and operation of a large nuclear reactor for plutonium production generally takes five years or more and costs billions of dollars.[105] Even a small reactor yielding only enough plutonium for about one nuclear weapon per year would require several years of construction and cost hundreds of millions of dollars.[106] Conversely, possession of a plutonium geologic resource would enable plutonium acquisition in substantially less than one year, for only a few million or tens of millions of dollars.[107]

In addition to making nuclear rearmament easier, a plutonium geologic resource could make it that possession of geologic deposits of uranium, a fissile material precursor, increases the likelihood of the development of nuclear weapons by the possessor state.[108] Similarly, Holdren observed that easy access to fissile materials "may constitute an irresistible temptation to produce nuclear weapons under provocation insufficient to motivate undertaking a weapons program from scratch."[109]

The sociotechnical basis for U.S.–Russian controversy over disposal permanence

We have here elucidated the technical basis for the recovery of plutonium from a geologic repository and the resulting U.S.–Russian discord over the permanence of plutonium burial. Yet these findings raise new questions. Why did U.S. assessment of the burial strategy overlook widely practiced mining methods, such as salt solution mining and in situ leaching? Why, in the first place, was the technical basis for stockpile elimination so controversial?

Technical matters are commonly taken to be objectively and unambiguously determined by material realities, particularly in the positivist tradition dominant in international security scholarship.[110] According to this logic, technologically capable states like the United States and Russia, having access to similar scientific and technical expertise, should broadly agree on the underlying technical basis for the geologic disposal and recovery of plutonium. This is clearly not the case. Instead, a more nuanced reading of the dynamics of technological controversy reveals a complex subjectivity at play in this dispute.

To analyze this facet of the stockpile reduction process, we turn to research in the sociology of technology and its social constructivist account of technological development. This work stresses the manner in which scientific and technical facts are not purely fixed in the physical world, but are rather subject to varying, flexible interpretation and negotiation by distinct social groups (e.g., Russian and American nuclear scientists).[111] Key to this understanding of the social basis for technological controversy is Bijker's concept of a technological frame.[112] This refers to "the understanding that members of a social group come to have of particular technological artifacts, and … local understanding of specific uses in a given setting."[113]

These collective "assumptions, expectations, and knowledge about the purpose, context, importance, and role of technology will strongly influence the choices made regarding the design and use of those technologies."[114] Armed with distinct technological frames, social groups tend to diverge in terms of "the recognition of what counts as a problem as well as the strategies available for solving the problems and the requirements a solution has to meet."[115] In assessing the threat of, for example, plutonium recovery, such groups "determine very differently what degree of risk these materials and machines constitute, they perceive different threats to their respective network, and they also identify and advance different solutions to countering these threats."[116] This provides a starting point for explaining why, despite the availability of similar technical information to both U.S. and Russian experts, discord arose over the significance and implications of the plutonium recovery problem. It further addresses the seemingly myopic nature of U.S. technical assessment in this area.

In this sociological conception of the plutonium recovery controversy, the central question is this: When it comes to buried plutonium and geologic repositories, how do American and Russian technological frames differ? Below, we provide brief historical surveys of nuclear thinking in each nation to illustrate relevant divergences.

Russia: the resource frame

The Russian technical community has consistently exhibited a unique framing of plutonium wherein this material is conceived of as a tool to be harnessed, controlled, and dominated for the advancement of humanity. As early as 1922 a prominent Russian expert on radioactive materials predicted that they heralded "a great revolution in the life of humankind … when man will get atomic energy in his hands."[117] This thinking later blossomed into an optimistic, technocratic Soviet nuclear culture buttressed by utopian iconography and rhetoric.[118] Internally, nuclear technologies became powerful symbols of "peace, progress, and modernity."[119] Externally, they served as a source of prestige; the state "situated nuclear energy at the pinnacle of Soviet science and its international recognition."[120] As predicted by the sociological theory, this framing shaped conceptions of when, how, and to what ends nuclear technologies should be used. The USSR's "strong association of peaceful nuclear technologies with the government's disarmament proposals," a utopian endeavor, "made Soviet citizens understand nuclear energy as a panacea for domestic and international problems."[121]

