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Joining Multiple Collaborations: Toward a Sociomaterial Perspective on Nuclear Waste Management between Society, Technology and Nature

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ABSTRACT

The article develops a sociomaterial perspective on nuclear waste management by illuminating the role of geological formations and therefore 'nature' with respect to site selection procedures. Besides technical barriers (containers) and geotechnical barriers (filling materials), geological formations should serve as 'natural' barriers in their function as host rocks in order to isolate radioactive waste for thousands of years. Referring to empirical insights into the German procedure of site selection and ethnographic research on practices in a nuclear chemical laboratory, the contribution illustrates how humans and materials are interwoven in an alliance of multiple sociomaterial collaborations united by the task to isolate a toxic object—here, high-level radioactive waste. In this way, the article sheds light on how nature is addressed not only as a resource for an anthropocentric project but also as an active collaborator in order to master such disposal processes in the long run. Such a sociomaterial perspective aims to enrich sociotechnical considerations by emphasizing the role of nature as an integral part of nuclear waste management and by studying its complexity.

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1. INTRODUCTION

The question of where and how to dispose of nuclear waste, especially high-level waste (HLW), is one of the great challenges of the present. Many nations using nuclear energy struggle to find adequate sites to store the produced toxic waste due to their respective geological, economic and political conditions. Even though it is expected that in Finland the first disposal will be in operation in the near future, and in Sweden a site for a repository has been located, processes of site selections are proceeding only slowly in many other countries. As Di Nucci et al. (2015: 26) argue, the nuclear industry has promoted the argument that reasons for these sluggish developments in finding long-term solutions to manage HLW could be identified in a lack of societal acceptance and political will to establish repositories, while opponents of using nuclear power, and therefore producing nuclear waste in the first place, argue that only the phase-out of this form of energy is acceptable.

Apart from this field of conflicts between proponents and opponents of nuclear energy and between societal actors in procedures of site selection processes in different countries there is a wide consensus that HLW should be disposed of in deep geological formations. In a metaphorical sense, the idea of involving these formations in order to isolate HLW could be described as establishing a 'geological vault' (*geologischer Panzerschrank*) (Barthe 2012: 93) with the potential to transform considerable uncertainties of human-related societies—including their institutions and future generations above ground—into uncertainties of the behavior of rock formations and climatical change, *inter alia*.

Some states pursue a strategy of reversibility and retrievability (R&R) (Lehtonen 2010), considering alternative solutions to manage nuclear waste in the near future and taking into account the possibility to intervene if the barrier effects of the repository appear too tenuous. Even though such strategies underline humans' ambitions to control and in a way correct material behavior, in certain ways the involvement of deep geological formations can be characterized as a posthuman task in the sense of decentering humans as permanent 'instances of care and management' in the long run (especially with regard to such disposal systems that should be irreversibly sealed in the future). Over time, rocks in combination with other installed materials, such as bentonite, copper or cement, may take on the function of isolating the radioactive materials for their lifetime. In this way, the challenge of disposing of nuclear waste does not only emerge as a challenge of human institutions, human-based strategies of governance and a human will to control material behavior in order to minimize risks in times of 'living with high-risk technologies' (Perrow 1999) and consequently living with productions of high-risk-waste. In the field of nuclear waste management, it is also a question of *material performance* in the context of isolating the produced radionuclides for thousands of years. Against this background and inspired by sociological and social anthropological discourses about material agency and nature in action, the article aims to provide a sociomaterial perspective on nuclear waste management as an alliance of multiple collaborations between society, technology and nature, or, in a more abstract way, between social, technical and geological affordances and requirements. Hence, the contribution aims to enrich environmental sociological, social scientific and especially sociotechnical debates on nuclear waste management by emphasizing the role of nature as an important agent or collaborator, respectively, for conceptualizing and realizing disposals and repository sites. Based on an environmental sociological and qualitative empirical point of view, nature here is not assumed in an essentialist way. First, it is taken into account as an empirical question: how is nature addressed by the involved Natural Sciences in the field of nuclear waste management?

