



Feasibility and Risks of Human Intrusion in WIPP

Cameron L. Tracy¹

¹ Belfer Center for Science and International Affairs, Kennedy School of Government, Harvard University, USA



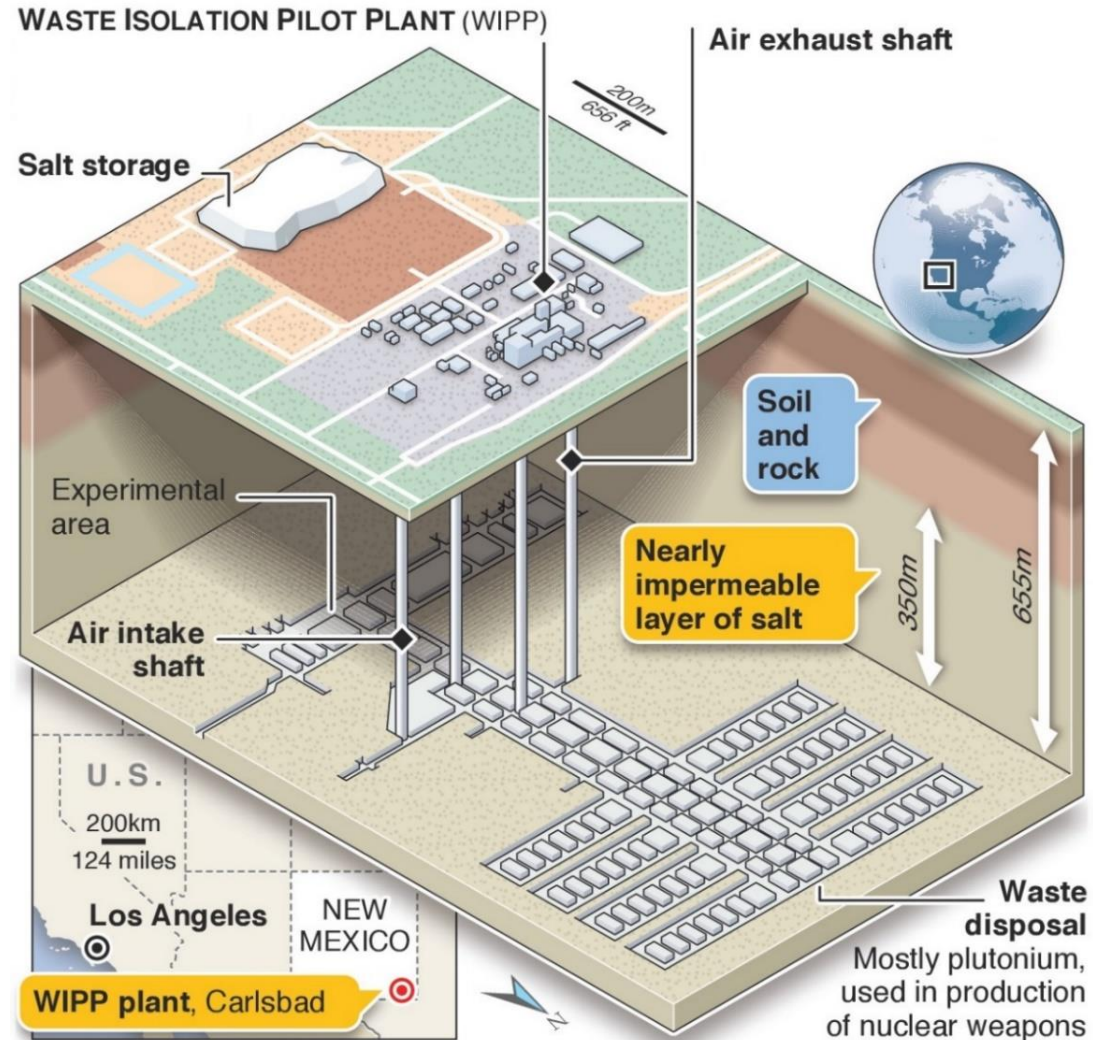
Reliance on the geologic integrity of WIPP

MOX disposal:

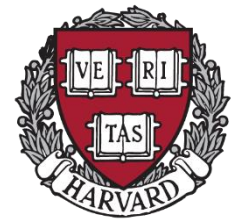
- ▶ Intrinsic alteration of weapons plutonium
- ▶ Transformation to highly radioactive spent nuclear fuel

Dilute and dispose in WIPP:

- ▶ Establishment of barriers to plutonium release
- ▶ 650 m of overlying rock and “stardust” dilutant



Source: SLAC National Accelerator Laboratory, wire agencies

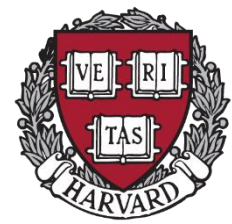


Human intrusion

Long-term stability of WIPP's geologic setting¹:

- ▶ Permian salt beds have remained stable for ~250 million years
- ▶ Relatively little groundwater flow
- ▶ Plastic flow that seals fractures

¹ L. Chaturvedi, "WIPP-related geological issues,"
New Mexico Geological Society Guidebook (1993)



Human intrusion

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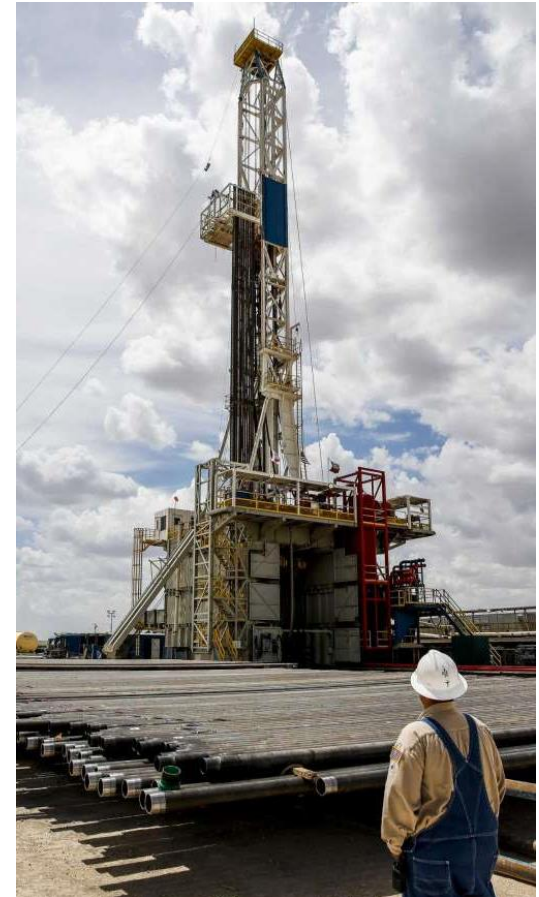
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Geologic factors do not account for human activity:

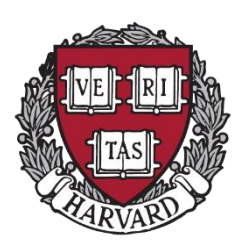
- ▶ Humans drill and excavate
- ▶ WIPP is located in an area rich in geologic resources

Threats to containment:

- ▶ **Inadvertent intrusion:** liberation to the biosphere
 - ▶ A threat to the environment and human health
- ▶ **Intentional intrusion:** acquirement of fissile material
 - ▶ A threat to arms control and nonproliferation



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Inadvertent Intrusion



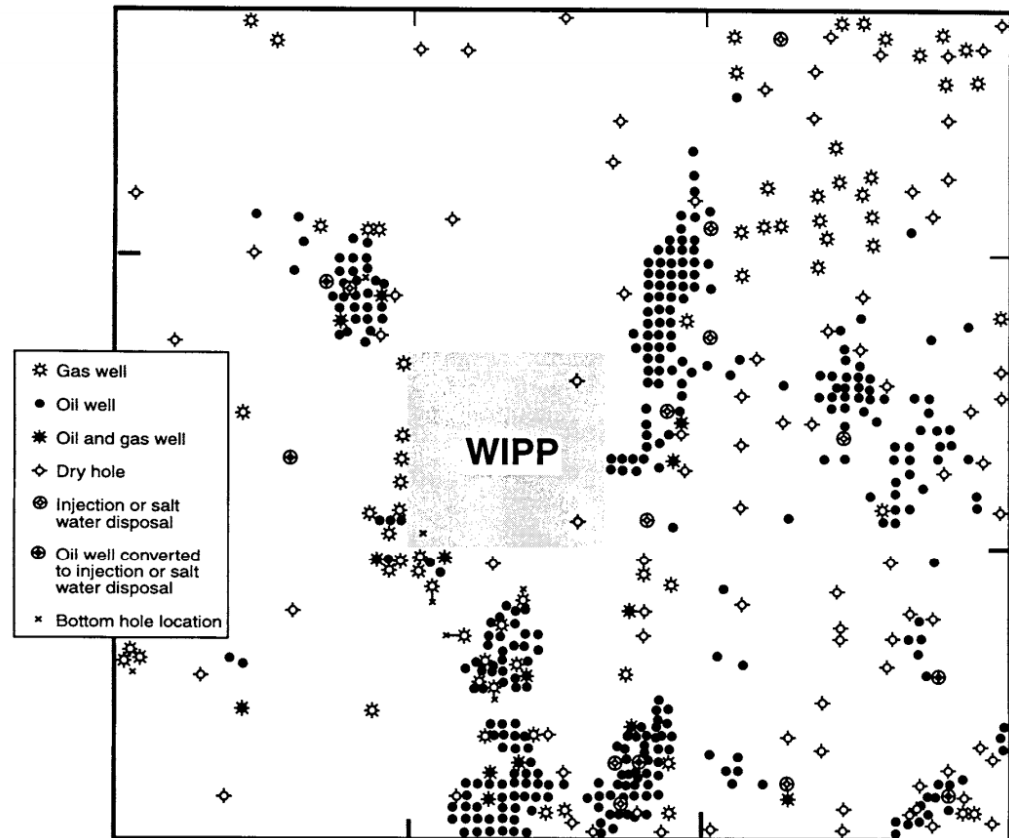
Assessing the risk of borehole penetration

Geologic resources near WIPP:

- ▶ Salt
- ▶ Potash
- ▶ Oil and gas

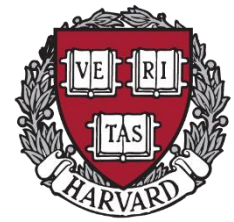
Probability of penetration:

- ▶ **Key determinant:** drilling rate
- ▶ **EPA's licensing requirement:**
“Identify deep drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.” – 40 CFR §194.33(b)(3)(i)
- ▶ **Projection of the 100 year average over the 10,000 year regulatory period:** 5 intrusion events¹



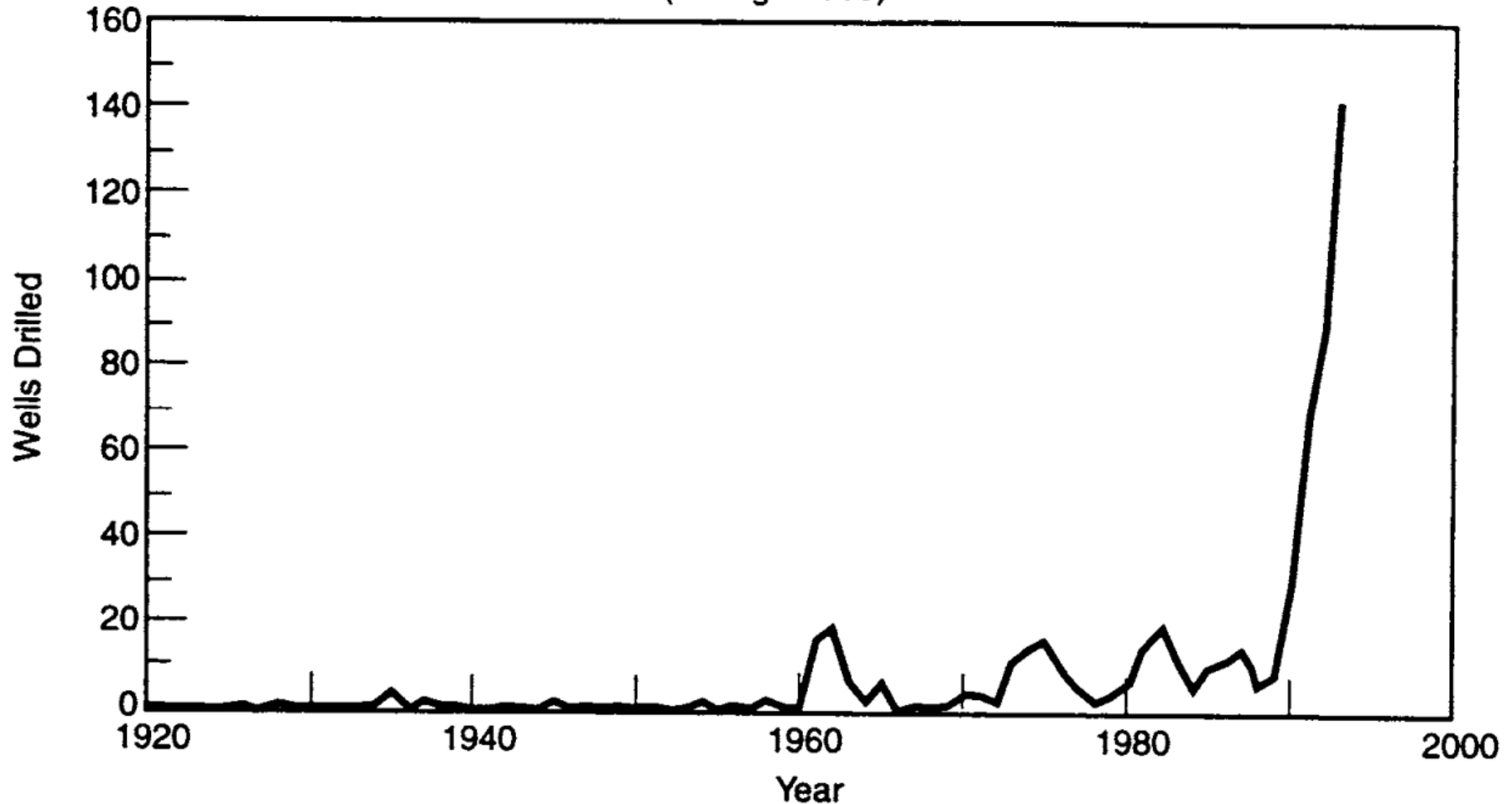
Waste Isolation Pilot Plant Disposal Phase Final Supplemental Environmental Impact Statement, DOE (1997)

