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Landscape Entrusted: Depositing Nuclear Waste in Geologic Time

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Taisuke L. Wakabayashi is a PhD student in Landscape Architecture at the University of Illinois, Urbana-Champaign. His research explores the role of modern and contemporary design thinking in the emergence of nuclear landscapes. Drawing on New Materialism, he examines these landscapes as sites of co-production and negotiation between humans and nuclear technology, shaped by military experiments, infrastructural projects, atomic disasters, and radioactive waste disposal. His doctoral thesis delineates four forms of nuclear landscapes in Japan and the U.S., theorizing how we have been, are, and will be forming relationships with nuclear matters, material agencies, and technological complexities.

Keywords

landscape, architecture, nuclear waste, waste management, new materialism, techno-politics

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Landscape Entrusted: Depositing Nuclear Waste in Geologic Time

_Abstract

The Waste Isolation Pilot Plant (WIPP) in New Mexico, USA, the world's first operational geological repository for transuranic waste, represents a planetary shift in human interaction with the natural environment. Mined 655 meters below the earth's surface in ancient salt strata, the WIPP is designed to exploit ecological processes, unfolding over geological timescales, to contain the radioactive byproducts of nuclear weapons development. Nuclear waste, especially that contaminated with plutonium-239, entraps human action for 241,000 years because of its lethal nature and long half-life, posing a temporal challenge beyond human comprehension. In addition to the New Materialist term entanglement and its derivative entrapment, I propose the term *entrustment*, which I define as an attempt to re-situate the human within the natural realm by offloading its own entrapping/entrapped responsibilities onto ecology's self-healing capacities. By anticipating that salt formations will shift over time to encapsulate radioactive waste, nature is being used as a reliable participant in solving a human-made problem. This *_Article* argues that the WIPP situates the human and its effort within geological timescales, entrusting the landscape with the responsibility of containing and mitigating its nuclear legacy.

1_Introduction: About Waste Isolation Pilot Plant

Constructed about 53 kilometers southeast and 655 meters below Carlsbad in New Mexico in the United States, the Waste Isolation Pilot Plant (WIPP) is a permanent deep geological repository for a special kind of radioactive waste. There are several categories of radioactive waste, depending on many factors including types of radionuclides, levels of toxicity, and purposes of a project (whether the activities from which the waste derives are civil or defense-related). These classifications are specific to each regulatory body and thus often differ from nation to nation. The WIPP houses nuclear waste categorized as defense-generated transuranic (TRU) waste—a byproduct of the U.S. war efforts in the twentieth century—containing human-made radionuclides that have atomic numbers greater than that of uranium, primarily produced by using transuranic matters to fabricate nuclear weapons.[1] This process of harnessing atomic power also entailed large amounts of poorly managed low-level and high-level radioactive waste, as well as chemical hazardous waste, some of which has been hurting cleanup workers even very recently.[2] As a relic of the Atomic Age, TRU waste has a complex and often contentious history. For some that history points to a legacy of technological progress, while for others, it acts as a haunting reminder of the destructive force that brought perpetual damage to human life and the environment.

TRU waste embodies atomic history in many ways, yet it is not just an object of the past but also an agential subject that continues to shape the present and the future. It is a radioactive inheritance that poses a visceral, material threat to human bodies. In the face of radiological toxicity and longevity, scientists and engineers have employed calculations, anticipations, and extrapolations to envision a future free of nuclear waste, in an effort to grapple with radiological scales of temporality far beyond that of the human body. The WIPP, designed to permanently isolate radioactive waste, is the result of these efforts and ambitions.

Fig. 1: An aerial view of the Waste Isolation Pilot Plant

The WIPP landscape consists of three major spaces.[3] The surface facilities operate as a nodal point where the radioactive leftover of the U.S. defense activities arrives from locations across the nation. This TRU waste is handled by both humans and machines in preparation for geological emplacement. To date, the WIPP has received over 13,000 shipments of TRU waste, contained in canisters made of concrete and steel.[4] Connecting the surface facility to the repository level are four shafts that transform a geological space into a habitable human realm.[5] The air intake shaft and the exhaust shaft ensure the flow of breathable air. The salt-handling shaft facilitates the commute of both humans and machines between the surface and the subterrain to complete the task of excavation necessary for creating repository spaces. Simultaneously, the waste shaft transports waste canisters—approximately 185,000 to date—from the surface facility to their permanent emplacement in the repository.[6] The disposal repository is a subterranean space characterized by voids carved out of geological strata of salt to create an architectural subterrain.[7] The main disposal area in the deep geological realm consists of eight groups of seven rooms, forming a ladder-like shape in the plan view.[8] Each room, measuring approximately 10 meters wide, 4 meters tall, and 91 meters long, sits parallel to another with an unexcavated portion of geological fabrics of salt in between to prevent collapse. With electrical wires bringing light into the dark space where day and night have never previously existed, this geological space is now an extended human territory for depositing unwanted radioactive waste. Deep beneath the earth's surface, this subterranean landscape operates as the endpoint for products of U.S. atomic history, environmental responsibility, and potential harm to humans.

