Lively Doings: Centring Waste in Nuclear Waste Management

WORLDWIDE WASTE
Journal of Interdisciplinary Studies

Volume 9, Number 1, 2026
Published online 1 April 2026

Submitted 11 September 2025
Accepted 26 February 2026

The White Horse Press
The Old Vicarage, Main Street,
Winwick, Cambridgeshire
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ABSTRACT

Nuclear actors often describe long-term nuclear waste management as a social problem, characterised by a lack of public acceptance and political will to implement waste management solutions. In public and social scientific discussions, waste itself tends to be sidelined. Analysing IAEA and NEA documents, we seek to shift attention to nuclear waste, with a focus on spent nuclear fuel (SNF). We trace some of the ways in which nuclear actors differently enact SNF through management practices, but also how SNF, as an agentic entity, informs to those enactments. We also explore how SNF, as a composite material, inspires and enables different kinds of futures. We propose that starting nuclear waste debates from SNF as an active entity shaping and engaging with systems designed to contain it, rather than from technologically fixed solutions, provides a better platform to deliberate what kind of nuclear future(s) and waste management solutions are societally desirable.

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KEYWORDS:

nuclear waste management, nuclear waste, spent nuclear fuel, materialism, material agency

TO CITE THIS ARTICLE:

de Villafranca, M.S. and R. Geysmans, 'Lively Doings: Centring Waste in Nuclear Waste Management' *Worldwide Waste* **9** (1): 1–14. https://doi.org/10.3197/whpww.63857928646681

INTRODUCTION

Nuclear wastes 'evoke imaginations of eternity' (Kasperski and Storm 2020: 704). The most dangerous nuclear wastes 'remain hazardous for tens of thousands of years and longer' (NEA, 2003: 13). Nuclear industry and policy actors see geological disposal, the placement of nuclear wastes in engineered disposal facilities underground, as the best available solution for managing nuclear waste in the long-term (e.g., EC 2011; IAEA 2019a, 2022b). Only a handful of nuclear countries have made any notable progress towards its implementation. For the International Atomic Energy Agency (IAEA), the lack of progress boils down to public reluctance and political indecision to implement geological disposal: 'there is broad agreement among the technical community that … geological disposal constitutes a safe option … political will and societal acceptance are the limiting factors for implementation in most countries' (IAEA 2019b: 7).

Framed this way, solving the 'nuclear waste problem' means generating public acceptance for geological disposal, and finding communities willing to host geological disposal facilities (GDFs) (IGD-TP 2009). Much effort has been devoted by industry, academia and decision-makers to understand the processes to generate this 'public acceptance' (Hietala and Geysmans 2022). While these efforts to find socially robust nuclear waste management (NWM) strategies are crucial, the focus on acceptance and social processes have relegated NWM into a 'social problem', whereby the issue lies with the 'public' rather than nuclear wastes (IAEA 2007, 2019a). In this sense, the 'nuclear waste problem' has become more about the various social and political processes around nuclear waste than about the actual matter 'requiring' management (Gregson 2012).

Against this background, in this article we aim to centre matter at the heart of long-term NWM implementation efforts. We focus on spent nuclear fuel (SNF), a material central to NWM, to highlight NWM as a sociomaterial challenge (Schürkmann 2022) whereby issues, practices, technological visions and realities are agitated into existence by and emerge from the radioactive material itself. We illustrate how NWM policies and practices perform SNF in particular ways, creating different SNFs, and different futures (Barad 2007, Mol and Law 1994), but also how SNF as an agentic entity shapes those performances and practices. Indeed, the different performances are enabled by SNF's transformative material qualities (Gregson et al. 2010). Containing uranium, plutonium and various other radioactive elements, SNF can be, and is being, treated as waste, resource or 'undecided' material by nuclear and policy actors (IAEA 2022a). The different ways in which nuclear actors engage with SNF have distinct infrastructural, economic and other consequences that shape nuclear futures (Barad 2023).

By exploring the doings of SNF (what it does, and how it is done), the interplay and interactions between SNF, and the handling and storage systems designed to manage it in the present, and how they shape and perform each other, we broaden the current discussion and understanding of how matter shapes NWM practices. Where social scientific analyses have explored NWM as a sociotechnical challenge (Bergmans et al. 2015), that includes a range of sociomaterial collaborations and considerations (Schürkmann 2022, Stsiapanau 2025), existing analyses still tend to, in a move reflexive of actual practice, peripheralise waste (Gregson 2012). Focusing on waste, we seek to broaden the scope of social scientific analyses of NWM, while also contributing to more general discussions in Science and Technology Studies (STS) on the role of matter and nonhuman actors in shaping the world.

The article has the following structure. First, we outline our shift from social processes around nuclear waste to the material itself, engaging with literatures on materialities and nuclear things. We then trace how nuclear actors enact different, yet ultimately containable, SNFs, and explore the active role SNF plays in shaping management practice and systems, focusing on the ongoing storage of SNF. We observe how the various doings of SNF are enacted through its relations with other entities (Barad 2007, Bennett 2010). Tracing these doings of SNF allows us to explore the relations between SNF and the futures that could unfold because of its activities and components. Zooming in on the matter of SNF illustrates the contested nature of its potential futures. Although this contested nature has been extensively documented (Foley 2021, Jasanoff and Kim 2009, Walker 2021), its connection to SNF's doings urges us to reconsider the arena of the contestation (Barthe et al. 2022). While NWM debates often focus on particular management strategies, especially geological disposal, we propose that it might be more fruitful to shift attention to SNF as an active entity entwined and engaging with systems designed to contain it. Starting from an agentic material rather than a fixed technological solution (Barthe et al. 2020) might provide a better platform to deliberate what kind of nuclear future(s) and waste management solutions are societally desirable.