There are different perspectives located within the Social Sciences and Science and Technology Studies (STS) dealing with nuclear waste management: national strategies of nuclear waste governance are discussed in international comparisons (e.g., Brunnengräber et al. 2015; Kuppler 2012; Lehtonen et al. 2021) and with regard to particular national policies (e.g., with a focus on Sweden [Sundqvist 2002]; with a focus on France [Barthe 2006]; with a focus on the US [Ialenti 2014]; with a focus on Germany [Brunnengräber 2016; Hocke & Renn 2009]); debates on nuclear projects are compared internationally in the context of climate change, energy security and risk assessment (Teräväinen et al. 2011); Brian Wynne's prominent studies on participation in nuclear projects have demonstrated the challenges of scientific and political communication and the relevance of lay knowledge in supposedly dominant expert cultures (Wynne 1996, 2011); further studies of participation examine processes of decision making in different countries (e.g., with a focus on Switzerland [Alpiger 2019]; with a focus on Germany [Themann et al. 2021]). Especially in the context of Technology Assessment, social scientists emphasize that nuclear waste management can neither be reduced to a pure technical problem nor to an exclusive human affair: as Catharina Landström and Anne Bergmans (2015) as well as Peter Hocke (2016) argue, nuclear waste management can be described as a complex sociotechnical system or challenge accompanied by technical developments in combination with questions of societal participation and acceptance. Hereafter, the necessity for legitimation through participation in processes of decision-making is one urgent issue with regard to 'technoacceptability' (Sundqvist 2002: 225, 227). Nevertheless a 'persisting socio-technical devide' is still identified (Hietala &

Geysmans 2020; see also Bergmans et al. 2014) in the realm of nuclear waste management, along with a 'technocratic dominance in an age of participation' (Blowers & Sundqvist 2010). In his studies of accidents in nuclear power plants and radioactive dams, the famous organizational sociologist Charles Perrow has demonstrated impressively how such sociotechnical systems require interactions between humans, material settings and the environment that 'alone can constitute a source of failure' (Perrow 1999: 75). Referring to the role of geological formations, such an evident differentiation between the sociotechnical system and its environment might become blurry: these formations are not reducible to an environment for a sociotechnical system referring to their fundamental and constitutive functionality for the disposal; furthermore, they are themselves exposed to environmental transformations such as volcanic and seismic activities or glacial periods that in turn can be technically modeled to design far-away-future-scenarios by geologists (Ialenti 2020). In addition, it might be imprecise to simply address them as part of a constructed sociotechnical system if we take into account the separation between geological and technological made by natural scientists in the field of nuclear waste management itself.

Sociotechnical perspectives on nuclear waste management emphasize the entanglement of the two spheres of society and technology. If we follow the assumption of interconnected and interwoven spheres, another sphere, beside human-related procedures of participation, governance and decision-making (socio) and material productions, infrastructures and equipment, including their functionality (techno), becomes identifiable that potentially might be taken into account in a more elaborated way: the sphere of nature, or more specifically nature in the sense of geological formations (geo). In collaboration with natural scientific research and with regard to different approaches focusing on material activity located within Sociology and STS, the contribution examines how nature is addressed in the field of nuclear waste management. The aim is to reconstruct an empirically based and theoretically informed sociomaterial perspective on nuclear waste management in order to enrich common sociotechnical approaches by inquiring into the role of nature, here, nature called on to 'do the work' (Groß 2016: 273) of disposing of our toxic waste. This requires an empirical design based on an ethnographic strategy combining multiple qualitative methods, such as participant observation (Atkinson et al. 2001; Emerson et al. 1995; Spradley 1980), grounded theory (Clarke 2005; Strauss & Corbin 1997) and document analysis (Atkinson & Coffey 2011; Prior 2011) in order to generate and integrate various empirical materials (protocols, documents, images) into the research process. Such an ethnographic approach is also interested in a collaborative relationship with the knowledge of its field and its participants in order to take into account scientifically attributed material activity (e.g., with regard to ethnographic research in the field of marine research [Bogusz 2021]; e.g., with regard to collaborative strategies in ethnographic research [Bieler et al. 2020]). To illustrate this perspective, I will inquire into the ongoing procedure of site selection for HLW in Germany. In Germany especially, the question of the appropriate host rock has developed into a dominant issue based on the possibility to select between different existing rock formations: rock salt, crystalline rock and clay rock are investigated in their potentials to serve as hosts for disposing of HLW.

The article is structured as follows: first, I will develop a sociomaterial perspective on nuclear waste management by emphasizing an alliance of multiple collaborations with reference to approaches deriving from STS, including Actor-Network-Theory, New Materialisms and Environmental Sociology, and also with respect to the differentiation between technology and nature in the field of natural scientific research on nuclear waste management itself (see Figures 1–3) (section 2). Empirically, I focus on how the involvement of geological formations is manifested in the procedure of site selection in Germany combined with ethnographical insights into experiments and practices in a nuclear chemical laboratory in which scientists investigate the migration of radionuclides in different materials. Referring to the empirical insights, it will be illustrated in which ways a material-related nature is addressed by different actors as a collaborative part, or even party, with its particular requirements, potentials and dynamics (see Figures 4–6) (section 3). I conclude with some reflections on the question of how far such a sociomaterial perspective might enrich studies of (nuclear) waste management (section 4).