This framing persists in modern Russia. The Soviet nuclear program is widely celebrated in popular publications.[122] Its technological legacy, Russia's large fleet of nuclear reactors, "appears in public discourses and official documents as an instrument to ensure the country's national prestige, technological modernization, and 'radiance' in the international arena."[123] Contemporary expansion of this fleet is driven by an "unwavering belief that nuclear energy will help societies progress."[124] The use of plutonium fuel in these reactors, as mandated by the PMDA, constitutes a key part of the Russian nuclear renaissance. The complex infrastructure for producing this fuel has received sustained state investment since the 1980s.[125]

This conception of nuclear energy, and particularly nuclear materials like plutonium, constitutes what we term a "resource frame." In line with a long legacy of Soviet/Russian thinking on nuclear technologies, the exploitation of plutonium resources is closely linked not only with economic advancement, but also with arms control and global security. The Russian approach to plutonium stockpile management is thus couched in terms of control and mastery of this valuable substance. In short, within the Russian technological frame plutonium is something to be harnessed, not discarded.

Under this framing of the proper use of nuclear technology and the necessity of that use for societal progress, narratives involving the mining of buried plutonium appear commonsense. The creation of a plutonium geologic resource, analogous to the deposits from which other valuable natural mineral resources are extracted, furthers such narratives. Indeed, Russian analysts have compared U.S. plans for plutonium burial to "[flushing] gold down the toilet"; gold is in fact a resourced commonly mined via in situ leaching.[126]

The United States: the waste frame

The United States exhibits a nuclear culture quite distinct from Russia's. An initial utopian optimism of the 1940s and 1950s, mirroring that seen in the Soviet Union, was replaced in subsequent decades with a pervasive skepticism toward all things nuclear.[127] The U.S. public has come to view nuclear technologies with a unique, enduring dread.[128] Opinion surveys show that nuclear materials are overwhelmingly associated with imagery of "danger," "death," "destruction," and "suffering."[129] To be sure, some American scientists and technologists hold more positive views of nuclear technology and the value of plutonium as an energy resource.[130] However, this position remains controversial. Support for the underground disposal of plutonium-bearing nuclear wastes is widespread among the American technical community.[131] In contrast to Russian framing, which associates advanced nuclear technologies like plutonium fuel processing with imagery of peace and disarmament, American technical communities commonly regard the processing of plutonium as a serious proliferation risk.[132] The use of plutonium for energy generation is often argued to be uneconomical, and commercial programs have not operated in the United States for decades.[133]

With plutonium widely seen as what Jasanoff and Kim term "a potentially runaway technology that demands effective containment," the common American conception constitutes what we call a "waste frame."[134] Plutonium is treated as an undesirable substance that must be sequestered deep under Earth's surface to protect society from the associated dangers. In fact, the U.S. consensus in favor of geologic disposal of excess nuclear materials is predicated in part on a desire to protect future generations from the burden of its management; in this way, permanence becomes an intrinsic characteristic of the burial scheme.[135] In this framing, recovery appears illogical, since the primary objective of burial is to forever be rid of this material. Mining for plutonium in WIPP would be akin to digging for garbage in a landfill: both materials are buried precisely because the possessor sees no value in their retention and no opportunity for reuse.

As in the Russian case, this framing of plutonium is evident not only in technical and policy decisions, but also in the associated iconography. WIPP's official seal, shown in Figure 3, is particularly revealing. The seal focuses exclusively on the radiant structures overlying the repository, in which waste is prepared for emplacement underground. The existence of the repository itself is only hinted at by a narrow shaft leading down into Earth's crust, out of the field of view. Just as the subsurface workings of the repository are omitted from this imagery, in the waste frame buried plutonium is essentially forgotten: out of sight, out of mind.