A TURN TO THE SOCIOMATERIALITY OF NWM

Social science literatures on NWM have tended to focus on the social context of NWM, and the manufacturing of trust and social acceptance for NWM solutions (Hietala and Geysmans 2022, Solomon et al. 2010). Yet, conceptualisations of NWM, and geological disposal in particular, as a socio-technical challenge have proliferated (e.g., Bergmans et al. 2015, Schröder 2016), while NWM technologies and nuclear waste are gaining increasing attention (Gregson 2012, Macfarlane 2003, Ialenti 2018, Schürkmann 2022, Stsiapanau 2025), and it is no wonder. Although confined to the fringes of society and presented to the broader public as 'tamed' or 'pacified' in industry representations (Gregson 2012), nuclear waste exerts an imperative to do something about it (Morton 2013, van Wyck 2005). Morton (2013) argues that nuclear waste, because of its long-term radiological threat, demands action. Gregson describes how, standing in an NWM storage facility, one can sense 'both the heat and the burden of responsibility that attaches to [the waste]' (Gregson 2012: 2012). Demanding action and radiating responsibility, nuclear wastes also have a vast temporal reach. Whether matter without a place (van Wyck 2005) or speculative matter existing 'in spacetimes that are in certain ways irreducible to conventional human time horizons' (Keating 2022: 6), nuclear wastes leak into the future (Adam and Groves 2007), defy human sense-making efforts (Geysmans et al. 2023) and render futures without them unimaginable (Pelopidas 2021).

A toxic legacy and future fantasy (Kasperski and Storm 2020), nuclear wastes are onto-epistemically challenging. Where nuclear social sciences often engage with the futurity of nuclear wastes (e.g., Keating 2022, Holtorf and Högberg 2020), wastes are actively involved and enmeshed in making and negotiating practices and relations in the present. Gregson's description of nuclear waste as radiating responsibility exemplifies what Bennett terms thing-power, or the 'curious ability of inanimate things to animate, to act, to produce effects dramatic and subtle' (Bennett 2010: 41). Approaching SNF as an agentic, rather than a passive, entity reflects a wider material turn in social sciences (Mukerji 2015), which has disputed a priori distinctions between active humans versus passive materials. Bennett emphasises relations as the locus of thing-power: 'agency always depends on the collaboration … of many bodies and forces' (Bennett 2010: 20). Barad (2007) similarly posits that matter does not pre-exist its relations. It rather becomes bounded and propertied within encounters between intra-acting agencies. She sees matter, and its ability to produce effects, as inherently situated, and holds that thought and practices perform things in different ways, producing differential effects. For Gregson et al. (2010) this performativity stems from the transformative qualities of things, which should be thought through their 'transformative states', and through practices that morph, disturb and animate them, enabling them to be performed in different ways.

Accordingly, waste studies approach waste both as a relational effect (Liboiron 2021, Stsiapanau 2025) performed into being through ordering practices such as sorting, recycling and disposal (Weber 2022), and as matter that is not so easily contained by those practices (Hetherington 2004, Hird 2013, Ureta 2016). Where the classification of waste and its separation from other materials seeks to create a world of containment and control (Liboiron 2021, Bowker and Star 1999), scholarship on materialities sees waste as lively; as moving and evolving, becoming and unbecoming (Hird, 2013). For Ureta, waste 'permeates barriers, transforming into different entities in the process: leachate, polluted water, dead soil, toxins, etc' (Ureta 2016: 1534). Gregson, similarly, describes nuclear waste as 'an energetic, colonising, and annihilating thing power' (Gregson 2012: 2017) that has a 'way of refusing containment and … leak[ing] into things' (Barad 2023; also Barthe 2010). If waste leaks, colonises and refuses containment, containment itself emerges as a mode of 'keeping things … absent, at least temporarily and provisionally' (Hetherington 2004: 164) or as 'a temporary stilling and stabilisation of a material that has not gone away' (Gregson et al. 2010: 1082).

That is, like waste, containment too is a relational, contingent effect (e.g. Hietala 2018, Schröder 2016). Schürkmann conceptualises NWM as a series of sociotechnical, geotechnical and sociogeological – that is sociomaterial – collaborations that include 'conflicts and challenges … inside and between … the collaborative spheres' (Schürkmann 2022: 7). This suggests that containment is never certain or guaranteed as technical and geological entities might resist enrolment to human plans and visions, while also having to 'struggle against migrating radionuclides' (Schürkmann 2022: 7). Stsiapanau (2025) and Schröder (2016), respectively, point to containment as a relational achievement. Where Stsiapanau argues that the dominant discourse on GDFs underscores waste's interactions with and through natural and technical elements designated to contain it, Schröder observes how the nuclear industry frames the ability of GDFs to contain nuclear waste through an erasure of its relations with humans. Here, the pacification and containment of waste entail the severing of its relations with society, and the delegation of responsibility to a more 'stable' and less unpredictable bedrock (Barthe 2010). Yet, Schröder argues that the long-term durability of the geotechnical 'relations preventing other relations', together with humans' willingness to stay away from waste, ultimately remains uncertain (Schröder 2016). Elsewhere, Hietala similarly argues that containment is better understood through the notion of contain-ability that highlights how containment is an emergent, rather than an inherent, feature of nuclear waste management facilities, a 'contingent and situated making, taking place, for instance …. through policy decisions, public documents and other representations of disposals and wastes' (Hietala 2018: 3, also Kinsella 2001). Meanwhile Geysmans et al. (2023) and Kim (2025) respectively examine the scientific and political processes rendering the underground governable and suitable for geological disposal (also Emmenegger 2025, Elam and Sundqvist 2011).