2. MORE THAN A TECHNICAL AND MORE THAN A HUMAN TASK: COLLABORATING WITH NATURE

As Raymond Murphy (1995: 688), amongst others, has pointed out in his critical analysis of social constructivism, 'nature matters' in social scientific analysis—including the activity or agency of materials and, further, non-human life and (co-)existences.[1] Over the past decades, various approaches and empirical case studies in the field of early and contemporary STS (e.g., Callon 1984; Gomart 2002; Latour 1995), Social Anthropology (Descola 2013; Ingold 2012; Tsing 2015), Organization Studies (Carlile et al. 2013), Social Sciences (e.g., Böschen et al. 2015; Kalthoff et al. 2016) and New Materialisms (Barad 2007; Bennett 2010; Coole & Frost 2010; Lemke 2021) have emphasized the importance of considering action or agency, respectively, emerging not only from materials but also from plants, animals, or even spirits. In the field of nuclear waste management, particularly, materials become sources of hope in their capability to isolate artificially produced radionuclides and therefore toxic material activity.

2.1 UNFOLDING A RUDIMENTARY PERSPECTIVE ON SOCIOMATERIAL COLLABORATIONS

Following the assumption of taking materials into account, I suggest conceptualizing the great challenge of disposing of nuclear waste with regard to *sociomaterial collaborations* (see Figures 1–3) in which material ability, capacity and performance (for instance with respect to retention capacities of host rocks) are brought into position in order to regulate and restrain the radiating materials. In other words, sociomaterial collaborations (e.g., scientists investigating the migration of plutonium in clay rock, politicians initiating legal procedures for disposing of HLW in deep geological formations, members of NGOs criticizing political decisions with respect to risks and uncertainty of using special materials, etc.) face sociochemical fabrications (artificial radionuclides) that require long-term separation and isolation from human and other life. From such a sociomaterial perspective, HLW itself can be conceptualized as a hybrid object of a chemicalized modernity at the interface of material activity and human action, of nature and culture on the one hand—for instance, in the sense of a 'quasi-object' in the way Bruno Latour (1993: 55) has characterized objects that '[...] are much more social, much more fabricated, much more collective than the "hard" parts of nature [...]. On the other hand, they are much more real, nonhuman and objective than those shapeless screens on which society – for unknown reasons – needed to be "projected."' With a more specific focus on the hazardous potentials of industrially produced 'critical matter' (Sundqvist 2002: 7) resulting from high-risk-technologies, such detrimental materials as HLW can furthermore be described as critical toxic objects (Schürkmann 2021) that require extensive sociomaterial collaborations in order to regulate their destructive activity in relation to almost all living organisms.

Conceptualizing nuclear waste management as an alliance of sociomaterial collaborations formed in order to face a produced critical toxic object implies an emphasis on the entanglement of a human-related and a material-related sphere (see Figure 1). In his well-known study of the incidents in St. Brieuc Bay, Michel Callon (1984) developed a perspective on an alliance of scientists, fishers and scallops and therefore on cooperation between humans and animals united by the joint task to save the scallops from their extinction and disappearance in this particular bay in order to preserve their fishing as an important economic activity. Applied to nuclear waste management, I would not assume a shared interest of the different human and material participants, but rather a joint task, here the joint task of disposing of a critical toxic object. The term collaboration, often used in wars for acts of working with the enemy, refers less to stable and trustful cooperation based on shared interests. Such collaborations are assembled around a highly critical toxic object and go beyond cooperation of 'different groups to work together without consensus' (Leigh Star 2010: 602) in the sense of 'groups who wish to cooperate' (Leigh Star 2010: 602). They tend to imply constraint, uncertainty and opportunity, and potentially even resistance of particular collaborators. In this sociomaterial alliance of multiple collaborations, humans (scientists, politicians, members of environment associations, engaged citizens, etc.) and materials (glass, cement, bentonite, clay rock, etc.) work together due to different actions and activities as the following image might illustrate in a rudimentary way.