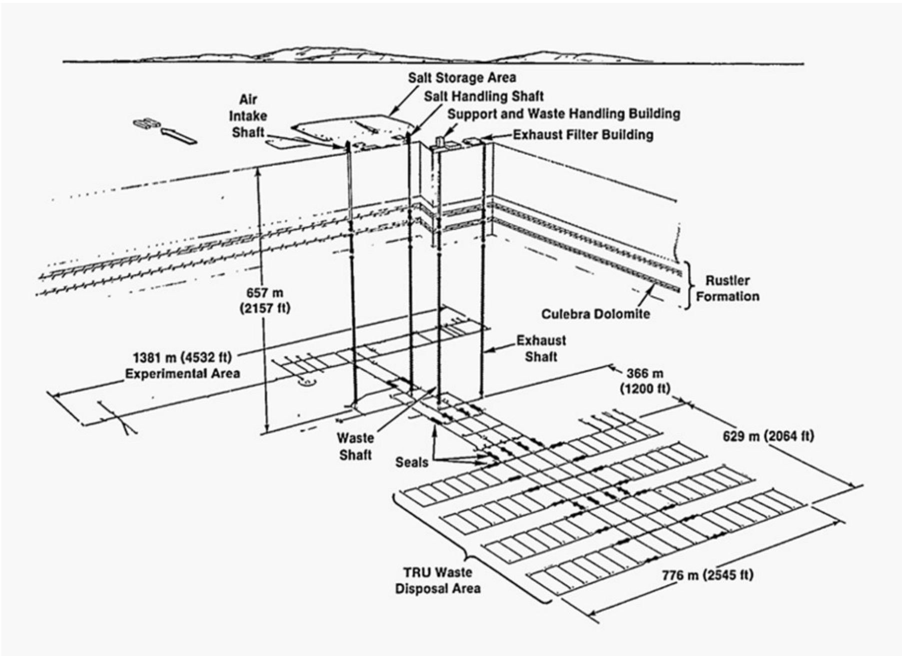

Fig. 2: A diagram of the WIPP, showing the surface facility, vertical shafts, and the underground spaces

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Fig. 3: The interior space of the geological repository during its construction phase

In the following sections, I interweave theoretical threads of the New Materialist discourse of more-than-human perspectives to explore the conceptual development from *entanglement* to *entrapment* and examine the agential capacities of nuclear waste within a wider context of human-radioactive relationships. In an attempt to conceptualize and describe the WIPP's unique reliance on ecological mechanisms in geologic time, I propose the term *entrustment.* Entrustment is an emerging concept that seeks to resituate the human within the natural realm designating humanity's attempt at offloading its own responsibility onto the self-healing capacities of ecology. The term is meant to contribute to the existing discourse by advancing the already accepted concepts of entanglement and its derivative, entrapment. The WIPP, I argue, symbolizes the attempt of the human—specifically, the U.S. of the Atomic Age—to position itself within the geological timescale by delegating the environmental responsibility of containing and mitigating the nuclear legacy to the deep geological strata and its ecological mechanism.[9] Tasked with severing the tie with nuclear waste from the human, the geological space and its temporality in particular, are treated in the design of the WIPP, not as static and unpredictable, but as an active, reliable participant that operates autonomously and effectively on our behalf. What unfolds in the facility below ground is a landscape entrusted with radioactive waste, its persistent legacy, and our environmental responsibilities.

2_Brief History of Human-Radioactive Entanglements in the U.S.

Human entanglement with nuclear weapons began with Trinity, the world's first plutonium-based atomic bomb, detonated by the U.S. Army on July 16, 1945, at a test site 338 kilometers south of Los Alamos in New Mexico. The explosion released 18.6 kilotons of heat, which instantly transformed the surrounding sand and asphalt into a material that humans had never seen before. This new glass-like substance of grayish green tint was later named trinitite, which marks the role of humans and nuclear technology in synthesizing the material composition of the earth. The success of Trinity quickly resulted in two atomic bombs deployed on Hiroshima and Nagasaki in August of the same year. The atomic drive to fabricate bombs and harness its political power behind World War II spilled over into the Cold War. With the formation of the Atomic Energy Commission (AEC) in 1947, the inventions and improvements of nuclear weapons became a primary and sustained effort as part of the international race for ever greater numbers of ever more powerful atomic weapons. Between 1951 and 1992, a total of 928 detonations took place in the Nevada desert, the indigenous land of Western Shoshone (also known as Newe Sogobia). Under the auspices of a nuclear testing program, the desert was named the Nevada Test Site (NTS) and was forcefully turned into a testing ground. The first one hundred bombs were detonated in the atmosphere and the remaining 828 underground—all for the purposes of measuring the magnitudes and effects of atomic power.[10] The four decades of nuclear explosions were a massive colonial project and a domestic 'war' against the land and the people of the remote American West. Its remoteness in both physical and symbolic terms prevented the public from knowing that all these underground explosions completely altered the form of the desert into a crated landscape. These destructive forces also emitted invisible yet toxic radioactive rays that permanently damaged bodies of both humans and the environment. The U.S. nuclear capacities were, and continue to be, forged at the expense of many life forms.[11]

What sustained these war efforts was the Nuclear Weapons Complex (NWC), a distributed, nationwide assembly line of factories, facilities, and laboratories. Each site was delegated a specialized task, as manufacturing nuclear weapons necessitated sequential work, including uranium mining, milling, refinement, and enrichment; plutonium reprocessing and separation; and weapons design, testing, assembly, and dismantlement. In New Mexico alone, four major sites have been part of the NWC network: Los Alamos National Laboratory for nuclear weapons research and design, Sandia National Laboratories for weapons engineering, the Trinity Site for weapons testing, and WIPP for nuclear waste management and disposal.

Built in 1989, the WIPP is the most recent addition to the complex, providing a permanent deep geological repository for radioactive byproducts of World War II and the Cold War. It is part of the cleanup program administered by the U.S. Department of Energy's (DOE) Office of Environmental Management (EM). The WIPP epitomizes a particular, or rather ideological, vision of what the contemporary human-radioactive entanglement looks like in its active role in stewarding nuclear legacy waste. In the twentieth century, the focus was on the enrichment and production of uranium and plutonium for nuclear weapons. Today, the discourse has shifted to one centered on their management and disposal. An immense amount of resources has been dedicated to cleanup in recent years; the annual budget for the U.S. federal cleanup program has been approximately six billion dollars since its launch in 2003, with about 5% of the budget supporting operations at the WIPP.[12] Entanglement with radioactivity lingers.