These accounts highlight containment as a contingent sociomaterial achievement and, while they clearly shift attention towards NWM materialities, their focus remains more on the containment of waste than waste itself. Here, we seek to begin to fill this gap in the existing literature. We explore what SNF does, and how it is being done through NWM practices. SNF is interesting for it encompasses various elements and multiple futures (Barad 2023). It is a composite material, but also an ambiguous one. Where NWM practices are built on classification practices with different types of wastes being treated differently (Bowker and Star 1999), SNF resists uniform or ready categorisation. This is exemplified by the fact that some countries treat SNF as resource, many countries categorise it as waste and some treat it as 'other', not belonging to any category (yet) (Bowker and Star 1999). Classification, the (necessary) determination of SNF as waste or resource, however, can be seen as a material-discursive precondition that sets particular material practices and trajectories in motion, shaping the ways in which nuclear wastes and fuel are managed, and in which futures are made. To gain a better understanding of the doings of SNF, we examine practices through which it is currently managed. Analytically, it is interesting to explore SNF in the early storage period where classification does not yet matter much. Meanwhile, as the implementation of geological disposal solutions seems to be withdrawing further into the future, the role and importance of 'interim' storage is ever increasing (IAEA 2019b) and warrants greater social scientific attention.

METHODOLOGY

Our analysis draws on careful engagement with documents from the two prominent international nuclear organisations: the IAEA and the Nuclear Energy Agency (NEA). Founded in the late 1950s, both organisations promote and advocate ongoing nuclear energy use, while the IAEA also oversees compliance with non-proliferation commitments. These organisations are key policy actors that shape the uses, practices, policies and sociotechnical imaginaries (Jasanoff and Kim 2009) of nuclear energy and containment (Kinsella 2001, Weichselbraun 2016) both on the international and national levels. The IAEA's Safety Standards documentation, for example, directly feed into national nuclear frameworks and legislation (e.g. ONR 2024, SSM 2023), while national nuclear waste organisation representatives are involved in advising, consulting and drafting IAEA documents (e.g., IAEA 2003). As such, the IAEA's imaginaries and policies are entwined with various national approaches to the management of SNF and nuclear materials more broadly.

For our analysis, we selected documents from the IAEA and the NEA on the 'backend' of the nuclear fuel cycle, and the management and storage of SNF. These documents allow access to an otherwise inaccessible material, and visibilise sociomaterial relations that SNF enters following its removal from a reactor. They also allow us to engage with SNF management practices that are otherwise contained in the societal periphery (Gregson 2012). As such, documents and documentary analysis enable the tracing of SNF at a distance (Latour 1992).

As Nimmo (2011) points out, documentary analysis can be challenging in and for research tracing material relations. He observes that to trace the agency of material entities through the layers of human symbolic and social mediation represented by documents might be problematic. Documents tend to present relatively neat descriptions of practices that are messy. They can be seen to enact realities in ways that are more one-dimensional than those available for and through ethnographic observations for instance (Law 2004). Yet, drawing on Latour and Woolgar's definition of writing as 'material operation of creating order' (Latour and Woolgar 1986: 245), Nimmo positions documents as intrinsic to practices, observing that most practices have their 'accompanying texts … without which the practice would be deprived of the oxygen of its networks' (Nimmo 2011: 114). Documents are 'not simply … representation[s], but rather … nonhuman agents' (Morton 2012: 215) that enact relations with SNF, shape and connect practices, and inscribe ontological boundaries and domains. As such, they provide suitable ground for tracing the otherwise untraceable or inaccessible, such as nuclear matter.

We searched for documents in the IAEA and NEA online repositories, relying on search words 'spent fuel', 'spent nuclear fuel', 'spent nuclear fuel storage' and 'spent fuel storage'. The search on the IAEA website yielded 124,000 hits for 'spent nuclear fuel' alone, which meant that we had to choose a cross-section of the data available to us. In the first instance, we decided to focus on reports and other documents rather than, for example, websites, as the aforementioned sources tend to guide and shape national nuclear industry safety, and other, practices, and thus enact different kinds of realities and practices (Law 2004) than more outward facing sources such as websites or brochures do. Secondly, we elected to analyse the chronologically more recent documents (published after 2000), as these often update older documents and can thus offer a current description of the state of SNF management, but also (often) provide descriptions of past practices and standards.

We leaned on reflexive thematic analysis to make sense of our data (Braun and Clarke 2019). Reflexive thematic analysis is about 'the researcher's reflective and thoughtful engagement with their data and with the analytic process' (Braun and Clarke

2019: 594), rather than about 'replicable' or 'accurate' coding. We coded data independently and collaboratively. We paid special attention to descriptions of what SNF does, how it behaves, what it requires and how it shapes the way it is handled. Where we undertook independent coding, we came together to discuss, interpret and reflect on our codes. We then proceeded to organise our codes into themes, such as 'doing SNF' and 'doings of SNF'. Throughout the process we reflected on the codes we created to ensure their consistency and that they described the data adequately.