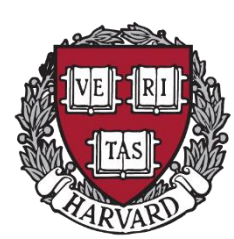
¹Title 40 CFR Part 191 Compliance Certification Application, DOE (1996)



Time evolution of the drilling rate

Yearly Drilling History
(through 1993)



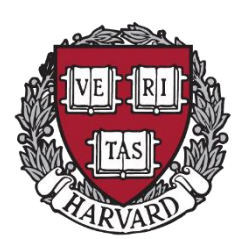


Time evolution of the drilling rate

NASA Landsat Program, Landsat 4, 5 TM, 7 ETM+, 8 OLI, courtesy of the USGS
Copernicus Sentinel Program, Sentinel 2A MSI Level 1C, European Space Agency

1990



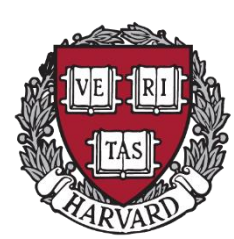


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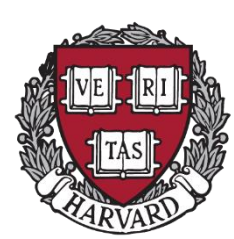


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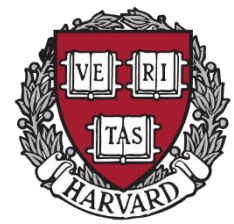


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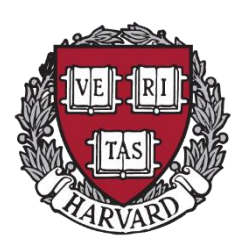


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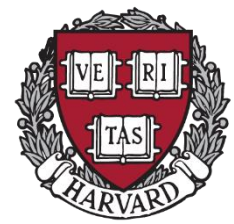


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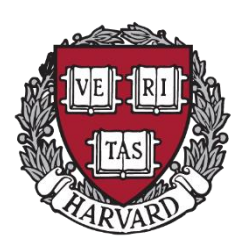


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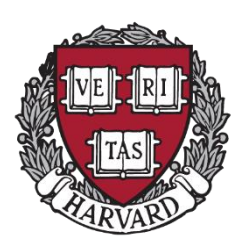


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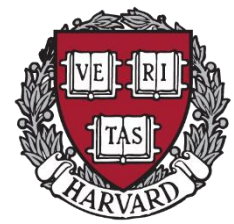


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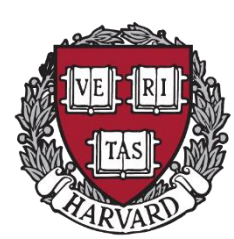


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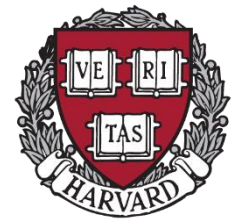


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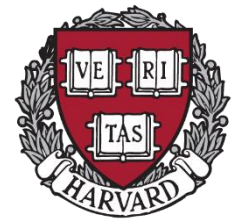


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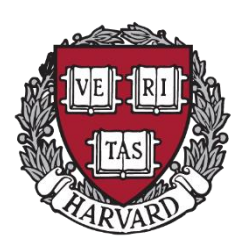


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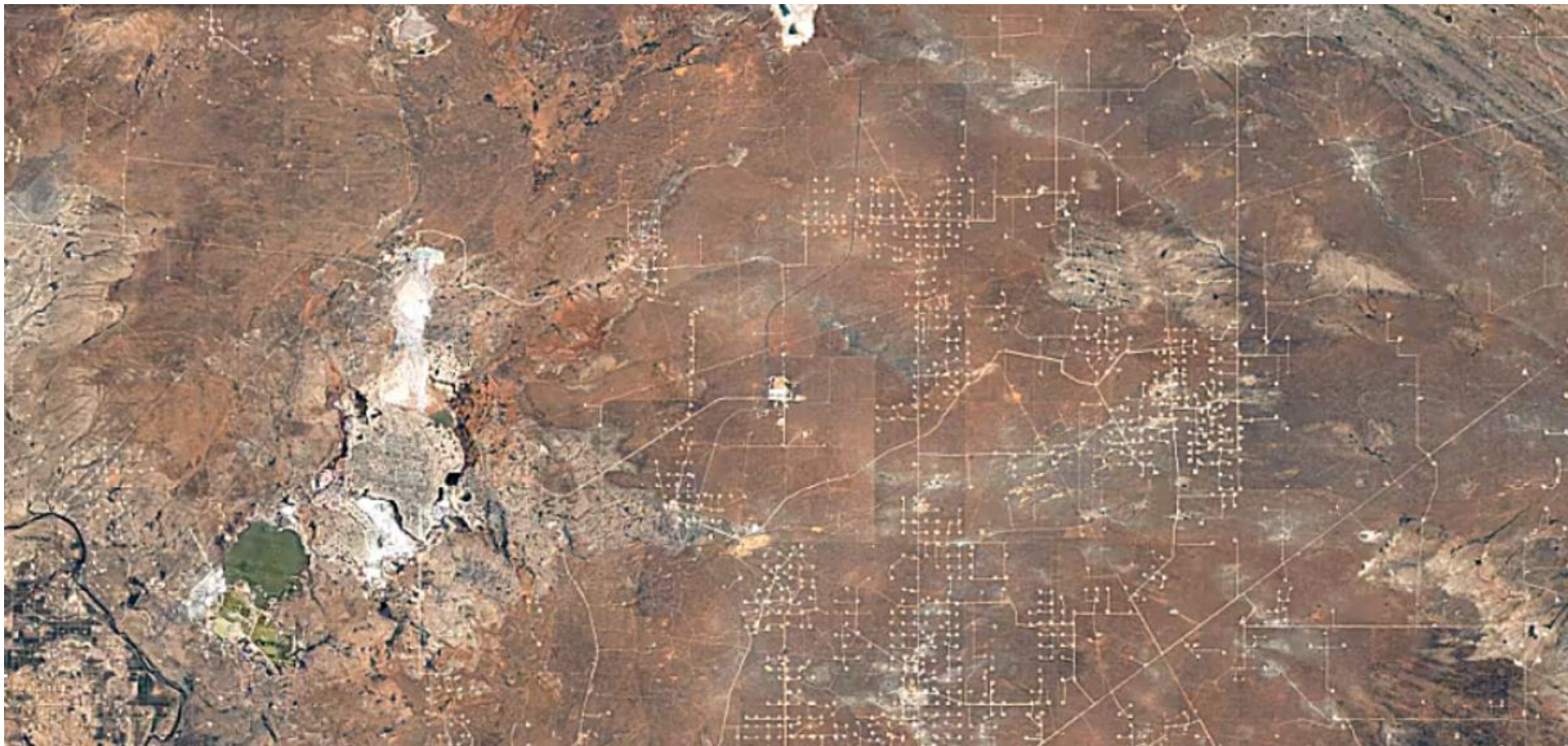


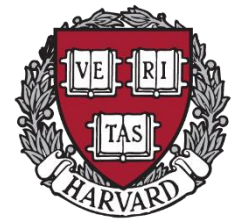


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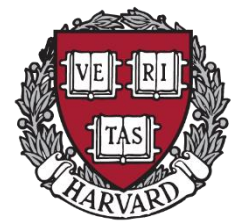


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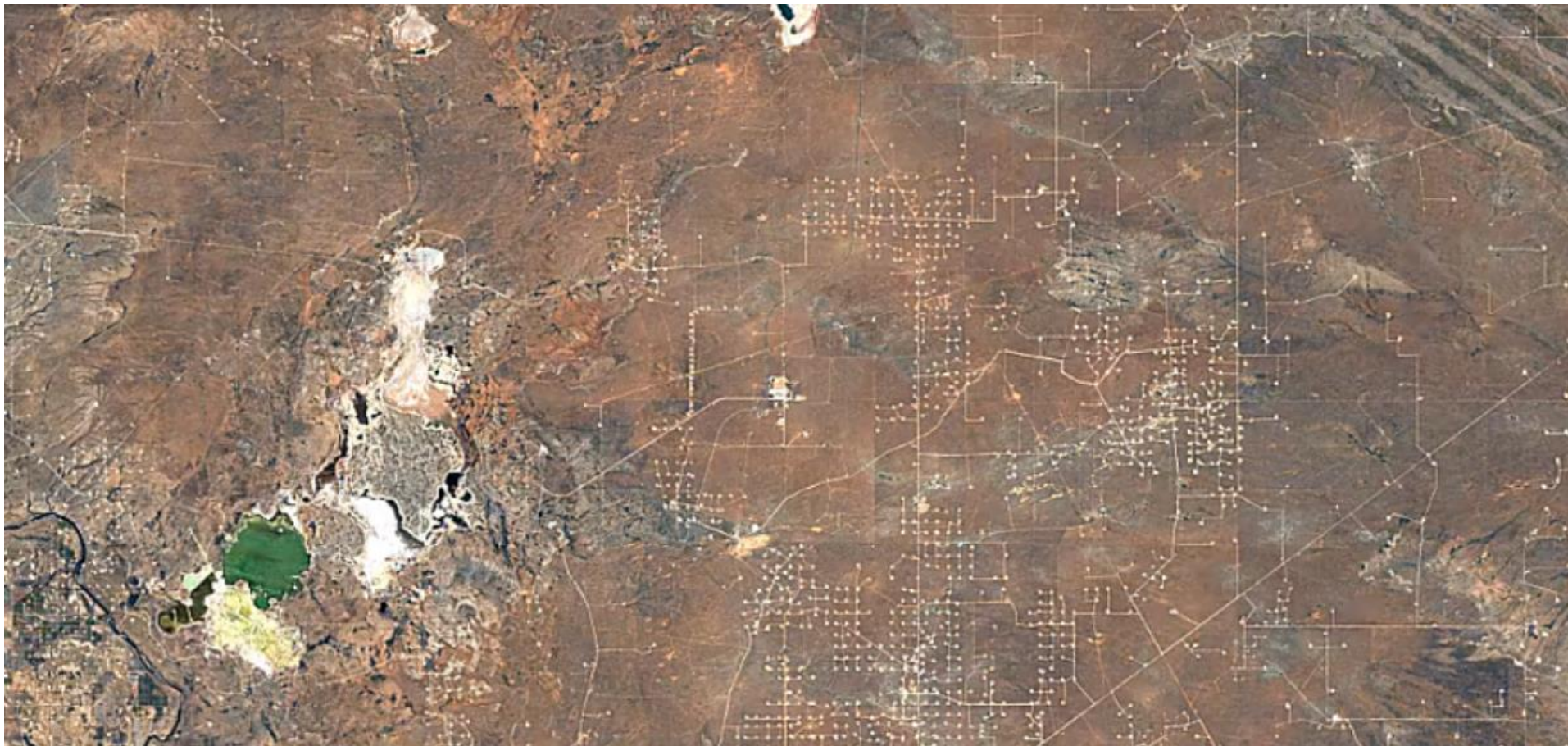


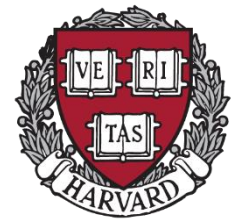


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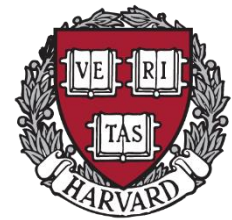


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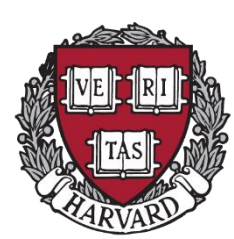


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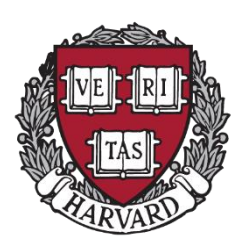


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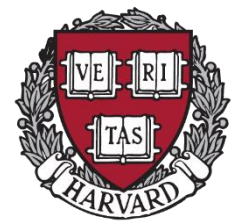


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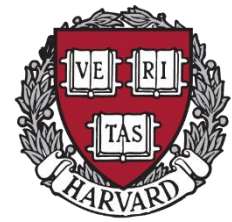


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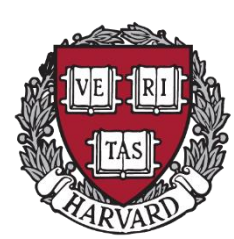


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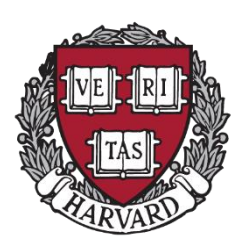


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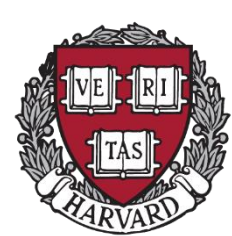