Figure 1 develops a first step to visualize a sociomaterial perspective on collaborations between humans and materials united by the joint task to isolate/dispose of HLW. While scientists develop disposal systems and conduct research on material behavior in laboratories, politicians implement strategies of governance and legal procedures and members of NGOs, as well as engaged citizens criticize or legitimate political decisions, materials and their activities are addressed as collaborators with special subtasks, too: retaining radionuclides and stabilizing the disposal system (for instance clay rock, rock salt) and being used as filling material (for instance bentonite). From such a perspective, the dualistic order of humans as superior cultural subjects who control materials may be irritated in referring to the idea of collaboration. Instead of a single-sided understanding of humans as controllers and materials as being controlled, different distributed competences of the collaborators become obvious: on the one hand, humans are not able to retain radionuclides; they or, more concretely, their bodies are not resistant and, as we know, would be simply poisoned. Whereas, materials are able to undertake this task; however, there are no materials that provide functional disposal systems without being investigated and constructed by humans and technology. Disposal systems in their material constitution have to be developed scientifically, they have to be legitimated politically and they also have to be accepted and criticized by the public in order to initiate and realize such an extreme long-term-project. In this way, material activity and human action might be differentiated but in a complementary rather than dichotomous way. In its linearity, this scheme (Figure 1) looks like a functional path. For all its reductions, which of course can be criticized, such a schematic view indicates that material capacities, activities and affordances play an integral part of managing this long-living toxic waste.

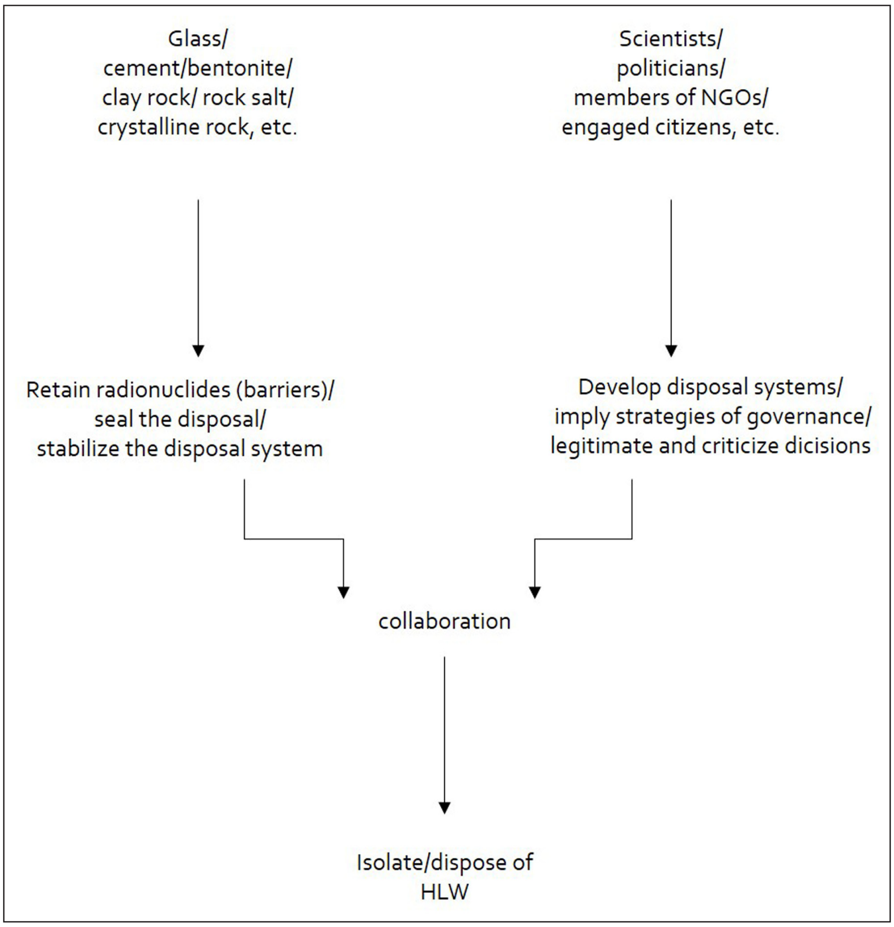

Figure 1 Nuclear waste management as an alliance of sociomaterial collaborations. Source: Christiane Schürkmann.