CONSIDERING SPENT NUCLEAR FUEL

SNF is a by-product of nuclear energy generation, and 'the most important continuous growing source of civil radioactive materials generated' (IAEA 2008: 2). It consists of fuel pins formed of stacks of cylindrical uranium oxide or mixed uranium plutonium oxide pellets encapsulated in metallic tubes. The pins are grouped together in fuel assemblies (IAEA n.d.). SNF contains approximately 95 per cent of the original uranium in unused nuclear fuel, as well as plutonium, minor actinides (americium, curium, neptunium) and fission products (caesium, iodine, technetium). Its exact composition depends on the 'initial fuel type … its enrichment … and the type and operating conditions of the reactor' (IAEA 2022a: 14). Two thirds of the generated SNF remain in storage pending (the implementation of) decisions regarding its management, while one third has been reprocessed (IAEA 2024b).

There are currently three established SNF management paths, and one speculative one. Most nuclear countries consider SNF to be waste and plan to dispose of it in GDFs (e.g., Sweden, the UK). Some treat it as a resource (e.g., France) and extract unused uranium and plutonium to be fabricated and reused as fuel. Others (e.g., Netherlands) have chosen what we might call a path of indecision, whereby the status of SNF remains unsettled to enable future policy flexibility. A fourth option, the partitioning and transmutation (P&T) of SNF, is still a speculative strategy (Kooyman 2021), that would take reprocessing a step further. Here, after the separation of plutonium and uranium from the 'waste elements', some of these elements, namely long-lived and highly radiotoxic minor actinides, would be further treated and transmuted into shorter-lived and less toxic elements to shorten the period nuclear wastes remain hazardous (Aït Abderrahim et al. 2020). An argument for P&T is that it would reduce the hazardousness of the deposited waste, and the size and cost of the GDF, thus potentially enhancing the public acceptability of geological disposal (IAEA 2004).

Irrespective of which strategy has been chosen, SNF needs to be stored for periods varying from a few years to several decades. Storage is envisioned as a temporary state during which SNF cools down, making it safer to handle (IAEA 2020a). For the IAEA, storage 'is by definition an interim measure that provides containment of spent fuel with the intention of retrieval for reprocessing, processing or disposal at a later time' (IAEA 2019a: 6). The expectation of the temporariness of storage is based both on the nuclear optimism of past decades (Keating 2022) and on expectations of linear sociotechnical progress (Kasperski and Storm 2020). Early nuclear development did not greatly concern itself with waste (Macfarlane 2003) that was considered first and foremost a technical issue (Barthe 2009). In the early days of the industry, SNF was envisioned as fuel for future fast-breeder reactors and the plutonium economy (Feiveson et al. 1976, Walker 2021). Nuclear actors expected this plutonium powered future to be a reality by the year 2000, and the design of storage facilities was premised on the assumption that SNF would spend little time in storage before being reprocessed. Conversely, the idea of interim storage also rests on a belief that, even without reprocessing and the plutonium economy, continuous technological and societal advances will deliver a permanent solution to deal with SNF (Kasperski and Storm 2020).

Yet, as the plutonium economy and other solutions have failed to materialise, 'spent fuel storage periods well beyond those originally foreseen [have become] a reality' (IAEA 2019a: 1). Meanwhile, as global reprocessing capacity has not increased, and disposal solutions in most cases are decades away, SNF 'will continue to accumulate at storage facilities [and] could [be] stored for 100 years or longer' (IAEA 2019a: 1–2). Although the IAEA holds that SNF 'can be safely and securely stored for as long as it may be necessary', it observes that 'the risks and costs of storing the growing inventory of spent fuel will continue to increase; and in the absence of an end point, it will eventually become a significant societal burden' (IAEA 2019a: 1). Prolonged storage, particularly wet storage (which we explore below), could cause issues. Knowledge loss is a real risk, as the nuclear operators who placed SNF into storage will not be available when SNF is retrieved potentially a century from now (Keating 2022, Ialenti 2020). Conversely, wet storage tends to rely on active safety systems, requiring continuous maintenance, and human resources for monitoring and handling waste and storage facilities. This illustrates the fragility of material order and the continuing work required to maintain containment (Denis and Pontille 2015, Kinsella 2001), antithetical to the dominant argumentation on the (passive) safety of geological disposal for instance (Schröder 2016). As new SNF is continuously being placed in expanding storage facilities, it is timely to explore what SNF does, how it is done and made containable, and how storage is justified and made contain-able, all the while calls are being made for more permanent forms of containment (EC 2011, IAEA 2019a, NEA 2008). Moreover, exploring SNF in wet storage, in particular, enables reflections on the doing and doings of SNF, at a time when the ontological status of SNF might still be up for grabs and its future trajectories remain undecided.

All reactors have a SNF pool associated with reactor operations. Whether SNF is to be dry stored, reprocessed or disposed of, it has to go through a period of wet storage that, as such, forms a sort of an 'obligatory passage point' (Callon 1984) for SNF. Although there are no internationally established design standards, most fuel storage pool designs are similar (IAEA 2013). Pools tend to be rectangular in horizontal cross-section and ten to thirteen metres deep, have a reinforced concrete structure and be lined with stainless steel, which is preferred for offering shock resistance and increased structural integrity. They can be composed either of one large pool or several interconnected pools (IAEA 2024b).