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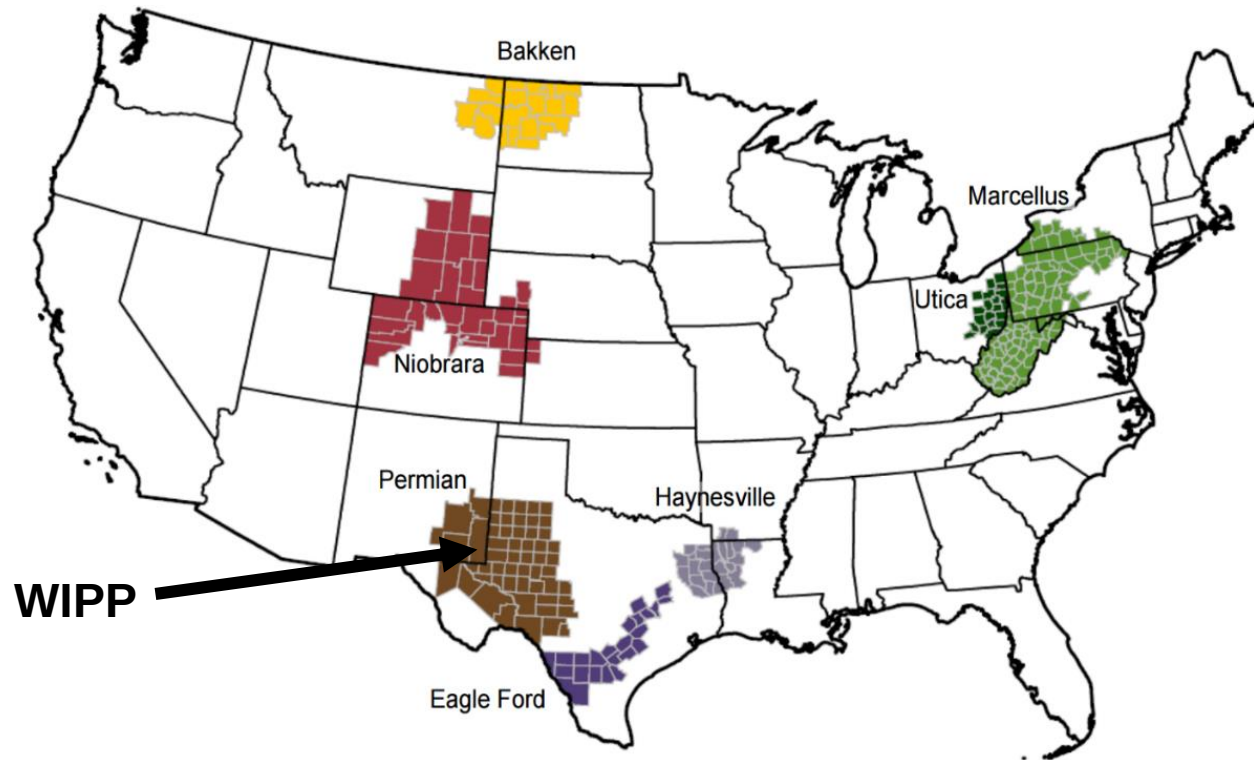
2016



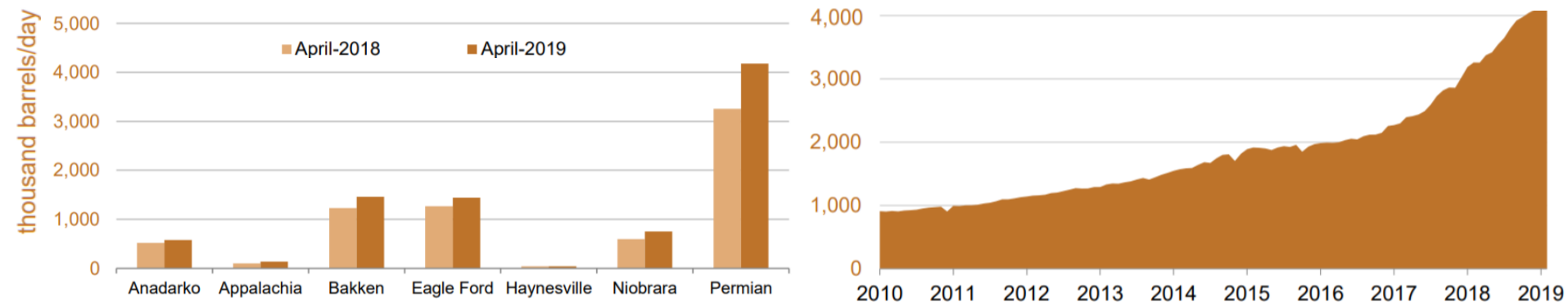


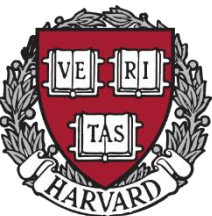
Oil and gas in the Permian Basin

Energy Information Agency, 2019 Drilling Productivity Report



Oil Production





The intrusion risk is poorly estimated

Changes in the projection over time:

- ▶ **1996:** 46.8
boreholes/km²
- ▶ **2014:** 67.3
boreholes/km²
- ▶ A 40% change over 18 years makes for a poor projection over 10,000 years!

Two lessons:

- ▶ WIPP will likely be subject to multiple inadvertent intrusions
- ▶ Shaky reasoning is hidden in the risk assessment



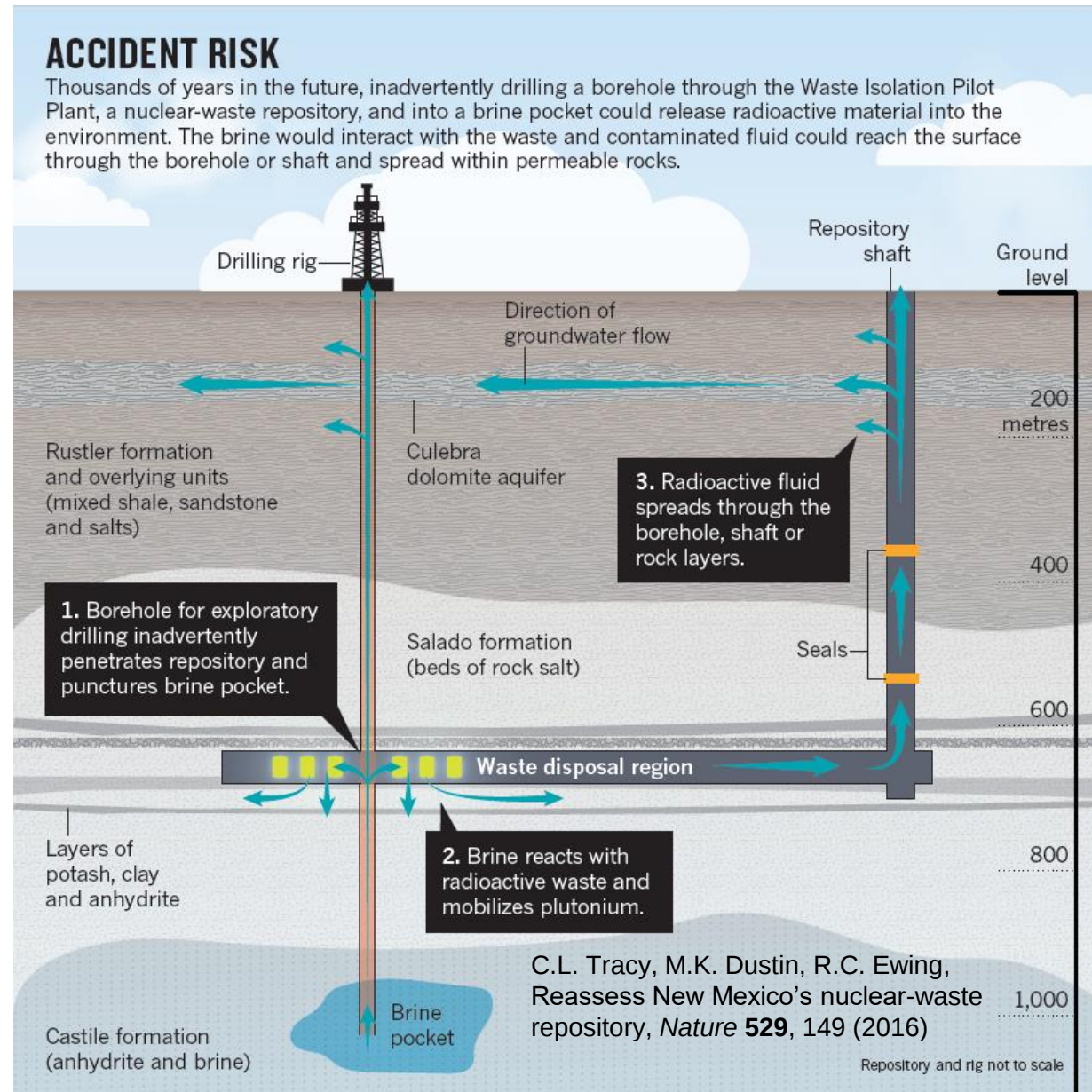
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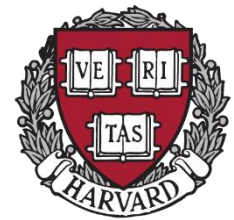
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Does intrusion matter?

“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...” — A. Van Luik, R. Patterson, G.R. Kirkes, “Influencing future exploratory drilling rates—a potential approach for the Waste Isolation Pilot Plant,” *WM2015 Conference*

“A disposition alternative not available in the nineties has been successfully demonstrated...downblending or dilution of PuO_2 with adulterating material and disposal in the Waste Isolation Pilot Plant (WIPP).” — *Final Report of the Plutonium Disposition Red Team*, DOE (2015)

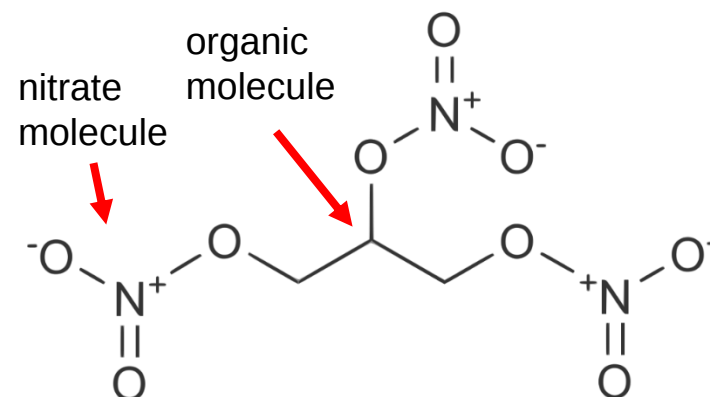


Demonstrated safety

Accident Investigation Report: Radiological Release Event at the Waste Isolation Pilot Plant, February 14, 2014, DOE EM (2015)

2014 release:

- ▶ LANL nitrate wastes required an absorbent
- ▶ A notetaker heard “inorganic” as “an organic”
- ▶ Wheat-based kitty litter was added
- ▶ Nitrates react exothermically with organic compounds





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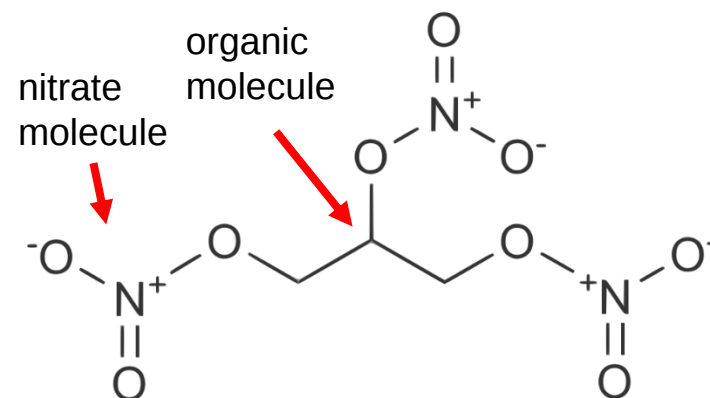
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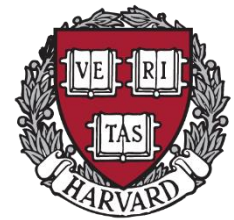
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“Normal” accident¹: a minor human error yielded a much more serious failure due to system complexity and material interactions

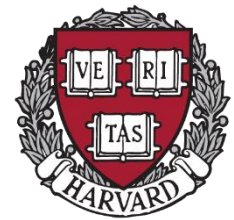


¹ C. Perrow, *Normal Accidents: Living with High Risk Technologies*. Princeton University Press (2011)



Lessons learned

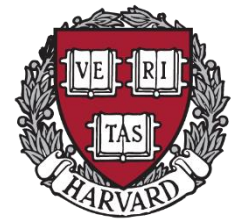
“There was no evidence that any type of technical evaluation occurred regarding the **compatibility of the agents** with the waste stream. Subsequent adjustments to the ratio of absorbent material lacked any technical evaluation to support making the change. The procedure change process was not driven by an overarching engineering change control process that should have ensured the necessary rigor to have caught and dismissed the selection of the organic product.” — *Accident Investigation Report: Radiological Release Event at the Waste Isolation Pilot Plant, February 14, 2014*, DOE EM (2015)



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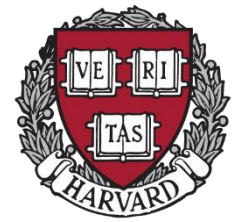
The addition of multiple reactive materials to the system without study of how they might interact invites trouble.