3_From Entanglement to Entrapment

As an attempt to include nonhuman agency, recent scholarship has introduced the term entanglement suggesting the complex, inseparable nature of human-nonhuman relationships. The U.S. atomic war efforts harnessed radionuclides into nuclear technology, and simultaneously the radiological properties of nuclear matters shaped the way in which U.S. atomic history took place. Humans and nonhumans are thus inseparable in the way the social-material world is produced; they can only be explained in reference to each other—as a co-production of ontologically distinct agencies operating together. In theorizing this entangled/entangling relationship, Jane Bennett, at the forefront of New Materialist thought, synthesizes the Latourian concept of social-material networks and the Deleuzian notion of assemblage to propose an alternative understanding of the world.[13] Bennett finds vibrancy in inanimate things in its 'thing-power'—the ability to affect other material entities through encounters.[14] Bennett's concept of thing-power redistributes agency across various ontological types by reconceptualizing things, including non-organic matter, as actants, which in effect blurs the traditional human/nonhuman divide. Assemblages, for Bennett, are "ad hoc

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grouping[s]" of different, numerous, vibrant materials that compose "confederations" which thereby shortens or rather cancels the distance between subjects and objects within.[15] The subject/object divide no longer exists; rather, they, as a "heterogeneous compound," become an entangled/entangling assemblage.[16] Bennett shows the working of this distributive agency with an example of the electrical power grid by focusing on the moment of the blackout. She argues that the blackout is not caused by a singular actant but should be understood as an instance of encounters between a "volatile mix" of co-producing actants.[17] Locating a source of agency and accountability becomes a difficult task, as Bennett writes: "there is not so much a doer (an agent) behind the deed (the blackout) as a doing and an effecting by a human-nonhuman assemblage."[18]

While this assemblage thinking is effective in highlighting the agencies of nonhuman actants as part of the ensembled compound, it raises a critical challenge in accounting for the power-differentials within. To this concern, Bennett herself notes that assemblages are composed of "uneven topographies" of agencies in which "power is not distributed equally across its surface."[19] In theorizing the human relationship to toxicity and its perilous effects on human bodies, how do we understand this entanglement as co-production, without flattening the power-differentials entailed, especially when the radiological toxicity and its longevity are made repulsive to compel a distancing from humans? This power of radioactive waste is typically not repulsive enough but insidious, because radioactivity is undetectable to human senses. It often takes years or even decades before radiological contaminations and health problems become apparent. The repulsive agency is produced when connected to, for example, state-sponsored bodies of knowledge, detection equipment, and regulatory standards that turn invisibility of radioactivity into visible sets of metrics, from which humans derive actions. This epistemic rendition of radiological dangers also often becomes a legitimizing means of governance and a mode of exerting scientific authority.[20]

From an archeological perspective, Ian Hodder defines entanglement as a "dialectical struggle" of dependence and dependency between humans and (non-human) things.[21] Hodder argues there are two mechanisms of human-thing relations: enabling and constraining. Enabling describes the human dependence on things, a condition in which humans employ things and produce tools to allow activities. Constraining refers to the relationship of dependency between the two, where neither of them can operate without managing the other. Humans need things, but simultaneously things need humans, often in the form of maintenance.[22] Here, Hodder introduces a special case of entanglement that requires a specific obligation on the human side of the relationship. He theorizes that the entrapping capacity of things arises from their reliance on maintenance by humans. Hodder, in focusing on dependence and dependency rather than on relationality, distances his theory from Bruno Latour's Actor-Network Theory (ANT), which presumes flat, symmetrical relationships between human and nonhuman actants.[23] While recognizing the absence of human/nonhuman dualism as the most positive aspect of ANT, Hodder contends that there is "insufficient attention to the way in which humans and things in their physical connectedness entrap each other."[24] Instead, Hodder argues that "our relations with things are often asymmetrical, leading to entrapment" from which it is difficult to disentangle.[25] Humans, therefore, are entrapped in the sticky web of "double bind" by relying on "things that [in turn] depend on humans."[26]

Hodder's critique of Latour's flat ontology aligns with Timothy Mitchell's concept of techno-politics. Mitchell defines techno-politics as a technical "alloy" of both the human and the nonhuman in which an intentional act of the human is often overrun by an unintended effect of the nonhuman.[27] The unintended consequences, in Mitchell's account, are caused by the human in their attempt to organize the nonhuman. Departing from Latour, Mitchell attributes accountability to the human for unintended outcomes and warns against flattening the agency of different actors, maintaining asymmetrical relationships between humans and nonhumans.[28] Where Hodder distances himself from Mitchell is in Hodder's conceptual interpretation of instability, which considers the way in which matter becomes within complex social material worlds, an approach in line with New Materialist theories. Hodder recognizes the agency of nonhuman things when he writes that "[t]hings have lives of their own that we get drawn into, and society depends on our abilities to manage this vibrancy of things effectively, to produce the effect of stability."[29] In Hodder's account, human interventions are understood as a tendency to productively seek stability in unstable dynamism of human-nonhuman complexes.