Below we examine how industry descriptions of SNF illustrate its thing-power, and how SNF actively intra-acts with the sociomaterial systems designated to contain it (Barad 2007, Schürkmann 2022). We explore systems of containment, home in on SNF and trace how SNF is always described and performed through its relations with other entities. Furthermore, we note that the more closely we look at SNF, the more readily it seems to dissolve before us. Instead, we are looking at the component elements of SNF – uranium, plutonium, minor actinides and fission products – which point towards the diverse futures and relations SNF contains and contributes to. Accordingly, we note how the materiality of SNF can perform different nuclear futures.

THE DOINGS OF SNF

The NEA and IAEA both describe SNF as dangerous. Where the NEA holds that SNF is a 'chemically poisonous and radioactive' material that 'can affect cells', make 'person[s] … ill', and 'interact with matter' (NEA 2021: 14), the IAEA describes SNF as a heat and radiation generating material that 'contaminates', 'corrodes' and 'degrades' other entities (IAEA 2013: 10), and that can emit lethal levels of gamma radiation 'for about the first 100 years' (cf. IAEA 2019a: 12). Thus, the NEA and IAEA argue that to ensure 'that people and the environment are protected … against radiological and other hazards' (IAEA 2018: 3), SNF 'must be managed with care' (NEA 2021: 14). Where these descriptions of danger argue for a need to contain SNF, the IAEA also mobilises these very qualities to make a case for the industry's ability to contain SNF. For the IAEA, the hazardousness of SNF renders it 'self-protecting', for its corrosive and colonising characteristics (Gregson 2012) mean that it can 'only be moved and processed with specialized equipment and facilities, beyond the practical capabilities' of heinous groups (IAEA 2019a: 12). In this way, the IAEA argues that, by emitting radiation and heat, SNF enacts or contributes to its own containment.

Yet, most industry descriptions perform the containability of SNF through its pacification. Like 'tabular classifications that state facts about the volume, weight, and radioactivity of the [waste]' (Gregson 2012: 2012), the NEA and IAEA's descriptions of SNF management strip SNF of its agentic properties and portray it as an object that is being acted upon. The NEA, for example, holds that 'spent fuel … can be kept [in storage] for at least 50 years before packaging or repackaging becomes necessary' (NEA 2013: 29). Likewise, the IAEA writes that SNF is 'stored under water for several years' after which it is 'shipped for reprocessing or else transferred to longer term … storage before being encapsulated in preparation for emplacement in a geological disposal facility' (IAEA 2018: 11). These depictions are devoid of the 'self-protecting', life-threatening hazardous activity present in the previous paragraph. Instead, the IAEA and NEA present SNF as a passive, tamed object without or with little capacity *to object* to the practices imposed on it (Latour 2000). Effectively, to do containment, the IAEA and NEA here have stripped SNF of its dangerous characteristics and enrolled it into a management programme (Weichselbraun 2016).

However, if we flip the table once more, the IAEA and NEA's depictions of a passive SNF, also illustrate a range of material configurations needed to keep SNF in place. From here, the pacification and containment of SNF emerge as ongoing achievements contingent on several successful sociomaterial collaborations (Schürkmann 2022; also Hetherington 2004). The IAEA lists some of the entities needed to deal with SNF in storage:

> Spent fuel handling operations in their simplest form involve a fuel handling tool, a hoist, travelling bridge, binoculars and an operator. The reliance is placed on operator judgement to engage the fuel handling tool, move the fuel (whilst still maintaining enough shielding and avoiding collision with objects) … fuel handling systems can be operated remotely [they have] closed circuit television units to aid handling tool engagement and fuel assembly number recognition (IAEA 2013: 9).

This quote suggests that a range of sociomaterial collaborations need to be in place and maintained to keep SNF under control. SNF, thus, mobilises various entities to keep it in check. Here, although not mentioned in the quote, water emerges as a particularly important entity. Water in storage pools 'serves two functions: protecting workers from the radiation emitted and evacuating the heat generated by the spent fuel' (NEA 2021: 14). Acting as a radiation shield and a heat absorber, water temporarily decreases nuclear risk, but it also 'provides a transparent medium to facilitate fuel handling and visual observation' of SNF assemblies (IAEA 2024b: 6). By cooling SNF down, containing radiation, and enabling the monitoring and handling of SNF assemblies when needed, water enacts the containability of SNF.

TOUCHING RELATIONS

Water, however, comes with trouble. The IAEA lists how storage pool water needs to be purified, its chemical composition, temperature and level in the pool actively monitored, while operators also need to avoid and monitor interactions that could lead to the pool leaking, rendering the pool itself a matter of concern (IAEA 2024b). As we observed above, water enacts material containment: by absorbing heat and radiation from SNF, it holds radiation risk in place and space. It also enables the monitoring, pacification and containment of SNF. It does this by mediating interactions between SNF and the world beyond by touching. Puig de la Bellacasa holds that touch 'expresses a sense of material embodied relationality that seemingly eschews abstractions and detachments' (Puig de la Bellacasa 2009: 279). Water, as a container, is constantly in touch. It is in touch with the pool and with SNF. It cools SNF down with and through touch, but it is touched back by SNF in return. As water absorbs heat from SNF and cools it down, it warms up and can turn against SNF and containment. Because 'many of the phenomena which adversely affect spent fuel integrity are thermally activated' (IAEA 2019a: 5), water, through touching intra-action with SNF, can activate rather than pacify SNF. That is, containment in and enacted by storage pools is always precarious and fragile (Denis and Pontille 2015).