Material complexity and interactions

WIPP's chemical environment:

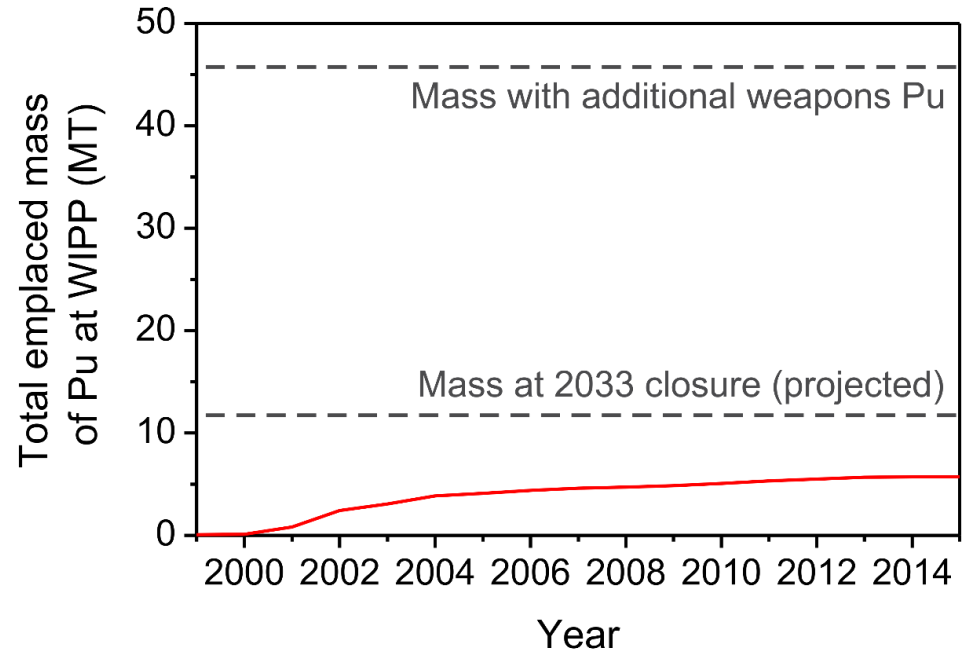
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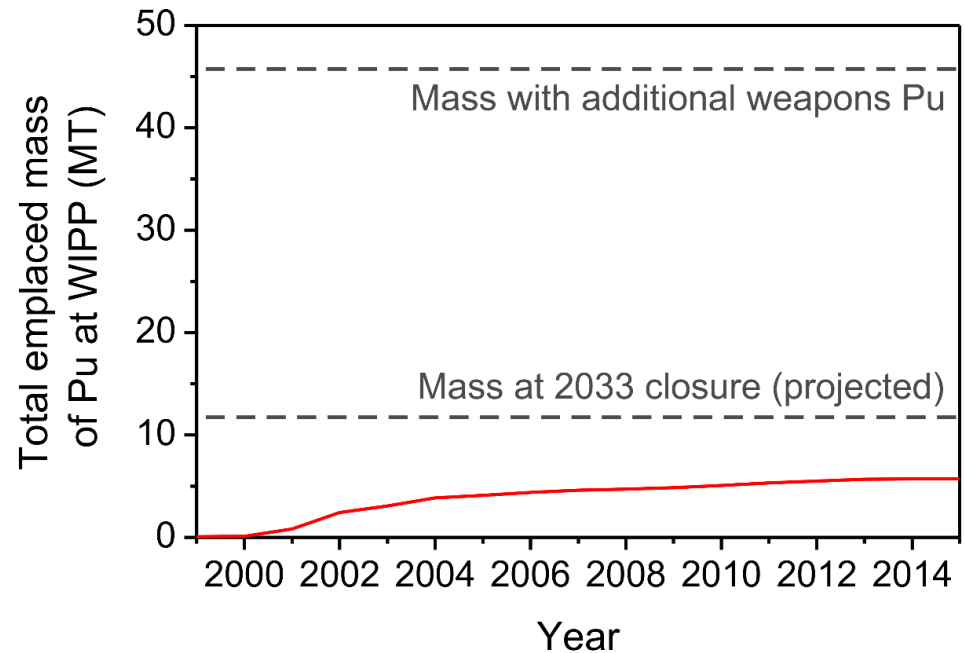
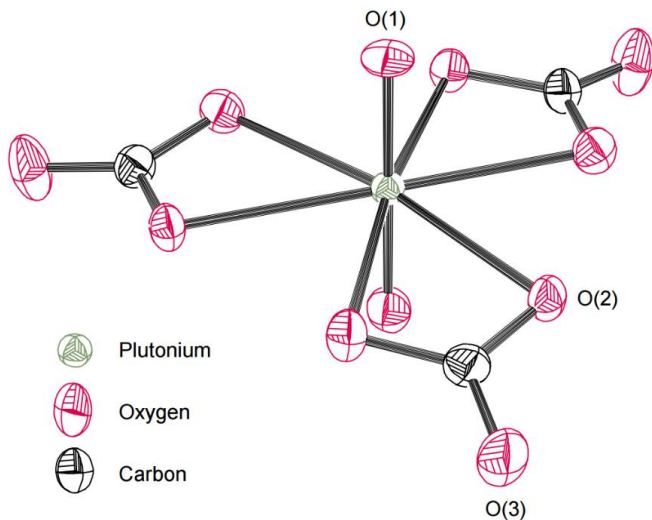




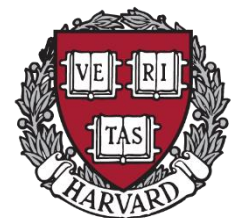
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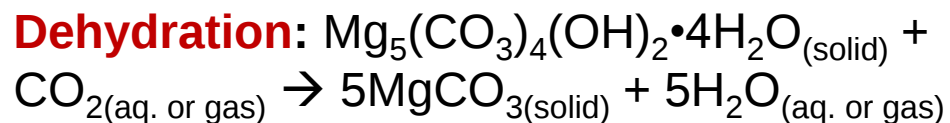
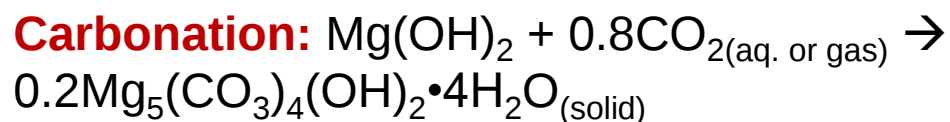
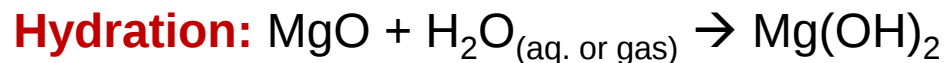
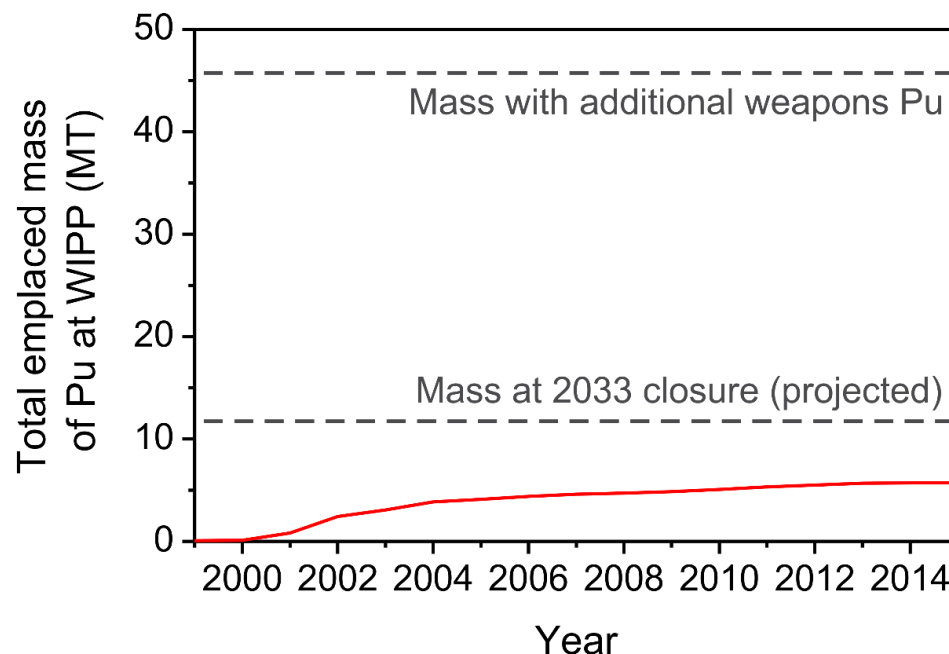
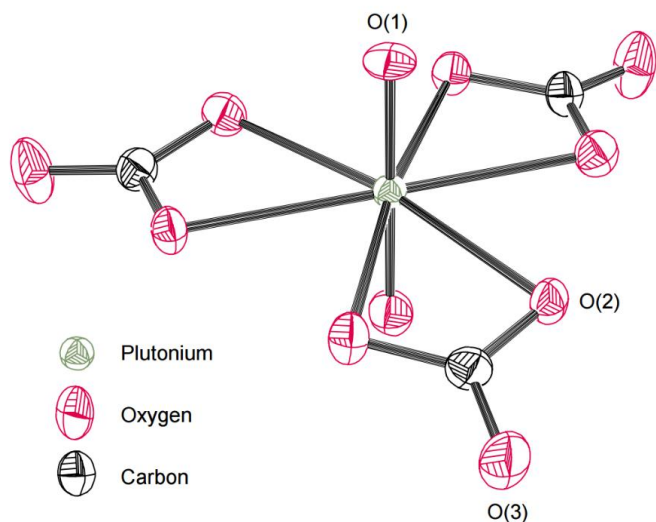
D. Clark, The Chemical Complexities of Plutonium, *Los Alamos Science* **26** (2000)



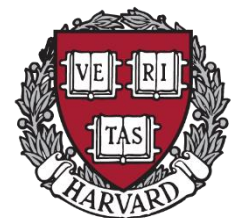
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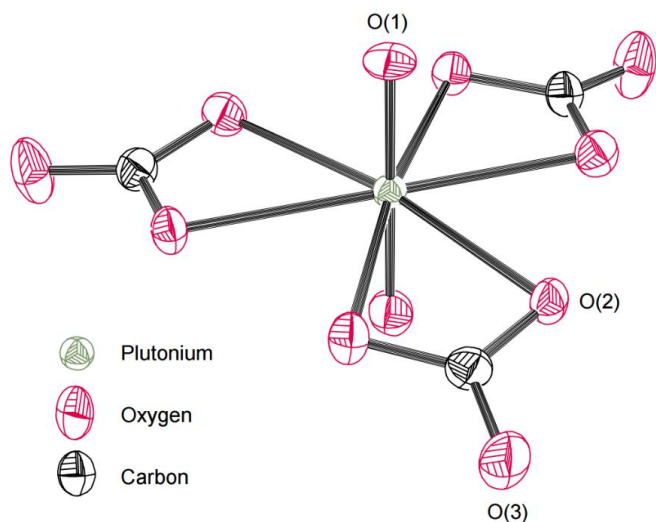
D. Clark, The Chemical Complexities of Plutonium, *Los Alamos Science* **26** (2000)



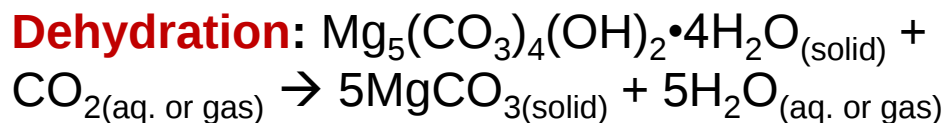
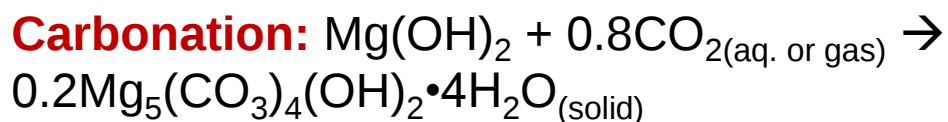
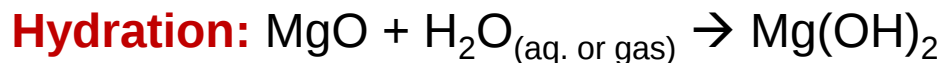
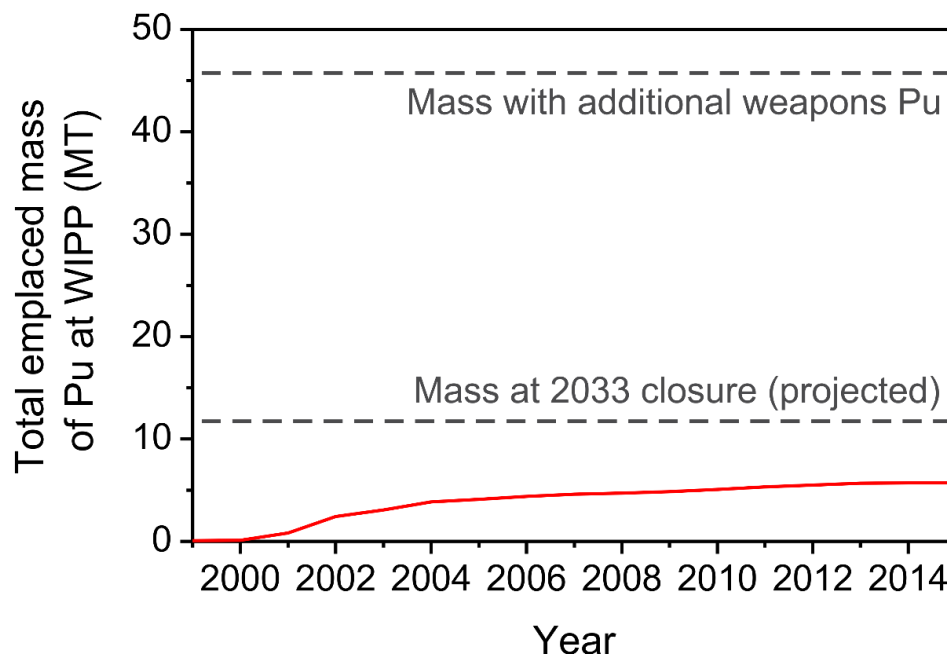
Material complexity and interactions

WIPP's chemical environment:

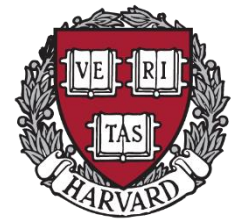
- ▶ Brine
- ▶ Plutonium
- ▶ CO₂
- ▶ MgO
- ▶ Stardust



D. Clark, The Chemical Complexities of Plutonium, *Los Alamos Science* **26** (2000)



An “inert adulterant” of classified composition –
Final Report of the Plutonium Disposition Red Team, DOE (2015)



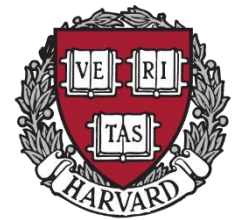
Chemical uncertainty

MgO and CO₂:

- ▶ “MgO acts as an engineered barrier by decreasing actinide solubilities through the **consumption of essentially all carbon dioxide** possibly produced by microbial activity. Since microbial activity is an uncertain process, the MgO engineered barrier **reduces uncertainty** in the repository chemical conditions...”
— *WIPP Compliance Recertification Application 2014 for the Waste Isolation Pilot Plant*, DOE (2015)
- ▶ “Considering the **uncertainties about the chemical performance** of the MgO backfill, the committee questions the value of its use...and, if its benefits to the long-term performance of the repository **cannot be verified**, the option to discontinue its use should be considered.” — *Improving Operations and Long-Term Safety of the WIPP*, National Research Council (2000)
- ▶ No specific study of MgO behavior in the presence of brine, plutonium, and CO₂

Stardust:

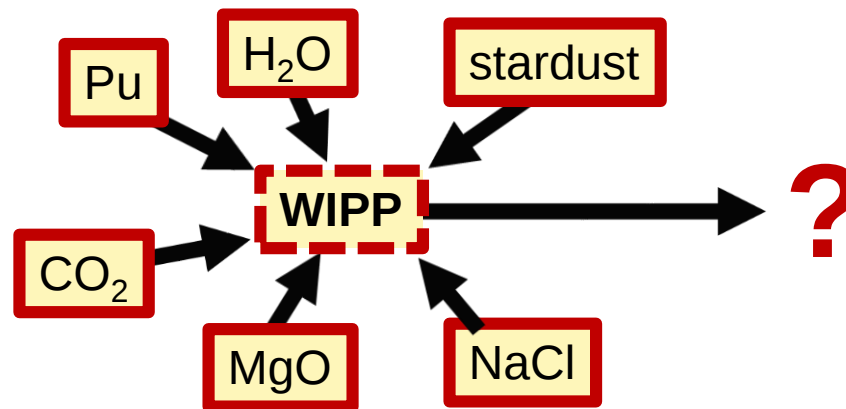
- ▶ An “inert adulterant” — *Final Report of the Plutonium Disposition Red Team*, DOE (2015)
- ▶ “Cementing, gelling, thickening, and foaming agents” — T. Hayes, R. Nelson, “Terminating safeguards on excess special nuclear material: defense TRU waste clean-up and nonproliferation,” *WM2012 Conference*

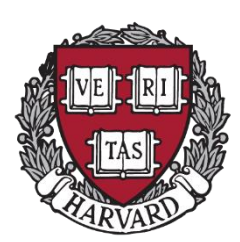


Conclusions: inadvertent intrusion

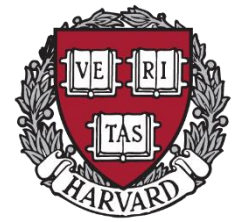
Conclusions:

- ▶ The best guide to WIPP's future performance is its past
- ▶ Proliferation of nearby drilling suggests underestimation of the intrusion risk
- ▶ The 2014 accident demonstrates pitfalls of adding new materials absent specific, rigorous technical evaluation
- ▶ The addition of vast quantities of new materials risks repeating past mistakes
- ▶ “Questioning attitudes were not welcomed by management...” — *Accident Investigation Report: Radiological Release Event at the Waste Isolation Pilot Plant, February 14, 2014*, DOE EM (2015)





Intentional Intrusion



The global security motivation for disposal

Preventing acquisition by non-state actors:

- ▶ ~6 kg Pu is sufficient to make a weapon
- ▶ “The acquisition of sufficient quantities of weapon-grade materials presents the greatest technological hurdle to the would-be proliferant.” - US Congress, Office of Technology Assessment, *Technologies Underlying Weapons of Mass Destruction* (1993)



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Making permanent arms control and disarmament progress:

SALT I, 1972



START I, 1991



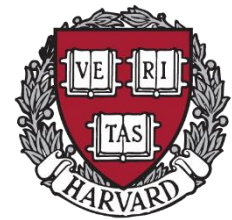
SORT, 2003



New START, 2011



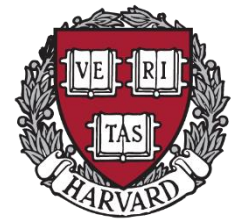
- ▶ Thousands of warheads/delivery systems removed from deployment
- ▶ Plutonium remains stockpiled
- ▶ Redeployment is fast and easy



US-Russian disagreement over efficacy

Varying interpretations of retrievability/irretrievability:

- ▶ Russian PMDA negotiators considered dilute and dispose to be “just another form of storage” — M. Bunn, “Troubled disposition: next steps in dealing with excess plutonium”, *Arms Control Today* 37 (2007)
- ▶ “Plutonium in weapons-useful quantities could be recovered from any of the forms in the disposition program. The resources required...would be relatively modest.” — J.P. Hinton et al., “Proliferation vulnerability red team report,” Sandia National Laboratory (1996)
- ▶ “This means that they preserve what is known as the breakout potential, in other words it can be retrieved, reprocessed and converted into weapons-grade plutonium again. This is not what we agreed on.” — President Putin, comments at the Truth and Justice Media Forum, St. Petersburg, April 2016:
- ▶ DOE Carlsbad Field Office representative: “I would consider it non-recoverable for all intents and purposes.”



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The critical, unresolved question: is the Russian objection valid? Could the US secretly mine plutonium buried in WIPP?



Prior assessment of recovery risks

General finding: mining is vulnerable to observation and thus preventable

G. Linsley, A. Fattah, "The interface between nuclear safeguards and radioactive waste disposal: emerging issues," *IAEA Bulletin* 2, 22 (1994)

P.F. Peterson, "Long-term safeguards for plutonium in geologic repositories," *Sci. Global. Sec.* 6, 1 (1996)

E.S. Lyman, H.A. Feiveson, "The proliferation risks of plutonium mines," *Sci. Global Sec.* 7, 119 (1998)

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Assumptions:

- ▶ Open-pit quarrying, drill-and-blast excavation, or tunnel boring
- ▶ Required to bring Pu-bearing "ore" to the surface
- ▶ Easily detected by imaging, seismic monitoring, etc.



Udachnaya mine in Siberia, similar in depth to WIPP



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This is not how salt or actinides (like uranium) are actually mined!



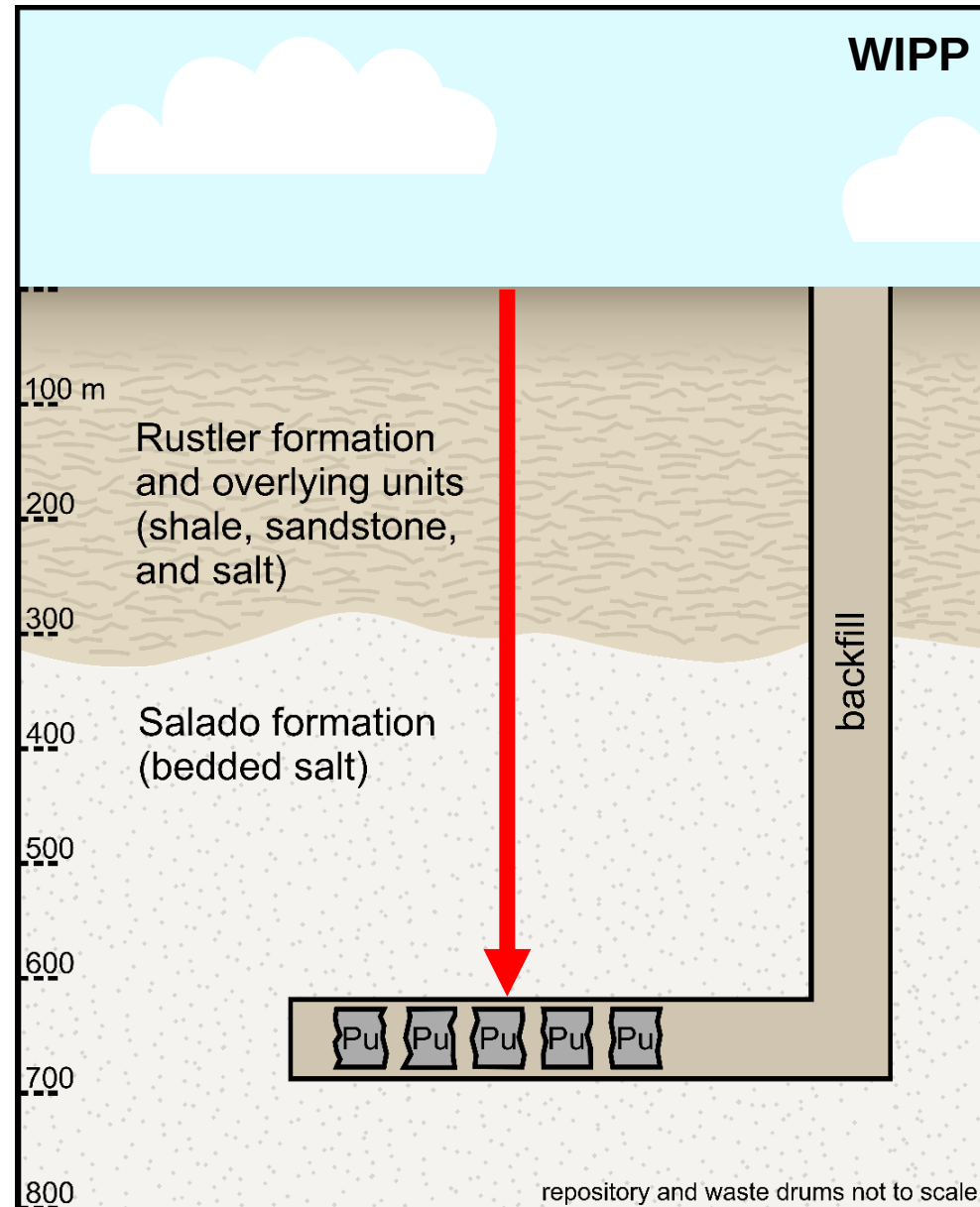
Udachnaya mine in Siberia, similar in depth to WIPP



Advanced mining techniques

Steps for clandestine recovery:

- Access the Pu-bearing solids with minimal excavation

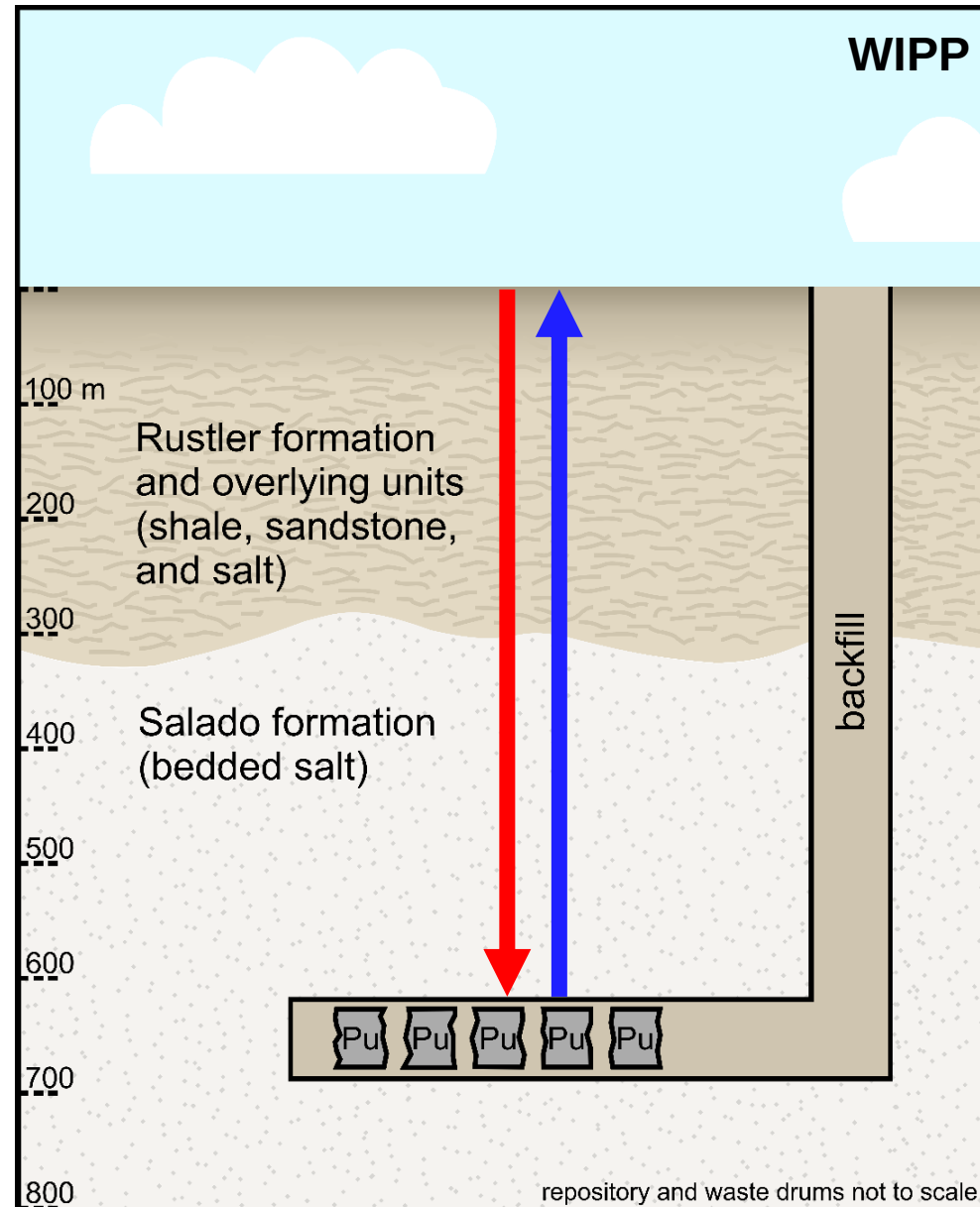


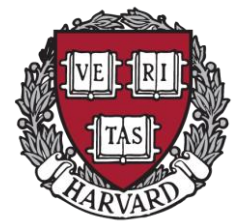


Advanced mining techniques

Steps for clandestine recovery:

- ▶ Access the Pu-bearing solids with minimal excavation
- ▶ Extract Pu underground and bring it back to the surface