Hodder's concept of entrapment suggests that it is nearly impossible "for humans to become less entangled," citing two reasons.[30] First, because "the costs that have been invested in existing technologies and material social worlds" are too expensive to retreat from; they instead encourage further investments.[31] Second, because "the increased rate […] of entanglement" continues to cause "the gradual decrease in the external environment," the environment of the Anthropocene has become and is already an artifact that requires maintenance by humans.[32] The expansion of entanglement translates directly into the shrinkage of natural environments untouched by humankind. Among the several definitions of the Anthropocene is that it is the epoch where the human role has become on a par with the natural in shaping and harnessing the environment. Hodder refines this view with a condition that humans must play a role in fixing, caring, and maintaining the world. Humans have been, are, and will be entrapping themselves by their own interventions, using yet more technology, things, and new materials, heading in "the inflationary direction of increased human-thing-entanglement."[33] There is a directionality in his conception of what the material world will become in the future, and it is a nihilistic one in which human agency is ultimately diminished. Hodder pictures a world where humans can no longer exist unless what it means to be human changes completely, concluding: "the moral choice is substantial; to change what it is to be human, to become something other than ourselves."[34]

What, then, does it mean to become something "other than ourselves?" Is there a way to disentangle ourselves from entrapment?[35] This question is worth asking in the age of the Anthropocene where, more than a simple biological being, the human has become a geological agent, capable of intervening in the mechanisms of ecology.[36] This question is in fact particularly pertinent in the present characterized by nuclear waste—the aftermath of the Atomic Age—by which the future has been entrapped to cope with substances that remain toxic to bodies of humans and nonhumans for hundreds of thousands of years. Plutonium-239 (^{239}Pu), for example, a key component of nuclear weapons, is known for its extremely long half-life of 24,100 years. Per scientific convention, a substance is considered decontaminated only after ten cycles of half-lives have passed. This means it takes over 241,000 years for Plutonium-239 to decay into something harmless. To imagine a decontaminated future 241,000 years ahead of the present moment is beyond any human comprehension because humans have never encountered such temporality in history. With such "epistemological challenges posed by deep time," Jessica Hurley argues, the WIPP's future can be imagined only in reference to "a present that would have to continue unchanged" and thereby the imagined future is "not qualitatively different from the present."[37]

The WIPP, however, is a particular case to consider when it comes to an imagining of speculative futures. Namely, it is often used in thought experiments to think about the consequences of disposing the nuclear waste. From the late 1980s and early 1990s, the U.S. government convened panels of interdisciplinary experts to come up with ways to communicate the radiological dangers of what is buried at the WIPP site in preparation of various scenarios of human intrusions over the course of the next ten millennia.[38] Briefly put, this effort has resulted in two ideas: (1) a series of speculative landscape designs that incite a physio-psychological response to the bodies of future inhabitants upon approaching to the site and (2) a special semiotic system that largely consists of and relies on graphic, pictorial means to convey the warning message. Both ideas began with an anticipation that people in the distant future would find it hard to communicate in any current language as the rate of linguistic evolution is rather high. What the experts saw was a temporal fissure between "a sender and receiver living in epoch so enormously time-distant from each other," and thus the design objective became to "cancel the time-borne cultural 'distance' […] by concentrating on fundamental and enduring phenomena shared by all humans" as a species.[39] This state-sponsored speculative effort has been of interest to scholarship, as art historical values of these warning systems have been articulated and analyzed by Andrew Moisey in great detail.[40] It also came to the public attention, in part, via *Containment*, a 2015 documentary film by Peter Galison and Robb Moss that weaves a narrative on the history of the WIPP site to describe humanity's speculative attempt to remain entangled with the radiological power through various types of warning systems, whether physical earthworks or nuclear semiotics, long after our civilization is gone. Yet, nuclear waste, the heritage of the age of the atomic race, is real and still obligates humans not to just speculate but do something about it physically and manage it by technological means.

Humanity's entrapped/entrapping ties with radioactivity can be illustrated using past and current disposal practice of nuclear waste. The instability of nuclear waste shapes the ways in which humans engage with or neglect the radiological material power. Ocean disposal, for example, was the most common disposal method in the U.S. and many other parts of the world from 1946 until the 1970s and was completely banned internationally in 1994.[41] During the 48-year history of ocean disposal, fourteen countries discarded radioactive materials at more than 80 sites across the globe. Tons of radioactive waste were dumped into the ocean on the assumption that nature would dilute the radioactive materials on its own, with no thought to adverse ecological consequences.

Surface disposal at remote areas was another method that had been in practice ever since the invention of nuclear technology, resulting in numerous environmental hazards and damages, particularly around NWC sites. Dumping radioactive waste in places far from where people live was somehow considered safe enough without understanding the hydrological movements that can carry radionuclides via groundwater. Recent environmental restoration efforts have attempted to mitigate the consequences of these practices. The Nevada National Security Site (NNSS), a government-owned dessert area previously known as the Nevada Test Site, is a unique example of surface disposal. Currently, this former atomic weapons experiment site houses two radioactive waste management sites within its boundaries. The numerous atomic explosions turned the entire 3,522 square-kilometer site into nuclear waste, now deemed too contaminated to salvage for any restoration. Taking advantage of the soil having already been contaminated, some of the subsidence craters, results of underground explosions, have been repurposed as pits for housing low-level, hazardous waste.[42] By appropriating what has already been forever altered, the DOE found a way to make use of this contaminated landscape to solve a contemporary problem.

Fig. 4: Area 3 of the Radioactive Waste Management Site, constructed within multiple craters

The buildings of NWC sites are themselves no exception to thinking about what makes up nuclear waste. When fabricating uranium and plutonium is deemed no longer necessary, any physical facilities charged with these tasks are decommissioned. Upon decommissioning, however, because these production complexes have been contaminated with radionuclides, they become nuclear waste themselves. One decommissioning method is known as entombment, in which the contaminated parts of the complex is encased with concrete to seal off radioactivity. In the case of the former Hanford Site, a major NWC site where plutonium was manufactured as part of the Manhattan Project, eight of the nine reactors have been cocooned. In the entombment process, reactor buildings are partially demolished, keeping the highly radioactive reactor cores intact. These cores are then encased in concrete, resulting in an ad-hoc architecture with added formal and material elements.[43] These concrete cocoons are intended to remain in place for up to 75 years—roughly the lifespan of modern concrete—to let the remaining radioactivity decay to the level that human contact would be barely possible. After this period, the plan is for the reactors to be removed and the whole assembly dismantled.[44] Entombment is indeed a long-term effort that entraps multiple generations ahead.