While SNF emits heat and radiation, corrupting water and other 'materials … in [its] proximity' (IAEA 2024b: 54), it too emerges as vulnerable. This vulnerability appears through the complex dynamics and multiple intra-actions in the pool (Barad 2007, Hird 2013). In the pool vulnerabilities, affects and actions flow in and from different directions. Always in touch with the pool, water slowly corrodes and leaches pool components, absorbing contaminants. For the IAEA these material flows and intra-actions are risky and need to be managed for the 'improper chemical composition of the cooling water' can corrode SNF assemblies (IAEA 2020a: 66). While corrosion is one of the 'main degradation mechanisms that have the theoretical potential to affect spent fuel … integrity' (IAEA 2024b: 60), 'the potential for degradation and consequent release of radioactive inventory [can be] kept low' by 'controlling water temperature and chemistry' (IAEA 2019a: 12). Containment, then, is enacted by repairing and maintaining the container, water. As the pool threatens to wear down and seek direct contact with SNF, and as water both shields and potentially consumes pool and SNF alike, touch in the storage pool is generative of both radiation protection and risk. That is, hazard and containment emerge and are moderated through intra-actions between SNF, water and pool (Barad 2007, Puig de la Bellacasa 2009). Indeed, the IAEA observes that, if SNF 'storage times lengthen, the potential for materials degradation increases' (IAEA 2019a: 4). Examining relations between SNF and water, thus, highlights the contingency and the fragility of the sociomaterial collaborations with and through which the industry describes and designates SNF as containable (Evens 2024, Schürkmann 2022).

Thus, the containment or stilling of matter is only ever temporary (Gregson et al. 2010, Hetherington 2004) and rests on the intra-actions and doings of various entities (Barad 2007, Schröder 2016). For the IAEA, relying on such diverse collaborations and relations to contain SNF is unsustainable. On one hand, the IAEA holds that 'the risks and costs of storing the growing inventory of spent fuel will continue to increase' (IAEA 2019a: 1). Additionally, it sees this 'reliance on active safety controls (e.g. maintaining water levels, water chemistry, cooling and make-up systems, and leak detection)' as a disadvantage of storage pools (IAEA 2020b: 2). While the IAEA, then, works to demonstrate the ability of storage solutions to contain SNF, it simultaneously argues against storage as a long-term solution, favouring disposal or reprocessing as 'defined end point[s]' for SNF (IAEA 2020b: 2). Unlike geological disposal that rests on a notion of 'passive' safety (Schröder 2016), storage that relies on the active work and doings of many actors will, in the eyes of the IAEA, eventually become a 'significant societal burden' (IAEA 2019a: 1).

Statements of increasing risks, costs and the societal burden of storage, the complex and, perhaps, contradictory enactments of active, passive, dangerous and vulnerable SNF do not simply describe SNF (management practices), but also 'enact realities and versions of the better and the worse' (Law 2009: 154). They enact sociotechnical imaginaries of desirable futures (Jasanoff and Kim 2009) held by the IAEA and shared by a range of nuclear actors. They also reflect a belief that better solutions for managing SNF are, or will become, available (Kasperski and Storm 2020). By reiterating this belief, the IAEA aims to demonstrate the nuclear industry's (improved) ability to contain SNF in the future, but also to justify the ongoing generation of SNF. For the IAEA the containment of SNF through reprocessing or geological disposal is linked with bright nuclear energy futures (also NEA 2011). Demonstrating 'permanent' containment through geological disposal or reprocessing and thus solving any waste problem the industry might be said to have, provides, from the IAEA's standpoint, a licence for further and future nuclear operations (Kinsella 2001). By describing storage as a 'societal burden' and reprocessing and geological disposal as desirable 'end points', the IAEA is actively seeking to lay down nuclear futures.

SNF FUTURES

Nuclear heritage scientists explore how 'the enduring materialities of nuclear things' contribute to the making of future worlds (Keating and Storm 2023: 97; also Rindzevičiūtė 2025, Ross 2024). While, in this section, we delve a bit deeper into SNFs future-making capabilities, it is worthwhile remembering that nuclear futures (certainly, the IAEA and NEA documents we have analysed here nod to futures in plural rather than singular) are always partially occupied by past and already existing nuclear infrastructures and material relations (e.g., Adam and Groves 2007, Barad 2023, Keating and Storm 2023). Indeed, SNF has organised its management from its inception, e.g. through its decay times, heat emission properties and differently radioactive components (IAEA 2019a), although how nuclear actors have aimed to shape that management has differed over time and space (Högselius 2009, Lennemann 1979). We suggest that, aside from policy interests, SNF's material characteristics have enabled and continue to enable different management strategies, and the enactment of various potential nuclear futures.

SNF is composed of an extensive list of elements, extending from uranium and plutonium, to americium, curium, neptunium, caesium, iodine, technetium and a range of other elements. All these elements have their particular characteristics: differing levels of radiotoxicity, differing half-lives, differing decay chains, and different kinds of political traction. They invite human interactions differently. Where Hecht (2012) has examined the oscillating nuclearity of uranium, Masco (2006) points to plutonium as embodying an 'unprecedented split future', entwining and entwined in the dream of the plutonium economy and the dread of nuclear weapons. As such, plutonium is more politicised and polemicised than americium, curium or neptunium, which, nonetheless, alongside plutonium, are 'accountable' for much of SNF's long-term radiotoxicity (IAEA 2015) and hence weigh heavily on its potential future(s).