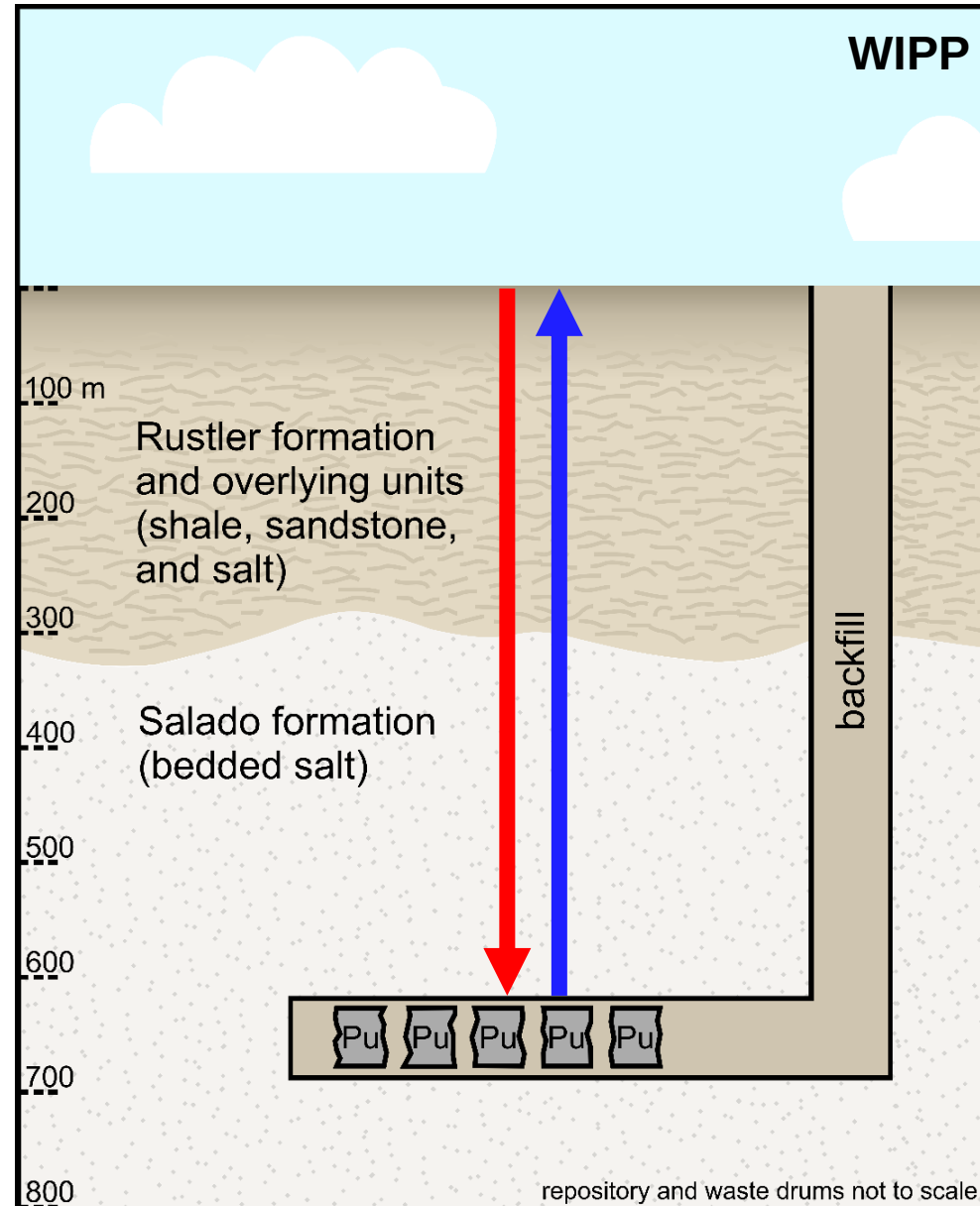
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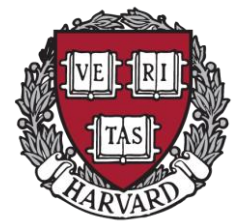
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Industry-standard approach:

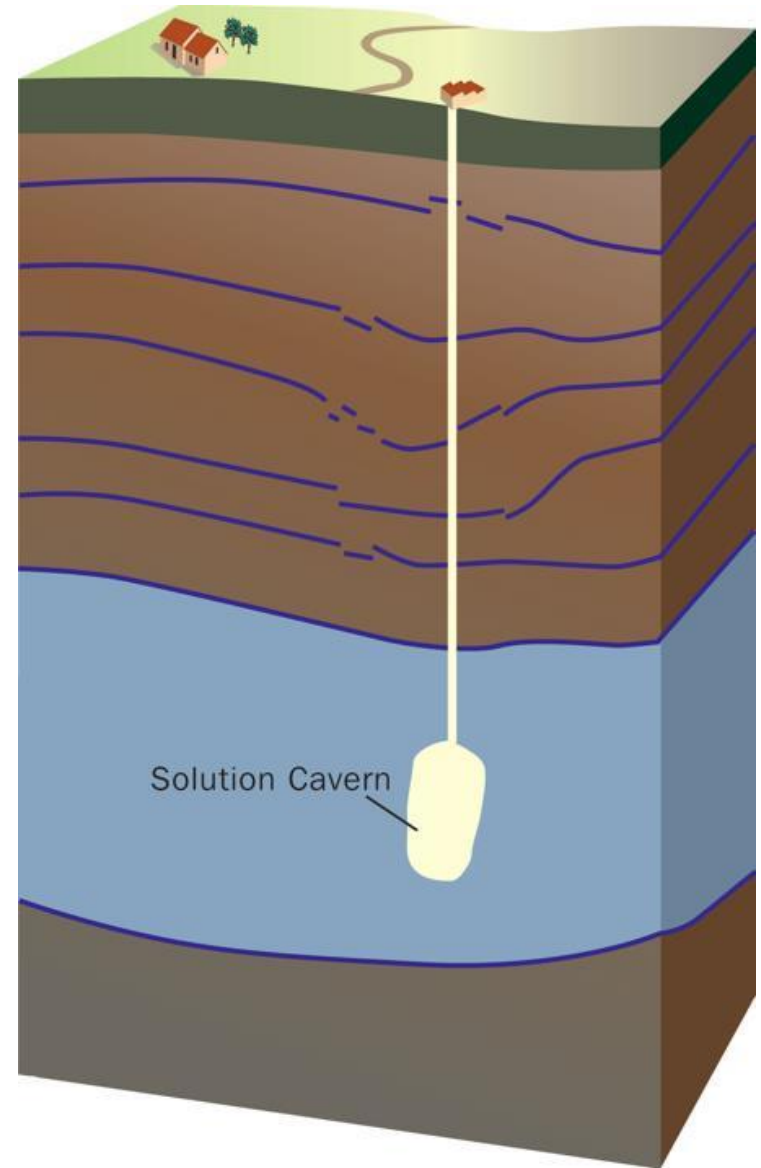
- ▶ Liquid-state methods, rather than solid-state
- ▶ Pumping to and from the Pu via a single, narrow borehole
- ▶ Techniques: salt solution mining and in situ leaching





Salt solution mining

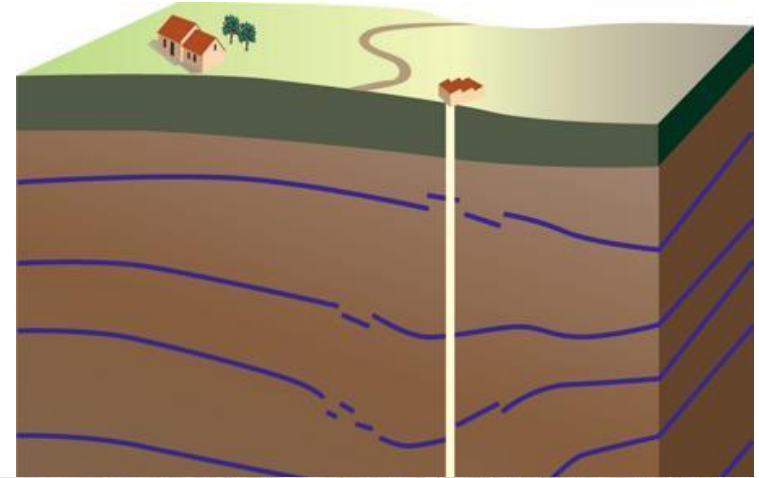
- ▶ A borehole is drilled into the salt deposit
- ▶ Water is pumped down, dissolving salt
- ▶ Brine is pumped back to the surface





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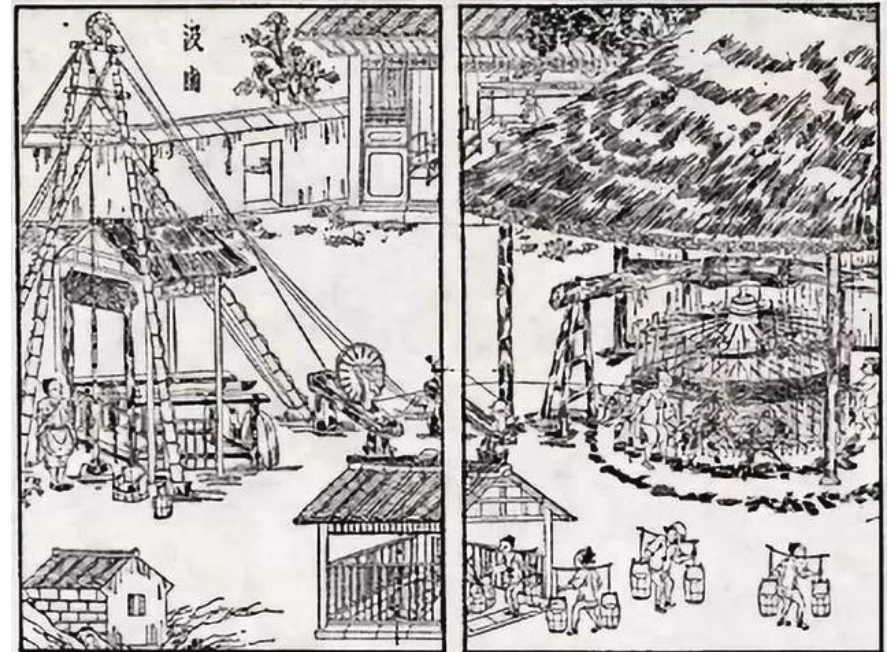


Feasibility¹:

- ▶ Developed in 300 BC
- ▶ Chinese wells reached depths >1 km by the 18th century
- ▶ Primary source of US salt production²
- ▶ Typical depths of 400-2000 m
- ▶ Requires minimal surface infrastructure

¹ J. Warren, *Evaporites: Sediments, Resources, and Hydrocarbons* (2006)

² US Geological Survey, *2015 Mineral Yearbook: Salt*

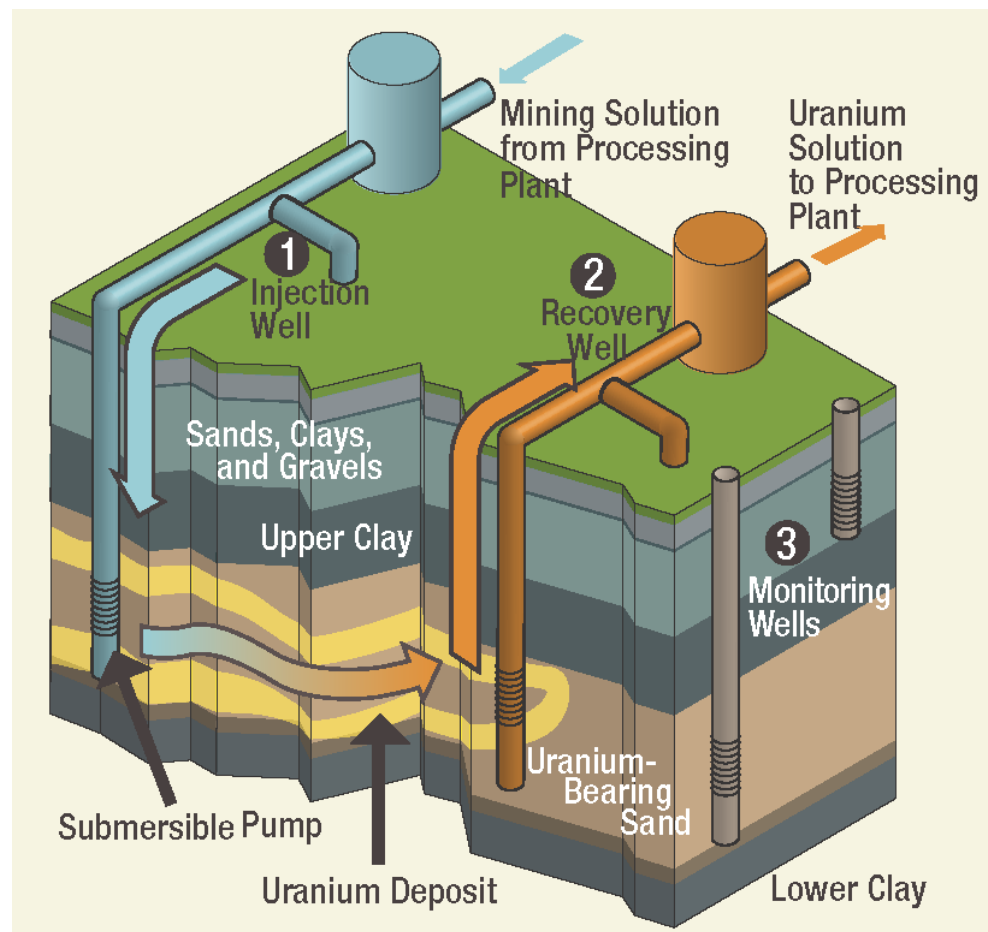


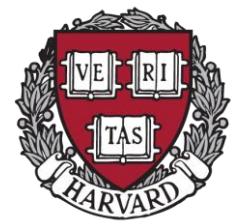
S. Yingxing, *The Exploitation of the Works of Nature* (1637)



In situ leaching

- ▶ A chemical lixiviant (e.g., water + CO_2) is pumped into the deposit
- ▶ The lixiviant reacts with the actinide metal (U, Pu), mobilizing it
- ▶ Pregnant solution is pumped back to the surface for off-site extraction





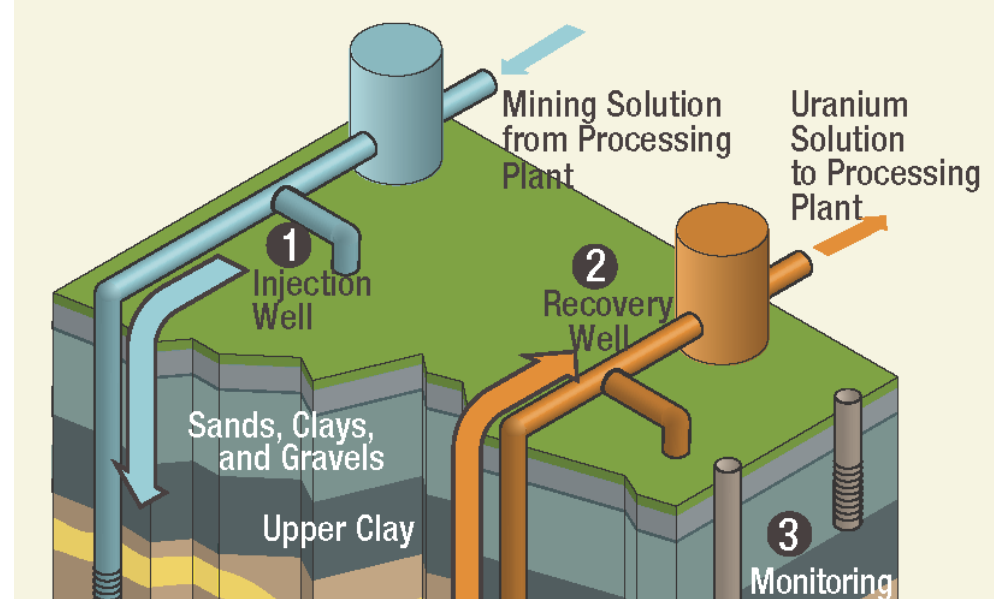
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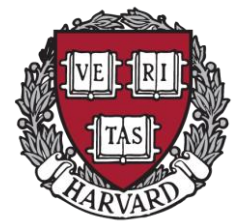
Feasibility¹:

- ▶ Developed in the 1950s
- ▶ Primary source of global uranium production
- ▶ Typical depths of 10-750 m
- ▶ Pu is chemically similar to U
- ▶ Requires minimal surface infrastructure

¹ M. Seredkin, et al., "In situ recovery, an alternative to conventional methods of mining," *Ore Geo. Rev.* 79, 500 (2016)



In situ leaching of uranium in South Australia

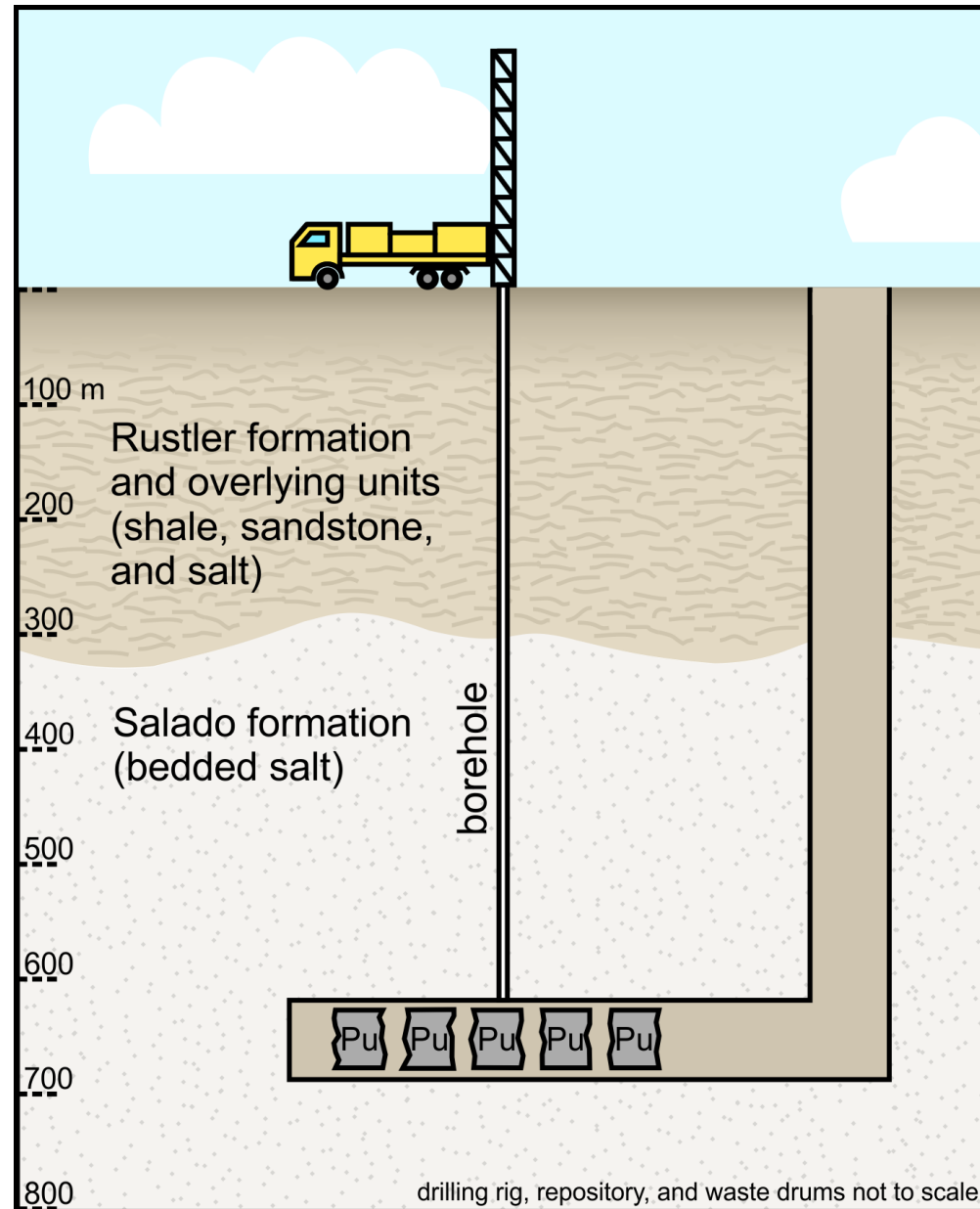


Application to Pu recovery from WIPP (1)

Drilling of a borehole:

- ▶ Mobile drilling rig
- ▶ ~30 cm diameter borehole
- ▶ Provides access to the repository panel in which Pu is known to be stored
- ▶ Acoustic signatures of drilling in salt are low¹

¹ P.F. Peterson, "Issues for detecting undeclared post-closure excavation at geologic repositories," *Sci. Global. Sec.* 8, 1 (1999)

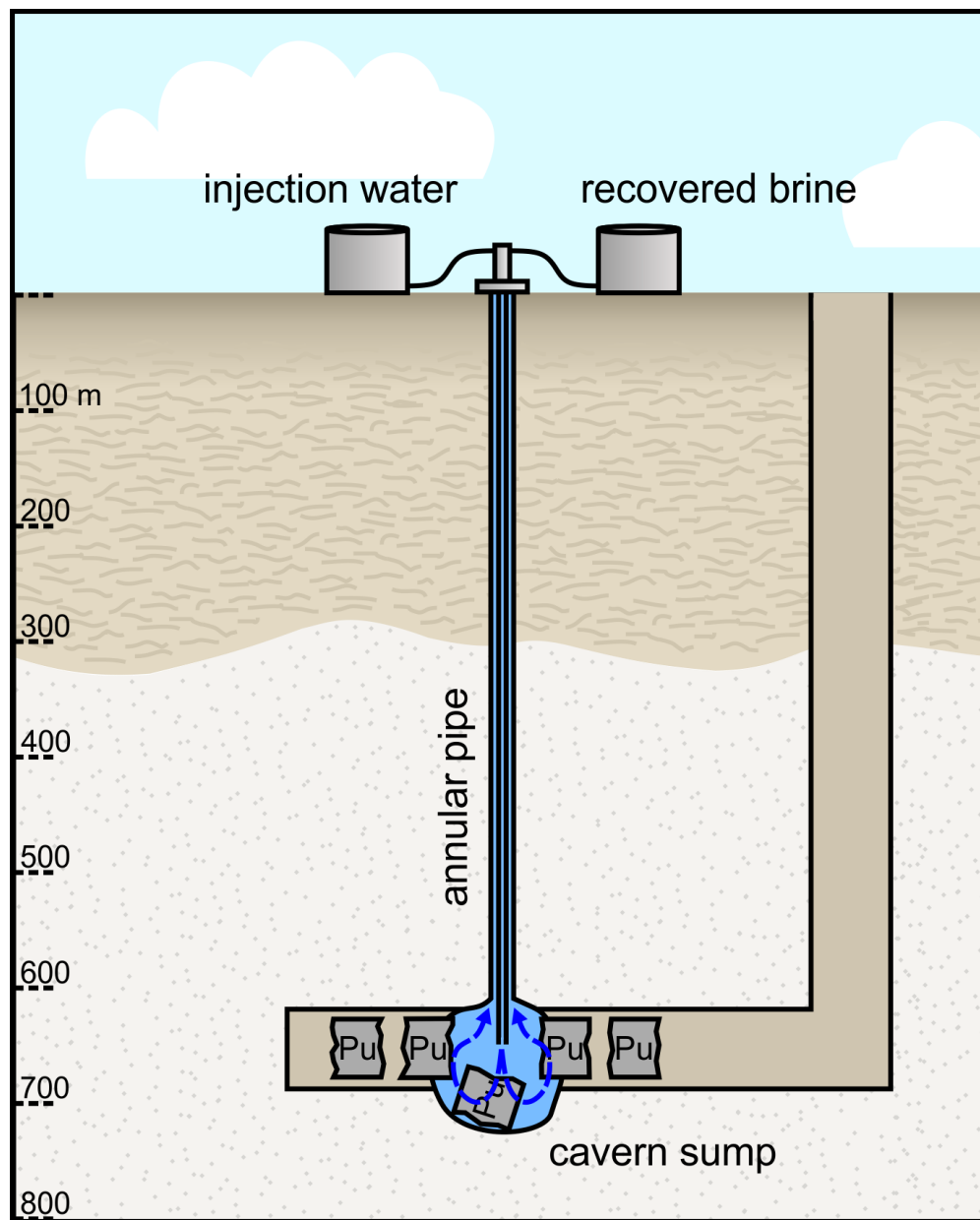




Application to Pu recovery from WIPP (2)

Salt dissolution:

- ▶ Insertion of an annular pipe
- ▶ Water is pumped down the center of the pipe and up the annulus
- ▶ Formation of a spherical cavern, containing Pu-bearing “ore”

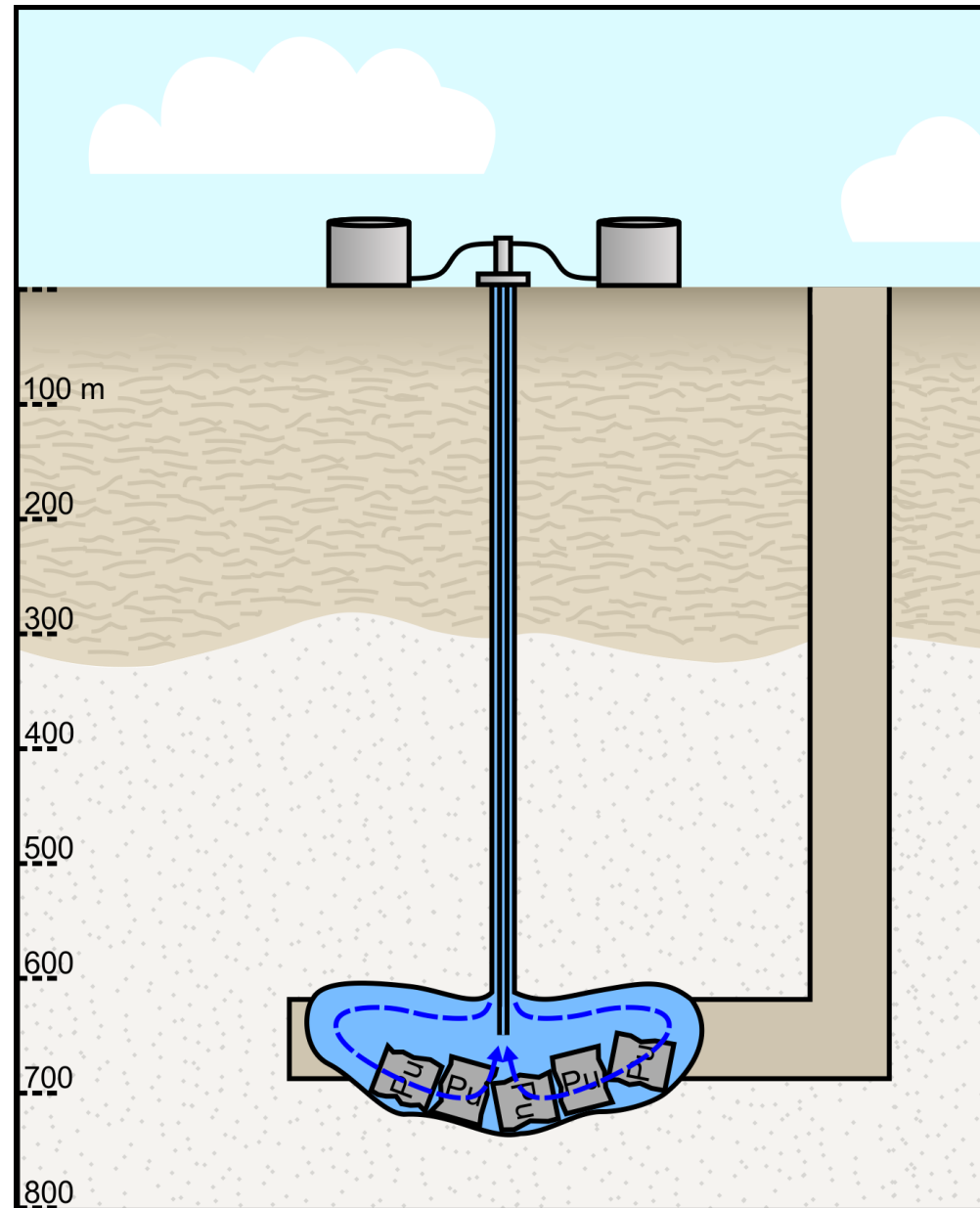




Application to Pu recovery from WIPP (3)

Expansion of the cavern:

- ▶ Water is pumped down the annulus and up the center
- ▶ The cavern expands horizontally
- ▶ Substantial quantities of Pu are accessible from a single borehole