Fig. 5: C-Reactor in the entombed, cocooned state still standing today at the Hanford Site, Washington

Spent nuclear fuels, generated from producing electricity at nuclear power plants, are also a form of radioactive waste that require some kind of disposal and management. Following the discontinuation of the Yucca Mountain nuclear waste repository project in 2011, there are no permanent designated facilities for the disposal of spent fuels in the United States. Consequently, spent nuclear fuels find temporary residence in interim storage spaces that are often sited adjacent to power plants, creating a persistent and eerie presence fraught with risks that casts perpetual uncertainty onto the environment. In response to these uncertainties, ongoing monitoring and maintenance are necessitated as crucial and integral components of disposal and management practices.

The entrapping agency of nuclear waste compels humans to seek disentanglement, that is, envision a collective path toward a future without nuclear waste. In (re)framing humans as "geological agents" with "a shared sense of catastrophe," Dipesh Chakrabarty encourages a speculative "thought experiment as a way of experiencing our present" by inserting "ourselves into a future 'without us' in order to be able to visualize it."[45] If this catastrophic future 'without us' is what Hodder's entrapment ultimately leads to, how do we view today's nuclear waste in response? One way to think about nuclear waste's agency is that its long half-life asks humans to (re-)conceive of temporality "far beyond the reach of human history" by scaling up the perspective from the human to the planetary or by turning ourselves into a human-as-a-species.[46] It places the human in an extremely long timeline. The WIPP is an example of efforts to put an end to the persistence of TRU waste in the human world.

A more specific way to grapple with the agential capacity of TRU waste, is to think through its *nuclearity*, a concept introduced by Gabriele Hecht.[47] Nuclearity is "a property distributed among things" that renders something as "being nuclear."[48] In other words, thinking about nuclearity is a way of contextualizing what this "being nuclear" constitutes, by parameterizing the contingencies upon the social-material world.[49] "There isn't one nuclear ontology; there are many," Hecht writes. 'Being nuclear' is therefore "not universal, singular, or stable" but rather it is an assemblage "shaped, unshaped, and reshaped unevenly across actors, time, and space."[50] This attention to nuclearity explains how the agency of radioactive waste works and why it is expressed so differently in different contexts. For example, the drinking water of the Navajo and many Pueblo nations, not far from the WIPP, has been contaminated with uranium and arsenic due to half a century of nuclear activities at nearby sites.[51] This poses serious health-risks to those who live in these nations, yet very little is actually being done by the state to disentangle radioactive waste from these marginalized bodies. Unlike the construction of the WIPP, meant to deal with TRU waste, in the case of the Navajo and Pueblo nations, the supposed entrapping agency of radioactivity did not compel the state to do anything. The agency of TRU waste was only enabled within the networks of the social material world and through political relations. With that in mind, it is crucial to see the WIPP as a project of disentanglement without falling into the danger of treating its agency as deterministic or overgeneralizing the human as a singular entity.

4_From Entrapment to Entrustment

The WIPP, the deep geological repository where nuclear waste can be stored and forgotten, is a product designed for a geological timescale of a preferred future—one without any ties to nuclear waste or rather its entrapping/entrapped responsibilities. Quite contrary to Hodder's nihilistic ontology, the WIPP ought to be seen as a mechanism that achieves a desirable future characterized by the absence of a relationship with nuclear waste. To this end, Sheila Jasanoff offers a counterpoint to Hodder's account by emphasizing the importance of power and the political roles of socio-technical imagination by humans, particularly those who are agents of authority. Like Hodder, Jasanoff departs from the flat ontology by critiquing the way that it disregards the power dynamics within society that give rise to networks, endowing all actants with equal empowerment or disempowerment. Rather than reducing "human agents to mere cogs in machines," Jasanoff contends that the durability of these networks relies on the thickness of horizontal linkages and the density of nodal connectivities, characterizing socio-technical imagination as "a crucial reservoir of power and action, [that] lodges in the hearts and minds of human agents and institutions."[52] Humans can build and modify the topography of networks manipulating contours and attractors within the nodal networks to transform dependency of the things on humans into dependence of humans on the ecological capacity of the planet. In this way, Jasanoff underscores the formative role of human agency, imagination, and authoritative decision-making in shaping the trajectory of human relationships with the environment and technological artifacts.

The WIPP represents a major shift in disposal methods because it engages geological systems and processes for its disposal of radioactive waste. It transfers the environmental responsibilities of the Anthropocene permanently onto geologic time, which operates on an enormous temporal scale. The WIPP's reliance on ecological mechanisms sets it apart from common disposal techniques that are essentially negligent towards ecological consequences or simply defer them. The WIPP, on the contrary, aims to be a permanent solution without the need to be maintained in the long run; it is in fact designed so nuclear waste will be inaccessible to humans. It deploys a planetary scale of temporality that anticipates the steady movement of geological strata by which nuclear waste is to be encapsulated and sealed off. This science-driven approach to intervene in the ecological mechanism, I argue, reveals a new dimension to the relationships between humans and nuclear waste, for which the appropriate term is *entrustment*. I propose that the WIPP is an example of humans entrusting geology to maintain and manage nuclear waste on a more-than-human, that is, a geological timescale. I thereby call this strategic reconfiguration of the relationship entrustment.