Partly because of the temporally expansive radiotoxic potential of these elements to corrode and colonise (Gregson 2012), nuclear actors point to geological disposal as the best available long-term NWM option. Indeed, decades of R&D and official discourses backing geological disposal have rendered it a definite and durable part of any nuclear future (Bergen 2016, IAEA 2024a, EC 2011). It is also key to the industry's claims of the sustainability of nuclear energy (IAEA 2022b). Even so, trajectories towards geological disposal are varied, and the materials that might ultimately be disposed of in GDFs depend on what kinds of relations are established with and through SNF components, and what kinds of work nuclear actors are willing to do with and for those components, and vice versa. Most nuclear countries currently treat SNF as waste, yet the IAEA (2008) and the NEA (2021) advocate for reprocessing in the name of the (future) sustainability of nuclear energy, noting how reprocessing conserves natural resources, optimises waste management and disposal conditions, minimises environmental impacts, and contributes to fuel cycle economics as well as proliferation resistance.

Although some countries have given up on it, reprocessing is an established SNF management strategy. It is a process that cuts into SNF to chemically separate and extract uranium and plutonium. In reprocessing, SNF dissolves in hot concentrated nitric acid that produces not just uranium and plutonium, but also highly radioactive and heat generating liquid waste composed of the remaining fission products and minor actinides (notably americium, curium, neptunium). This liquid is commonly calcinated, and the resulting dry material is incorporated into borosilicate glass, and stored to wait geological disposal (WNA 2024). Reprocessing, interfering in the form and composition of SNF, represents a 'disruption of, and termination of particular associations and arrangements of materials … to bring about new associations, arrangements, and conjunctures' (Gregson et al. 2010: 1068). It assigns value and differentiates between 'useful' (uranium and plutonium) and 'waste' materials (minor actinides and fission products) in ways that strategies of direct SNF disposal do not. By separating 'useful' materials from 'waste', reprocessing disrupts existing relations and generates new ones. Uranium can be enriched and re-used as fuel, while plutonium can be stored to wait for potential future use or be mixed with uranium to produce mixed oxide fuel for reuse. Meanwhile, reprocessing generates new types of high-level waste and alters the range and types of waste requiring management. Reprocessing, then, is generative of different kinds of infrastructures, waste material relations and entities than geological disposal (Hietala 2018). Intervening in the materiality of SNF, valuing its composite elements differently, generates alternative futures that, nonetheless, seem to depend on and incorporate geological disposal.

Meanwhile, P&T takes the material intervention of reprocessing further. Unlike reprocessing, P&T does not begin from the valuation of different SNF components, but from the long-term hazard, the radiotoxicity and activity of minor actinides. According to the IAEA, the 'partitioning and conditioning of long lived radionuclides into *stable* matrices may be a … step' towards 'reducing their migration' from a GDF (IAEA 2004: 2, emphasis added). Additionally, 'P&T can help to reduce the time during which nuclear waste should be isolated from the biosphere from 130 000 years to between 500 and 1500 years' (IAEA 2004: 5). That is, P&T aims to enhance the contain-ability of GDFs by intervening in waste matters by reducing the toxicity, and the spatial and temporal hazard posed by wastes (IAEA 2004). As such, the IAEA sees that P&T has the potential to increase the public acceptability of geological disposal (IAEA 2004). Yet, the potential of P&T remains uncertain and necessitates the formation of relations, industrial and research infrastructures that do not yet exist (Hietala and Geysmans 2021).

These three technologies, geological disposal, reprocessing and P&T, exemplify how the compositeness of SNF can shape futures and enable nuclear actors and policymakers to perform SNF in different ways (e.g. Velasquez et al. 2021). The starting point for geological disposal and P&T appears to be the activity, corrosive potential and temporal reach of SNF elements, in different, yet complementary ways. Our brief exploration of these different paths suggests that different SNFs can be performed depending on which of its components or relations are made valuable, with consequences for the future. The geological disposal of SNF focuses on long-term hazard and containment and seeks to impede the formation of relations between SNF and the world aboveground (Schröder 2016, Harvey 2024), whereas P&T seeks to cut millennia out of necessary containment timelines to render a desired geological disposal future more realisable (Kasperski and Storm 2020). Meanwhile, reprocessing focuses on the economic value of uranium, in particular, and aligns with the IAEA's preferred sociotechnical imaginary (Jasanoff and Kim 2009) of expanding reliance on nuclear energy. While these technologies focus on different SNF components, the nuclear industry tends to present SNF as a black boxed matter of fact (Gregson 2012).

Yet, SNF elements continue to cause trouble for the longest time. This is reflected in the rationale for P&T, but also in the decades of scientific work that points towards the challenges to find and engineer containers that can withstand the heat and radiation wastes emit and tame waste for long enough (Li et al. 2023, Thorpe et al. 2021). Ialenti's (2018) account of the 2014 accident in the Waste Isolation Pilot Plant (WIPP) underground repository in the US illustrates how containment is always conditional and reliant on situated doings (Hietala 2018). In the WIPP case a wrongly configured system of containment caused a 'waste [canister] burst open and spew out fire' (Ialenti 2018: 262). There, waste reacted to an inappropriate containment material in an explosive manner, illustrating how even in disposal facilities waste continues to intra-act and form relations with materials surrounding it with differing consequences (Schürkmann 2022, Stsiapanau 2025, Hird 2013). Where modelling can help to predict SNF's behaviours in the long-term, and engineering and other sciences can seek to shape the kinds of relations SNF will be able to enter and form in the long-term (Geysmans et al. 2023), unforeseen relations with entities such as microbes (Lloyd and Cherkouk 2020), water (Schwartz 2012) or future humans (Schröder 2016) can facilitate new and unpredictable opportunities for SNF to act and do. Indeed, waste scholarship, highlighting disposal as a temporary stilling (Gregson et al. 2010), a placing of absence (Hetherington 2004), and geological disposal, in particular, as an ongoing socio-technical experiment (Schröder 2016), argues against the industry and policy vision of geological disposal as an endpoint (EC 2011, IAEA 2019a, NEA 2008). Or rather, geological disposal might present an endpoint for policy, but not for the liveliness of SNF (Hird 2013).