Clashing technological frames

The sociological account of technical controversy explains how international distinctions in the framing of plutonium and geologic repositories as technological artifacts led the United States and Russia to arrive at wildly different conclusions regarding the security implications of plutonium burial, despite starting with identical technical information.[136] The inability of each to convince the other of the inherent security or insecurity of this means of stockpile reduction aligns with sociological predictions: "arguments, criteria, and considerations that are valid in one technological frame will not carry much weight in other frames."[137] To a Russian analyst situated in the resource frame, the burial of plutonium suggests an abrogation of the U.S. commitment to its arms control obligations; to an American analyst situated in the waste frame, these concerns are baseless.

Figure 3. The seal of the Waste Isolation Pilot plant. Emphasis is placed on the buildings overlying the repository. The only hint of the existence of the subsurface rooms in which wastes are stored is the narrow shaft on the lower left side.

Conclusions

This analysis indicates that clandestine recovery of plutonium buried in WIPP, using a combination of salt solution mining and in situ leaching, is feasible. These techniques were overlooked in the prior literature, a symptom of inadequate incorporation of geology and mining engineering into the analysis. The possibility of quick, covert recovery and reuse of buried plutonium raises serious concerns regarding the effects of burial on global nuclear security. In a world where fissile material exists as a crustal resource, like iron or gold, mining technology poses a persistent proliferation risk.

These findings provide several lessons for future stockpile reduction efforts. First, flexibility in the U.S. disposal strategy and adjustments to the dilution and burial approach might allay the risk of clandestine recovery. The use of an unclassified dilutant, assuming it acts as an effective chemical obstacle to the separation of plutonium from the diluted waste form, could demonstrate to international observers a more credible U.S. commitment to irreversibility. The design of more robust packaging, that might be expected to survive long-term burial in salt, could do the same. A rigorous, international program of verification including both onsite monitoring and dedicated satellite observation could increase the likelihood that any attempt at recovery would be quickly discovered.

That said, these technical tweaks would raise new challenges. For example, the use of more durable packaging would keep plutonium in place long after burial, easing the process of locating and drilling to these containers.[138] Monitoring and limiting mining activities in the Delaware Basin, where WIPP is located, may prove infeasible given the area's rich hydrocarbon and potash resources, which have prompted rapid expansion in nearby commercial exploration.[139] Ultimately, more dramatic changes may be needed to render geologic disposal sufficiently irreversible. For example, burial in deep boreholes, reaching to less-soluble rock several kilometers below the surface, might hinder mining of buried plutonium.[140] Such changes would add substantially to the cost of plutonium disposal, raising financial issues analogous to those that hampered the PMDA.

Facing this controversy over the irreversibility of burial and its deleterious effects on bilateral nuclear arms control efforts, the United States should assess with whether burial, which precludes direct monitoring of emplaced plutonium packages, provides significant advantages over safeguarded, above-ground storage. In the latter case, the accessibility of the packages could allow for simpler verification that plutonium has not been re-weaponized. In contrast, isolation of weapons material deep underground is, according to the IAEA, "in direct conflict with the basic premise of international safeguards, that nuclear material can be made available for inspection at suitable intervals."[141]

Beyond insight into the technical basis for stockpile reduction, this analysis draws attention to social dynamics at play in the interface between nuclear technology and global security. A great deal of work in the security studies literature has focused on the effects of technological change on global security.[142] Yet this literature typically treats technology as a "black box," neglecting the social roles of technologists in interpreting, shaping, and reacting to it. Here, we demonstrate that what matters most in the U.S.–Russian controversy over geologic disposal is not some novel technical aspect, salt solution mining and in situ leaching are, after all, quite old technologies, but rather social factors: state-level distinctions in the social framing of the associated technologies.