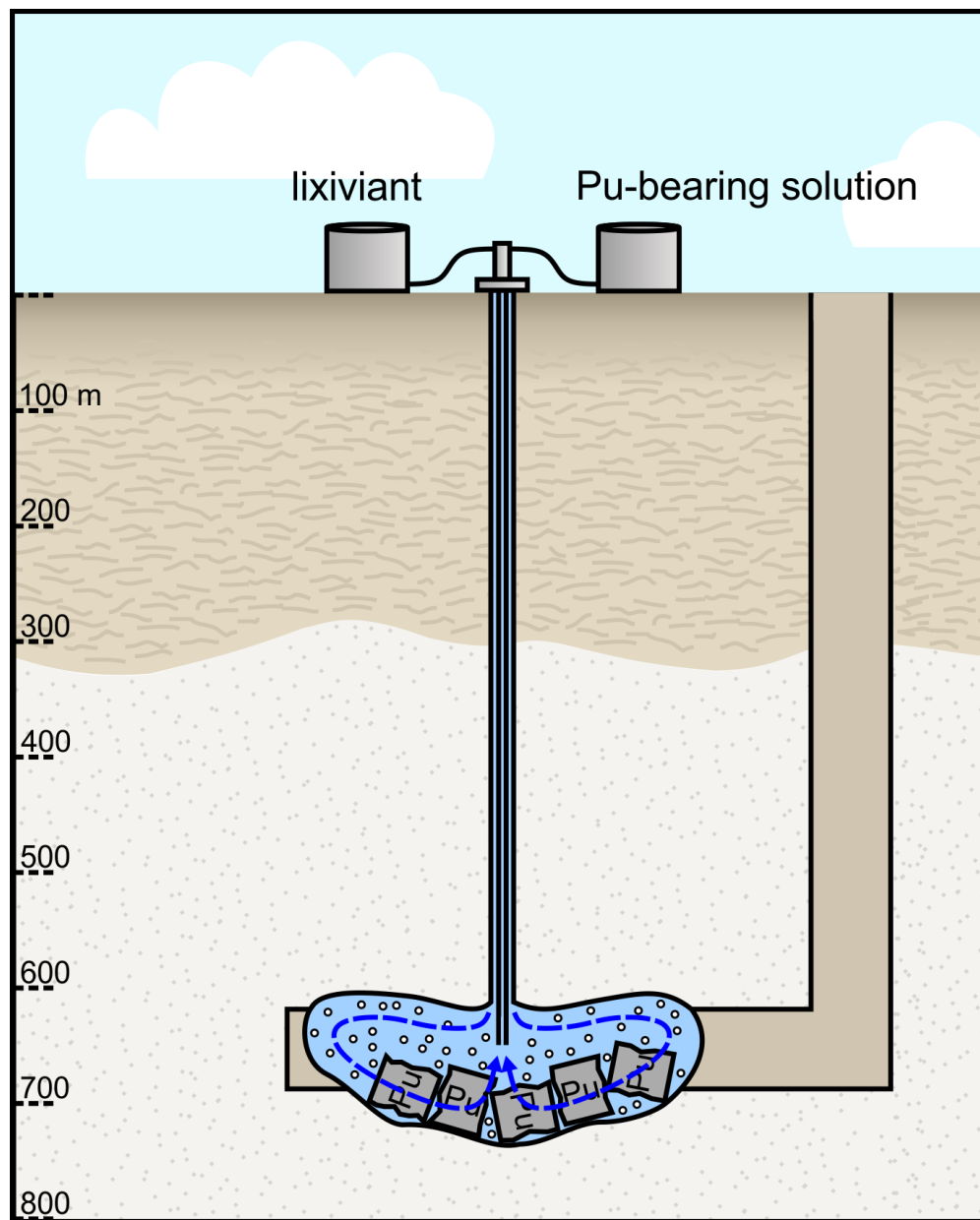


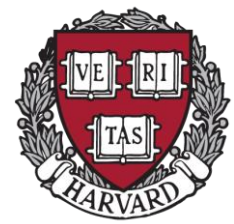


Application to Pu recovery from WIPP (4)

In situ leaching of Pu:

- ▶ Lixiviant is pumped throughout the cavern
- ▶ Pu is oxidized or complexed by carbonate ions, mobilizing it
- ▶ Pregnant solution is pumped back to the surface
- ▶ Pu is extracted from solution off-site

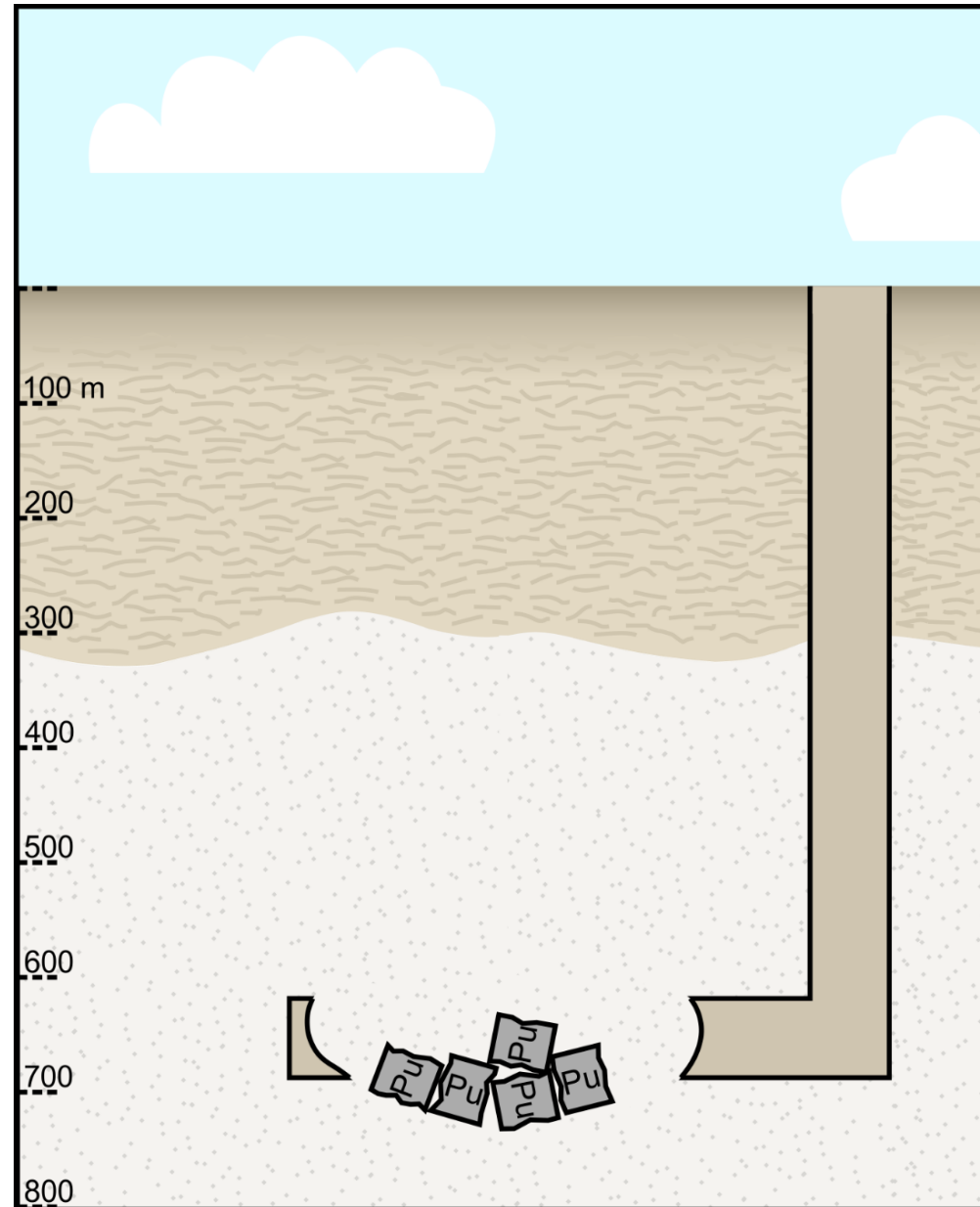




Application to Pu recovery from WIPP (5)

Removal of equipment:

- ▶ All surface equipment is removed
- ▶ Minimal tailings or other evidence of mining remain
- ▶ Plastic flow of salt seals the borehole





Potential impediments to recovery

Dilution:

- ▶ Mixed with to concentrations of $<10\%$ in stardust
- ▶ “Cementing, gelling, thickening, and foaming agents” that make plutonium “more difficult and more complex to recover”¹
- ▶ “Recovery of plutonium from disposition end-forms...would not be seriously complicated by the lower concentrations....recovery would still be feasible”²
- ▶ In situ leaching is routinely used for concentrations $<0.1\%$ ³
- ▶ Classified status prevents further analysis (by both myself and the rest of the world)

¹ T. Hayes, R. Nelson, “Terminating safeguards on excess special nuclear material: defense TRU waste clean-up and nonproliferation,” WM2012 Conference (2012)

² J.P. Hinton et al., “Proliferation vulnerability red team report,” Sandia National Laboratory (1996)

³ International Atomic Energy Agency, *In Situ Leaching of Uranium: Technical, Environmental, and Economic Aspects* (1989)



Potential impediments to recovery

Packaging:

- ▶ Steel pipe overpack containers or similar in 55 gallon drums
- ▶ Exposure to brine in WIPP corrodes and perforates drums in a matter of years¹
- ▶ Flowing salt will crush the drums and release their contents²



Salt:

- ▶ In situ leaching has never been performed in salt
- ▶ Studies of WIPP show substantial Pu uptake into natural brine³

¹ M.A. Molecke et al., "Results from simulated contact-handled transuranic waste experiments at the Waste Isolation Pilot Plant," *Mat. Res. Soc. Symp. Proc.* 333, 681 (1993)

² Pecos Management Services, "An analysis of the monitoring of rooms and panels at WIPP," (2006)

³ V.M. Oversby, "Plutonium chemistry under conditions relevant for WIPP performance assessment," New Mexico Environmental Evaluation Group (2000)



The feasibility of clandestine recovery

Advanced mining techniques, previously unconsidered, provide a strong technical basis for clandestine recovery.

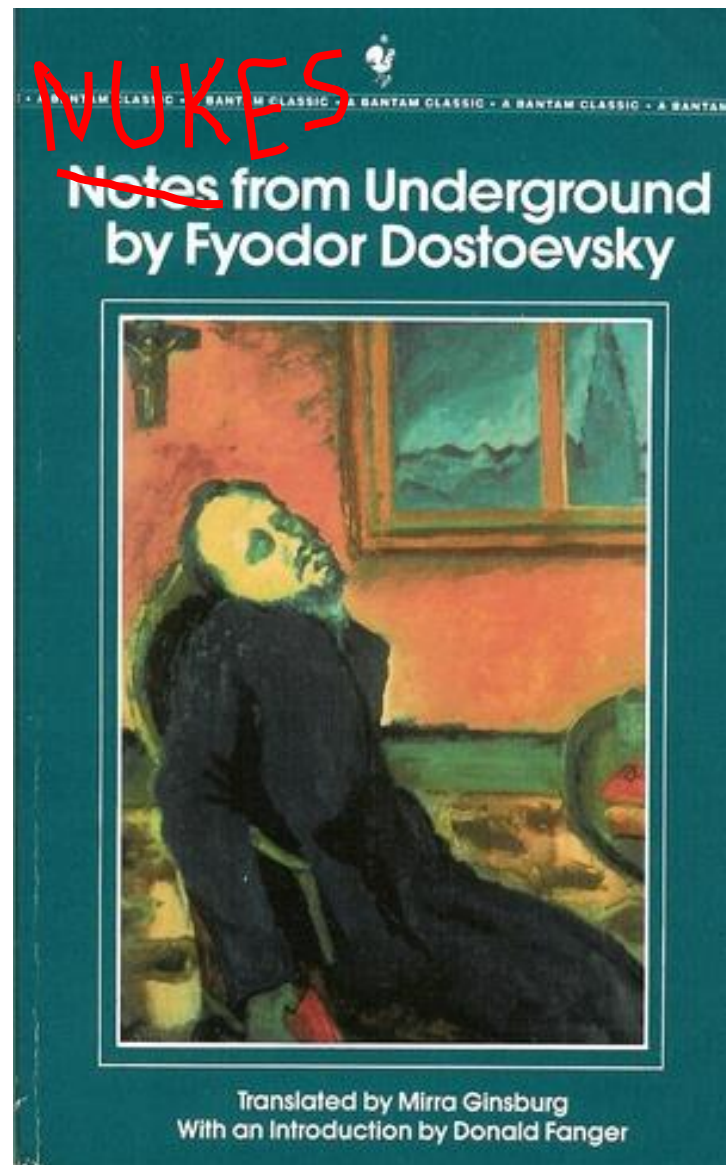


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What does this mean for the arms control and disarmament implications?

- ▶ Russian objection is likely to persist
- ▶ Several design choices are conducive to clandestine recovery, raising suspicions
- ▶ Absent international involvement, the permanence of stockpile reduction is questionable





Implications for arms control and disarmament

Creation of a plutonium geologic resource:

- ▶ An unprecedented route to fissile material
- ▶ A contributor to the strategic balance: “having the capacity to build nuclear weapons, like possessing an atomic arsenal, may bolster deterrence.” — M. Fuhrmann, B. Tkach, “Almost nuclear: introducing the nuclear latency dataset,” *Conflict Manag. Peace Sci.* 32, 443 (2015)



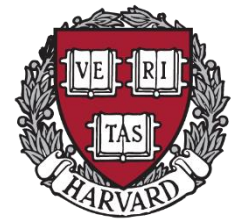
A hindrance to arms control:

- ▶ Part of the stockpile is put in a state of limbo
- ▶ A form of hedging: “a way of retaining the option of restarting a weapons program that has been halted or reversed.” — A.E. Levite, “Never say never again: nuclear reversal revisited,” *Int. Security* 27, 59 (2003)



A hindrance to disarmament:

- ▶ Establishes a floor on the possible extent of disarmament
- ▶ Locks in a degree of nuclear latency (capability to build weapons)



Recommendations

On inadvertent intrusion:

- ▶ Introduction of new, reactive materials to WIPP necessitates new research and substantial revision of the performance assessment.
- ▶ **More broadly:** WIPP's risk assessment is a regulatory exercise, not a glimpse into the future. Complex systems fail in unexpected ways, and complexity only increases the uncertainty.

On intentional intrusion:

- ▶ International collaboration on barriers to plutonium recovery, with Russia or the IAEA, are necessary to preserve the arms control effects of disposal.
- ▶ **More broadly:** “Disposition options beyond storage should be pursued only if they reduce overall security risks compared to leaving the material in storage” — *Management and Disposition of Excess Weapons Plutonium*, National Academies Press (1994)