CONCLUSION

Long-term nuclear waste management is a highly discussed topic both in social science and society at large, yet nuclear waste itself often sits at the periphery of these discussions (Hietala and Geysmans 2022) that often focus on technologies of containment and their public acceptability (e.g., Lagerlöf et al. 2022, Landström and Bergmans 2015). In this article, we have sought to focus on waste instead by zooming in on spent nuclear fuel (SNF). To do so, we analysed IAEA and NEA documents on SNF management. Both organisations are much invested in the further use and expansion of nuclear energy, and as such are motivated to present SNF as a tamed and containable material (Gregson 2012, Kinsella, 2001) rather than as something needing 'eternal care' (Kasperski and Storm 2020). Indeed, the documents we analyse here re-enact nuclear pasts, past and current waste management practices, highlighting some aspects, while obfuscating others, to perform and demonstrate the industry's ability to manage and contain SNF in the present and the future (Kinsella 2001).

Yet, this containability that the IAEA and the NEA aim to convey would be better understood as or through contain-ability, a notion that underscores the situatedness of containment as something that 'emerges through relational sociotechnical doings' (Hietala 2018: 27), and that is always shaped by how SNF is done (e.g. is it considered waste or resource), but also by what SNF does. Indeed, above we have suggested that SNF, as an agentic lively entity (Bennett 2010), is always shaping and intra-acting with the systems designed to contain and manage it (Barad 2007). We drew on Bennett's (2010) notion of thing-power to trace how the IAEA and the NEA enact SNF and observe that those enactments vary between active and passive matter depending on the relations through which SNF is described. When SNF is depicted through its relations with human society and nature, it emerges as an active entity able to harm, contaminate and lethally damage. This activity, in turn, is put forward as the main justification for geological disposal, for instance.

Meanwhile, where the IAEA and the NEA describe SNF through its relation with the nuclear industry, it appears as a manipulatable, manageable and passive material. Here, the nuclear industry rather than SNF sets the tone of interactions as the former works on the latter.

Simultaneously, descriptions of SNF in storage, however, illustrate some of the material practices and entities required to contain SNF (Kinsella 2001). Leaning on Barad's (2007) work on intra-action we traced how SNF emerges as containable, vulnerable and risky through its touching encounters (Puig de la Bellacasa 2009) with water and storage pool components. As SNF acts, it is simultaneously being acted upon. Water cools SNF, reflects SNF's own activity back on it, but it also subjects SNF to the corrosive encounters it has with pool components. Examining SNF and storage through intra-action and touch blurs the dichotomy or distinction between active and passive material. Containment is less about pacification, and more about what materials encounter each other, and how. As our exploration of SNF storage illustrates, managing those encounters and maintaining material order requires much work (Denis and Pontille 2015), meaning that the safety of storage is a precarious achievement of sociomaterial collaborations (Schürkmann, 2022).

Finally, we traced how SNF contributes towards various nuclear futures in different ways. Through its long-term hazardousness, SNF demands action (Morton 2012). Yet, its various components are differently open to various nuclear waste management strategies, treatments and material practices. We explored how the nuclear industry seeks to harness SNF elements in different ways to realise nuclear futures. However, rather than illustrating what can be done to SNF, we sought to highlight that, because of its composite character, and the differing radioactivity and radiotoxicity, heat emission capacities and half-lives of its components, SNF is shaping and organising nuclear futures and imaginaries in ways that can have long-lasting consequences. That is, SNF is an active legacy of past decisions, material practices and actions, which continue to enact and interact now and in the (distant) future.

Thus, if we come back to the problematic of geological disposal, the currently dominant nuclear waste policy and imaginary, with which we began this paper, we posit that placing waste, rather than technology or engineering, at the heart of nuclear waste management deliberations offers an alternative and, perhaps, more productive basis for discussing how to deal with nuclear waste in the present as well as in the future. The dominant framing of long-term nuclear waste management as a 'social' problem has reduced deliberation processes to efforts to understand why people support or oppose certain technological solutions, and how those attitudes and perception could be incorporated into the nuclear waste governance process. Shifting attention to nuclear waste itself can reframe contestation not as divergent views on one nuclear waste reality, but as the co-existence of different nuclear waste realities. Turning the focus away from particular SNF management trajectories to SNF itself can facilitate more nuanced approaches to and understandings of the desirability of different management trajectories by considering the different kinds of relational performances of SNF, the various sociomaterial collaborations necessary to keep SNF in check, and the different ways in which SNF can shape and engage containment systems. That is, approaching SNF as an agentic entity with a capacity to act can offer a better platform to consider and deliberate on what kind of nuclear future(s) are societally desirable.

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ACKNOWLEDGEMENTS

We would like to thank the anonymous reviewers for their helpful comments and remarks, which helped to improve the manuscript. MSdV would also like acknowledge the Research Council of Finland that funded her contribution (grant no 360116).

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