The history of bilateral stockpile reduction efforts might have played out quite differently if the American and Russian technologists involved were entirely neutral actors assessing objective technical data informed by unambiguous material characteristics of plutonium, repositories, and related technologies. But technical facts are mediated by social interpretations and translations of technologies, and only when this is accounted for can clashes between rival technological frames be understood. The consideration of national technological frames in analyses of interstate nuclear technology controversies over topics such as the efficacy of U.S. missile defense systems, or of novel Russian nuclear warhead delivery systems could lend new insight into the bases of these disputes and strategies for their resolution.[143]

Finally, how does this sociotechnical insight inform the prospects for future progress on bilateral stockpile reductions? In the sociological framework, Bijker points to the role that technologists with simultaneous inclusion in multiple technological frames can play as "agents of change," bringing closure to technological controversies through the amalgamation of technological frames.[144] This suggests that direct interaction, exchange, transparency, and cooperation between American and Russian scientific/technical communities could prove fruitful. Joint, cooperative work on the technical initiatives described above (unclassified dilutants, robust packaging, etc.) could serve as a starting point for building trust and mutual understanding of technological frames.

Such efforts would extend a long history of productive bilateral engagement in arms control. During the Cold War, transnational initiatives such as the Pugwash movement served as a nexus between Western and Soviet scientists.[145] More recently, technical cooperation between Russian and American nuclear weapons laboratories served the same purpose.[146] Both offer a model for progress on stockpile reductions. That said, these activities would likely be difficult to implement in the near-term, given current geopolitical tensions and conflict between the United States and Russia. Ultimately, research and development will be necessary to enable the elimination of plutonium in a mutually agreeable manner, but even more urgent is the need to reach agreement on precisely what constitutes a "working" plutonium disposal process.

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64. Seredkin, Zabolotsky, and Jeffress, "In Situ Recovery," 501–502.
65. Ibid., 506.
66. Modification of the method described here could increase the rate or cost efficiency of plutonium recovery. The approach we present is not necessarily optimal, but is simply one possible low-profile method that could bypass reasonable safeguards and validate international objections to dilution and burial.
67. If higher extraction rates were desired, additional boreholes could be drilled.
68. Donald E. Garrett, *Potash: Deposits, Processing, Properties and Uses* (Dordrecht: Springer, 1996), 304–324.
69. Peterson, "Issues for Detecting Undeclared Post-Closure Excavation at Geologic Repositories," 9.
70. Ibid. 16; G. Eilers et al., "Evaluation of the Applicability of Some Geophysical Techniques for Geological Repository Safeguards in a Salt Dome," *Proceedings of the ESARDA 19th Annual Symposium on Safeguards and Nuclear Material Management: Proceedings, Le Corum, Montpellier, France, 13-15 May 1997*, 227–235.
71. E. Biurrun, H.-J. Engelmann, P. Brennecke, and H. Kranz, "Safety and Safeguards Aspects on Retrievability: A German Study," in *Retrievability of High Level Waste and Spent Nuclear Fuel* (Vienna: IAEA, 2000), 238.
72. Seredkin, Zabolotsky, and Jeffress, "In Situ Recovery," 501–505.
73. On this point, the ability of India, Israel, and Pakistan to hide their nuclear weapon development activities from satellite monitoring proves instructive. Israel and Pakistan evaded imagery by disguising their nuclear facilities as textile factories and goat sheds, respectively. India concealed nuclear activities by, for example, working at night and concealing equipment with sand and native vegetation. See Vipin Narang, "Strategies of Nuclear Proliferation: How States Pursue the Bomb," *International Security* 41 (2017): 122; Robert M. Clark and William L. Mitchell, *Deception: Counterdeception and Counterintelligence* (Washington, DC: CQ Press, 2019), 24–25.
74. Seredkin, Zabolotsky, and Jeffress, "In Situ Recovery," 501.
75. U.S. National Research Council, *The Waste Isolation Pilot Plant: A Potential Solution for the Disposal of Transuranic Waste* (Washington, DC: National Academies Press, 1996), 41–46, 48, 123–128.
76. U.S. Nuclear Regulatory Commission (NRC), *Generic Environmental Impact Statement for In-Situ Leach Uranium Mining Facilities*, NUREG-1910 (Rockville, MD: U.S. NRC, 2009), 2–38.