ENTRUST (v.) carries two primary meanings. Firstly, it denotes delegation—the action of assigning responsibility for something to a person or organization.[53] It is a transference of accountability, so the delegate operates autonomously on behalf of the delegator. Secondly, it refers to trusting—the act of putting one's confidence in a person or organization concerning a specific task or responsibility.[54] It involves finding confidence in the capability or reliability of the entrusted to successfully carry out the assigned duties. Entrustment can therefore only take place if the delegator has confidence in the credibility of the delegated to be an autonomous substitute. The WIPP perfectly exemplifies this concept as the scientific epistemological modality exploits the geological mechanism to become its replacement to take care of the nuclear waste on its own. This both depends on and instrumentalizes the futurity of the geological layers in the way that the science predicts, models, and desires, even though the temporal scale of radionuclides as well as its geological temporality are well beyond the lifespan of any human being or human civilization.

Perhaps entrustment, then, is a human response to the entrapping agency of nuclear waste. It aims to overcome entrapment by offloading environmental responsibility onto the ecological. Humans cannot reduce the radioactivity through any known human engineering; instead, they store the materials in the hope that over the millennia, the stuff will decompose 'naturally.' The next question, then, is to decipher where this confidence comes from and how it is manifested in the form of the WIPP.

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5_Drawing an Analogy between Nature and Human-made

In 1972, French scientists discovered traces of nuclear fission reaction in nature, in the open-pit uranium mine in Oklo, Gabon. Scientists noticed a depletion of the fissile isotope uranium-235 (U-235) in its uranium core samples, which challenged the belief that fission reactions only occurred through artificial enrichment. The concentration of U-235 in natural uranium is normally 0.72%, but here it was as low as 0.44%. This difference of 0.28% may sound trivial, but it was significant enough to extrapolate the story of geological activities that happened well before the history of homo sapiens. Drawing from the unusual isotopic composition, further geological analyses revealed the presence of more than 30 elements that usually occur as fission products.[55] This was both strange and intriguing because fission reactions were thought to occur only by artificially enriching the concentration of U-235. Such enrichment, however, was apparently not required in this natural occurrence two billion years ago, because its concentration would have been 3–4%, making a self-sustaining chain reaction possible in natural uranium with groundwater as a reaction moderator. Because many of the products of fission reactions are radioactive, as is uranium itself, their decay can be dated and used to determine rates of migration of individual elements. Oklo was identified as a site where natural fission reactions had occurred around 1.7 billion years ago, for about 800,000 years, consuming about six tons of U-235. However, most elements there did not migrate as they were contained in crystalline uranite and clay minerals.[56] Oklo, and its long-term geological stability as natural barriers, became a model for designing nuclear waste disposal, as it is a naturally occurring formation analogous to conditions expected in a geological repository.

Natural systems, processes, or phenomena, that function as a source for understanding similar features or behaviors in human-made artifacts, are called natural analogues. They are instrumental for extrapolating findings to larger temporal scales. In the case of radioactivity, because the extremely long half-lives of radionuclides render direct experimentation impossible in a lab or in the field, these extrapolated calculations make it possible to see the performance of the geological repository in preventing radionuclides from migrating in the distant future. When researchers refer to this natural representation of a disposal system that closely mirrors experiments that cannot be directly executed or tested, they instill confidence in the credibility of a long-term waste disposal method.[57] Naming natural nuclear fission reactions uncontrolled by humans as natural analogues constructs a parallel between human and nature. Nature with its stark contrast to human artifice, offers "a conspicuous point of reference" in searching for a reliable way to justify and legitimize human actions.[58] Here, nature is harnessed through a technological lens to become a representation and projection of what is already technologically manifested. In other words, prior knowledge of fission reaction is necessary to identify Oklo as an analogue for it. Similarly, the idea of geological repositories must precede it in order to recognize Oklo as a model.

Despite this analogy being a common justification for the WIPP in the relevant scientific literature since the 1980s, the WIPP was conceptualized without the prior knowledge of Oklo. This is evident in the absence of any mentioning of natural analogues or Oklo in its initial design documents. The construction of the WIPP commenced in 1989, but its design conceptualization dates back to as early as 1955 when the National Research Council, tasked by the U.S. Atomic Energy Commission, examined the permanent disposal method.[59] Its 1957 report concluded that emplacement of radioactive waste in salt deposits would be the most promising method.[60] No action was taken for some time but a renewed nationwide search for a suitable site for "exploratory work and extensive field investigation," suddenly began in 1973 and quickly chose the current WIPP location, about 52 km east of Carlsbad.[61] By 1977, Sandia Laboratory in Albuquerque had conceptualized the first design iteration of the WIPP in comprehensive detail. The initial design, though similar to the one standing today, was much more extensive in size of the underground disposal area. The disposal area was designed for two stories, one at 654 meters below the surface and the other at 839 meters below.[62]

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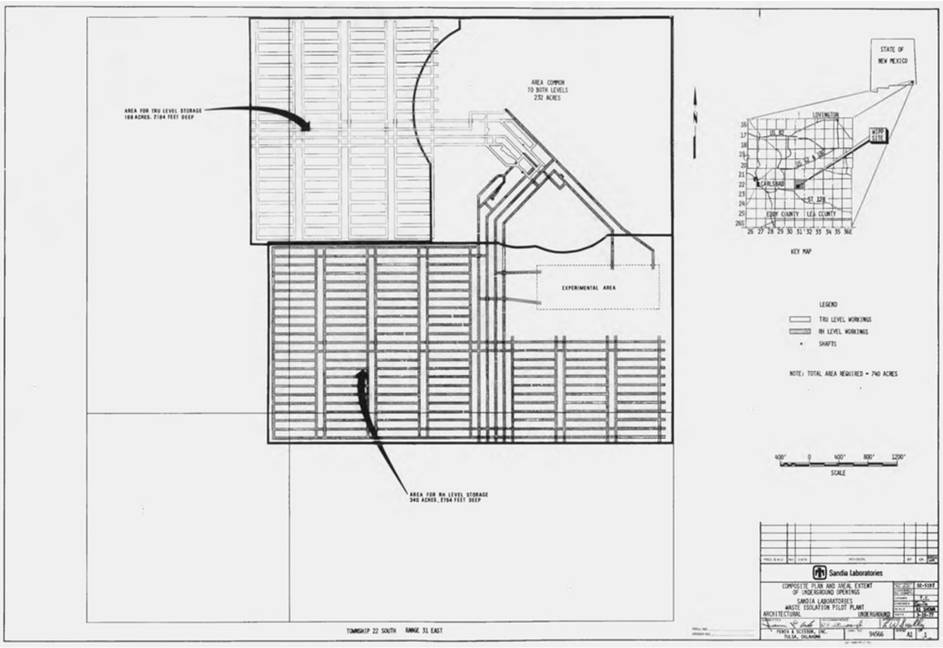