77. U.S. DOE, Waste Data System (WDS)/WIPP Waste Information System (WWIS) Public Access System, http://www.wipp.energy.gov/WDSPA.
78. U.S. Delegation to the International Nuclear Fuel Cycle Evaluation, IAEA, *Safeguards for Geologic Repositories*, 18.
79. Ibid, 20.
80. Commercial in situ leaching operations can begin recovery in as little as a few months. This start-up time would be reduced in the case of a military operation exploiting a spatially well-characterized, highly-localized geologic resource. In contrast, comparable conventional open pit mines typically take three or more years for start-up. See, for example, Doris Schüler et al., *Study on Rare Earths and Their Recycling* (Darmstadt: OEKO, 2011), 23; Keith R. Long, Bradley S. van Gosen, Nora K. Foley, and Daniel Cordier, *The Principal Rare Earth Elements Deposits of the United States—A Summary of Domestic Deposits and a Global Perspective*, SIR10-5220 (Reston, VA: USGS, 2010), 22–24.
81. Julia Krause, Jana Nicolai, and Horst M Märten, "Hydrological Characterization and Optimization of In-Situ Recovery," in *Mining Meets Water – Conflicts and Solutions*, edited by Carsten Drebenstedt and Michael Paul (Freiberg: TU Bergakademie Freiberg, 2016). Commercial in situ leaching operations commonly entail hundreds of wells.
82. IAEA, *In Situ Leaching of Uranium: Technical, Environmental, and Economic Aspects* (Vienna: IAEA, 1989), 17.
83. The plutonium concentrations that might be achieved in the lixiviant solution are uncertain. Reed et al. have observed a range of plutonium concentrations of up to ~5 milligrams/liter in simulated WIPP brines (naturally-present fluids, as opposed to the engineered lixiviants that would be used for in situ leaching), even in the presence of strongly reducing chemical conditions caused by the addition of excess iron. See Donald T. Reed, J. F. Lucchini, S. B. Aase, and A. J. Kropf, "Reduction of Plutonium(VI) in Brine under Subsurface Conditions," *Radiochimica Acta* 94 (2006): 591–597. Similarly, the WIPP performance assessment performed by the DOE predicts a median plutonium concentration in these natural brines of greater than 1 milligram/liter. See Donald Reed and Russell Patterson, "Actinide Containment Safety Case in a TRU/HLW Repository in Salt," paper presented at the Waste Management 2016 (WM2016) Conference, 6–10 March 2016, Phoenix, Arizona, USA. Plutonium uptake would surely be much higher when an engineered lixiviant were used during in situ leaching. For example, Yamaguchi et al. have shown that the addition of carbonates or bicarbonates—common ingredients in commercial lixiviants—increases the solubility of plutonium in water by many orders of magnitude. See Yamaguchi et al., "Effect of the Complexation on Solubility of Pu(IV) in Aqueous Carbonate System." Variation in the 50 milligram/liter plutonium concentration we assume in the lixiviant would cause corresponding variation in the rate of plutonium extraction.
84. Thomas B. Cochran and Christopher E. Paine, "The Amount of Plutonium and Highly-Enriched Uranium Needed for Pure Fission Nuclear Weapons" (Washington, DC: NRDC, 1995).
85. David Albright, "North Korean Plutonium Production," *Science & Global Security* 5 (1994): 72–77. Operation of the Yongbyon reactor is also much more observable than a clandestine mining operation would be, as it is highly vulnerable to a variety of surveillance methods including satellite imagery and atmospheric isotope monitoring.
86. U.S. DOE, *Report of the Plutonium Disposition Working Group*, 18.