Fig. 6: Sandia's original plan for the WIPP, showing the disposal areas that were to span two levels

It is important to note the presumed neutrality of natural analogues in the service of nuclear waste disposal, and that natural analogues were actually a means to legitimize the WIPP and its performance. Nature therefore became not merely a reliable reference but an innocent source of retrospective justification to bolster confidence in trusting radioactive waste in the working of geological strata. The fact that the analogy was drawn after the fact, casts doubt on the impartiality of the scientific process.

6_Conceiving Geological Strata as Fluid

The WIPP is designed to be taken care of by the geological mechanism. The presence of Halite, the mineral form of sodium chloride (NaCl), in the subterrain was the decisive factor in selecting the New Mexico site for the permanent radioactive waste disposal. The WIPP emplaces most of its architecture in deep geological strata called the Salado Formation. The geology of southeast New Mexico was formed during the Permian Period, consisting of an ancient 250-million-year-old layer of sedimentary salt rock. The selection of the WIPP site was driven by four primary considerations.[63] First, most deposits of salt are found in stable geological areas with little seismic activity, minimizing the risk of destruction or resurfacing of the facility. Second, the presence of salt deposits signifies the absence of flowing groundwater that could potentially move waste laterally or to the surface. It is via ground water that radionuclides can migrate through chemical processes such as dispersion, diffusion, dilution, and precipitation, caused by the concentration differentials. Third, salt is relatively easy to mine with the existing means of technological construction as a medium to create a space in the subterranean. Fourth, and most importantly, over time, rock salt heals its own fractures because of its plastic quality. Salt formations will slowly yet steadily move in to fill mined areas and seal radioactive waste from the environment. Thus, eventually, the geological strata will engulf the radioactive waste, turning the whole repository into an inaccessible space. Consequently, the geological force works as an active, stable parameter that fixes the problems of the irreversible human deeds.

What is most striking about WIPP's architecture is that it was designed to be temporary. In anticipation of the geological plasticity described above, the WIPP's future decommissioning is an integral part of a design that acknowledges the entire lifecycle of the facility, from its current operational use to its eventual closure in 2030.[64] The decommissioning of the WIPP unfolds through a three-step process. Firstly, the underground repository space undergoes backfilling with substances with the capacity to absorb and retain groundwater, forming natural barriers. Over time, the salt layer envelops the repository space, exerting pressure that could potentially crush the waste containers, presumably decayed and fragile at that point. Despite this, the surrounding substances act as a safeguard, preventing the potential migration of radionuclides into new areas. Subsequently, the four vertical shafts, crucial conduits connecting the surface and repository levels, will be sealed with concrete. This step, outlined in the original planning document, not only addresses sinking methods and excavation tools but also minutely details the sealing processes.[65] Following the closure of the repository, attention will turn to the surface facilities. Here, a deliberate dismantling process will take place, systematically erasing any physical traces of the WIPP's existence on the surface. This disappearance, synchronized with the disposal of nuclear waste and its associated connotations, encapsulates the ultimate function of the WIPP. By taking on the responsibility of nullifying the human-radioactive entanglement, the WIPP emerges as the final, crucial piece of the Nuclear Weapons Complex.

The essence of the WIPP lies in the act of emplacing radioactive waste within a geological space that has existed for 250 million years in slow, yet perpetual motion. This insertion of human intervention into an inherently dynamic geological realm forms the crux of the WIPP's purpose. While the salt's geology provides a sense of solidity, compressed by gravitational forces and contributing to the Earth's stability, the WIPP challenges us to reconsider stability within the context of continuous geological movement—a new perspective on the human-radioactive relationship that extends across temporal dimensions. In contemplating the temporal nature of this geological space, there is a shift in perspective that marks "the turn from at-ness to withness" that transforms our focus "from the being of materials to their becoming, from succession to duration […] from thinking in terms of stability and change to thinking in terms of growth and movement."[66] The WIPP thereby prompts us to conceive of temporality not in anthropogenic but in geologic terms, where time scales up to the point that halite bedrocks are conceptualized no longer as solid, but as fluid and always already in motion.

7_Landscape Entrusted: in Lieu of a Conclusion

Entrustment unfolds as we humans endeavor to sever our ties with nuclear waste. The WIPP stands as a symbolic convergence, linking the brevity of the human world with the expansive temporal dimensions of geology, through the disposal and management of TRU waste. This legacy of waste, deemed too formidable in the realm of human temporality, has been entrusted to that of geological time as a way to delegate the environmental responsibilities onto the self-healing, plastic, and fluid qualities of the salt strata of southeast New Mexico. To legitimize this transfer of responsibility, science has transformed the anticipation of geological plasticity from a speculative hypothesis into a reliable scenario within the vast scale of geologic time. Geology, its movement, and its temporality come together as the third entity mediating the human-radioactive complex. They emerge to operate as an entrusted medium that separates the human from the entangling/entrapping agencies of radioactive waste. Humans are drawn to this capacity of nature that rescales the duration of time, from that of human to that of planetary.