87. IAEA, *In Situ Leaching of Uranium*.
88. U.S. House of Representatives, Committee on Armed Services, *Plutonium Disposition and the MOX Project: Hearing Before the Subcommittee on Strategic Forces*, 114th Cong., 1st sess., 7 October 2015, 8.
89. Hayes and Nelson, "Terminating Safeguards on Excess Special Nuclear Material," 6.
90. U.S. House of Representatives, *Plutonium Disposition and the MOX Project*, 34.
91. Hinton et al., *Proliferation Vulnerability Red Team Report*, 4–5.
92. Kaiser-Hill Company, "Variance Request for Safeguards Termination Authorization for all Attractiveness Level D Waste Derived from Plutonium Bearing Residues," (1998), 12. Knowledge of the precise composition of stardust, which the United States has, would aid in the design of a lixiviant specifically engineered for use at WIPP.
93. U.S. National Academy of Sciences, *Disposal of Surplus Plutonium at the Waste Isolation Pilot Plant: Interim Report* (Washington, DC: National Academies Press, 2018), 12.
94. Pecos Management Services, *An Analysis of the Monitoring of Rooms and Panels at WIPP* (Carlsbad, NM: Pecos Management Services, 2006), 7, 13.
95. Gregory T. Roselle and Christi D. Leigh, "Iron-Based Waste Packages as Engineered Barriers in a Salt Repository," in *Proceedings of the International Workshop ABC-Salt (II) and HiTAC 2011*, edited by Marcus Altmaier et al. (Karlsruhe: KIT, 2012), 81–82.
96. E. Smailos, W. Schwarzkopf, B. Kienzler, and R. Köster, "Corrosion of Carbon-Steel Containers for Heat-Generating Nuclear Waste in Brine Environments Relevant for a Rock-Salt Repository," *Materials Research Society Symposium Proceedings* 257 (1991): 399–406.
97. Martin A. Molecke, N. Rob Sorensen, and James L. Krumhansl, "Results from Simulated Contact-Handled Transuranic Waste Experiments at the Waste Isolation Pilot Plant," *Materials Research Society Symposium Proceedings* 333 (1993): 681–686.
98. Lawrence E. Allen and James K. Channell, *Analysis of Emplaced Waste Data and Implications of Non-Random Emplacement for Performance Assessment for the WIPP*, EEG-85 (Albuquerque, NM: Environmental Evaluation Group, 2003), 16.
99. See Seredkin, Zabolotsky, and Jeffress, "In Situ Recovery," 505–506.
100. Graham Taylor et al., *Review of Environmental Impacts of the Acid In-situ Leach Uranium Mining Process* (Adelaide, SA: CSIRO Land and Water, 2004), 14.
101. Virginia M. Oversby, *Plutonium Chemistry Under Conditions Relevant for WIPP Performance Assessment*, EEG-77 (Albuquerque, NM: Environmental Evaluation Group, 2000), 12–18.
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103. See, for example, Harold A. Feiveson, Alexander Glaser, Zia Mian, and Frank N. von Hippel, *Unmaking the Bomb: A Fissile Material Approach to Nuclear Disarmament and Nonproliferation* (Cambridge, MA: MIT Press, 2014).
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105. U.S. Congress, Office of Technology Assessment, *Technologies Underlying Weapons of Mass Destruction*, 158.
106. Ibid., 156.
107. Peterson, "Long-Term Safeguards for Plutonium in Geologic Repositories," 24.

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109. John P. Holdren, "Nuclear Power and Nuclear Weapons: The Connection Is Dangerous," *Bulletin of the Atomic Scientists* 39 (1983): 42.
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114. Orlikowski and Gash, "Technological Frames," 179.
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133. Bunn, Matthew, John P. Holdren, Steve Fetter, and Bob van der Zwann, "The Economics of Reprocessing Versus Direct Disposal of Spent Nuclear Fuel," *Nuclear Technology* 150 (2005): 209–230.
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138. IAEA, *Advisory Group Meeting on Safeguards Related to Final Disposal of Nuclear Material in Waste and Spent Fuel*, 50.
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140. U.S. National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium*, 196–199; Mongiello, Finch, and Baldwin, Safeguards Approaches for Geological Repositories, 9.

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