I believe that we need to think further about this emerging phenomenon with a sense of urgency. Despite my description of the WIPP as a project of ambitious thinking, or rather a wishful one, to emancipate the human from the persistence of nuclear waste through entrustment, this future may not come soon enough or even at all. First, even after its dismantlement, the site boundary of the WIPP needs an active deterrence measure for at least 100 years followed by a passive deterrence, as demanded by the Land Withdrawal Act of 1992.[67] The DOE must exercise active institutional controls on a perimeter of land to prohibit any human intrusions including resource extractions.[68] In anticipation of the future, what is unstable or unpredictable is ultimately human presence. Second, the invention of an end point for disposals might encourage more production of nuclear waste. For example, the success of the WIPP may accelerate the dependence on nuclear energy and, thus, the production of more spent fuels, just like the success of Trinity heralded the Atomic Age. Third, the WIPP is indeed experiencing an extension; the fifth shaft has just been added in preparation for expanding the repository spaces.[69] The WIPP may not emancipate us from nuclear waste but may rather instead incentivize a perpetual desire for getting more out of the facilities that have already been constructed. The WIPP may be too precious to let go of, and the day of the decommissioning may never come.

While this *_Article* is in part a case study of the WIPP, the discussions should not be limited to the U.S. context, but rather address the global stage. Despite its leading role, the U.S. is by no means the only nation that has produced nuclear weapons. Many nations have their own atomic histories and possess radioactive waste that needs to be dealt with. TRU waste is not limited to that produced for defense-related activities, i.e., bombs, but also for civilian uses; spent fuels, the waste products of nuclear energy, are often TRU waste as well. In the present where the future without a reliance on nuclear energy across the globe is difficult to imagine, discussions about our relationship to radioactive waste, disposal, and management practices are of great importance. This urgency is underscored by the global construction of geological repositories, a current and projected trend observed in many countries, including Germany, China, Sweden, Finland, and the United Kingdom.[70] There will be a handful of geological repositories for radioactive waste across the globe, and experts will have to keep an eye on them, with the emerging attention to waste in a broader context. I hope this *_Article* has offered a new perspective that serves as a catalyst to get us ready and think through the evolving, maturing human-radioactive relation that has only recently started taking shape.

_Endnotes

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2 “Chemical Vapor Exposures,” Hanford Challenge, accessed August 25, 2024, <https://www.hanfordchallenge.org/chemical-vapor-exposures>.

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8 See figure 2 for the overall understanding of the floor layout of the repository space.

9 I would like to provide a clarifying note here. In this *_Article*, my use of terms such as ‘our,’ ‘the human,’ and ‘humans’ is not intended to homogenize the diverse U.S. populations or the global ones into a singular category or to overlook the significant power differentials between those who have taken, and continue to take, active roles in shaping environmental consequences, and those who have not. I acknowledge that overly universalizing human-environment relations is a common issue in Anthropocene-focused discourse—a term that is itself highly contested, as it can imply that responsibility for environmental destruction is equally distributed among people of different geographical and economic backgrounds. In reality, accountability is disproportionately borne by certain groups, particularly through the mechanisms of capitalism, colonialism, political economies, and knowledge systems. Rather than using ‘the human’ as a universal category, I argue that ‘the human’ is a construct that is continually shaped and contested. In the context of the Waste Isolation Pilot Plant (WIPP), for instance, ‘the human’ is relationally defined through its interactions with the material and radiological power of radioactive waste, geological strata with its spatial and temporal dimensions, historical patterns of radioactive waste disposal, and nuclear activities—many of which stem from the post-World War II U.S. government. Thus, my use of terms like ‘the human,’ ‘humans,’ ‘our,’ ‘us,’ and similar language is meant to emphasize the binary between ‘the human’ and ‘the radioactive’ through these practices of the particular, powerful actors. This serves as a conceptual strategy for navigating the theoretical and methodological challenges of discussing ‘humans,’ while empirically referencing the global power structures that have driven and continue to shape these problems.

10 The Nevada Test Site (NTS) is now called the Nevada National Security Site (NNSS) with its renaming in 2010.

11 The U.S. and many other nations including China, France, India, Israel, North Korea, Pakistan, Russia, and the UK spent a combined total of 91.4 billion dollars on their nuclear weapons in 2023, which was 10.7 billion dollars more than the previous year. This shows an increase in the

international scale at an accelerated rate. The international race for nuclear armament as well as nuclear infrastructure is certainly not a thing of the past but what characterizes our present and likely the future. For more, see: "Global Nuclear Weapons Spending Surges to $91.4 Billion," The International Campaign to Abolish Nuclear Weapons (ICAN), accessed August 16, 2024, <https://www.icanw.org/global_nuclear_weapons_spending_surges_to_91_4_billion>.

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28 This interpretation of Mitchell's techno-politics is partially from the lecture titled "The Material(ity) Turn" by Zsuzsa Gille, a professor of Sociology at the University of Illinois, Urbana-Champaign (UIUC). Gill gave this lecture on 1 November 2022, as a part of the Modern Critical Lecture Series of the Unit for Criticism and Interpretive Theory at UIUC. Gille's scholarship was centered around several New Material theories that discussed how human-nonhuman complexes form socio-political agencies, often activated by technological objects including infrastructures and built-environments. As a response to Gille's lecture, I wrote an article in which her interpretation and my reading of Mitchell's chapter "Can the Mosquito Speak?" in *Rule of Experts: Egypt, Techno-Politics, Modernity* are discussed in a broader context of human-nonhuman relationships. For more, see Taisuke Wakabayashi, "Material(ity) Turn, Didactic Readings of Five Texts," Unit for Criticism and Interpretive Theory (blog), November 28, 2022, <https://criticism.illinois.edu/blog/materiality-turn-didactic-readings-five-texts>.

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