2.2 ALONG HUMAN INTERVENTION: TECHNOLOGY AND NATURE IN THE FIELD OF NUCLEAR WASTE MANAGEMENT

Sociomaterial approaches emphasize the entanglement of humans and materials or things, respectively, in accordance with their aim to suggest perspectives beyond a dualistic thinking, thus challenging definite distinctions between nature and culture, between nature and technology in order to analyze 'interactions with material objects and the natural environment' (Coole & Frost 2010: 3–4). Such distinctions are present in the natural scientific field of nuclear waste management if we take a closer look at the established differentiation of technical, geotechnical and geological barriers. These barriers are addressed as 'natural or technical components of a disposal system' (*natürliche oder technische Komponenten des Endlagersystems*) (Lersow 2018: 430), and are investigated, *inter alia*, by geologists and chemists in order to locate adequate sites for repositories. To give a brief insight: regularly, technical barriers refer to disposal containers with special material affordances concerning corrosion and high temperatures (e.g., Yim & Murty 2000). Geotechnical barriers are related to backfill materials, including natural materials such as bentonite as a mixture of different clay minerals or salt breeze. In this way, geotechnical barriers consist of materials that naturally occur and that are processed by humans to be deployed for compression, or more concretely, they are used to seal shafts, routes or boreholes of the disposal. Geological barriers should become effective between storage location and biosphere and might consist of materials such as clay rock or rock salt, for instance. In this way, the question of site selection depends not least on the special geological setting based on materials or formations, respectively, and their qualities for building a repository.

If we follow this assumed differentiation in the natural scientific field it becomes obvious that, firstly, geological barriers are related to nature in the sense of a *non-human-related material sphere*. Secondly, technical barriers are related to an understanding of technology as a *human-related material* sphere, or in other words, a sphere in which humans produce and operate produced materials. Thirdly, geotechnical barriers, in the sense of hybrid, are characterized as natural materials but are practically used by humans as a kind of building and constructing material with the aim to seal the openings of the disposal. The following diagram visualizes these differentiations between technical, geotechnical and geological with a special focus on relations between humans and materials.

Referring to these differentiations in the field of nuclear waste management it becomes obvious that they are related to a question of the graduation of human intervention: the more humans are involved in production processes, the more such material products are classified as technical; vice versa, the less humans are involved in material genesis, the more they are classified as natural.

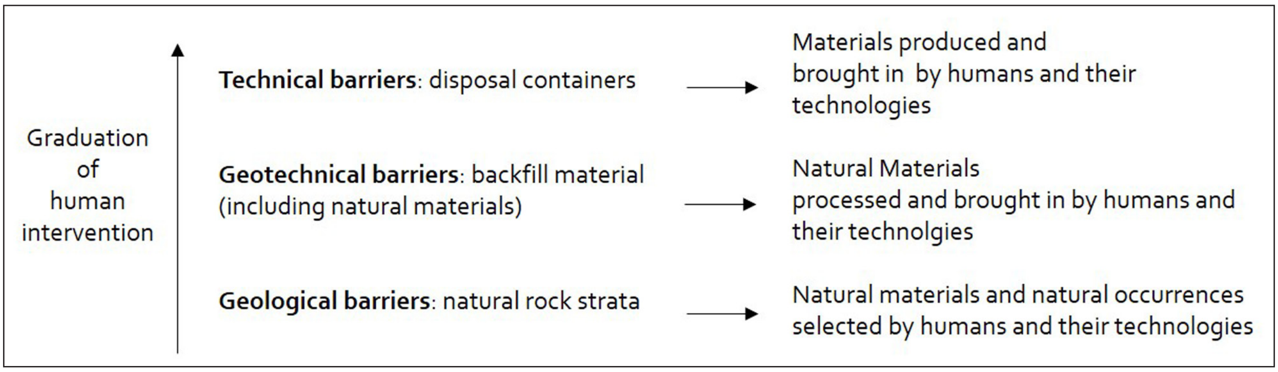

Figure 2 Differentiating nature and technology with regard to the graduation of human intervention. Source: Christiane Schürkmann.

While technical barriers consist of materials that are produced and brought into the repository under human influence, geotechnical barriers refer to materials that are addressed as being natural in the sense of existing without any human influence. However, these materials require being brought into the disposal system to be used for the backfilling and sealing of boreholes, shafts or drifts. Conversely to technical barriers, geological barriers are there as they are; they are characterized as natural based on their development in the course of geological time scales. Although in times of the Anthropocene (see Crutzen & Stoermer 2000) the separation of a human-related and a geo-related era might be irritated, geological formations are characterized as results of geological processes separated from human life and action. At first glance, we might identify the notorious dualistic model of a natural scientific segregation of a *humanized techno-material culture* and a *dehumanized geo-material nature* that follows its own rules and principles. This dualistic model has often been criticized in its implicit ontological assumption of a superior sphere of human-related culture and a marginalized sphere of a non-human-related nature that is reduced to a resource (e.g., von Verschuer 2021) for imperialistic capitalized and politicized systems and ways of living (Haraway 2016; Latour 2018). Here, materials being addressed as technical and as natural function as barriers retaining hazardous artificial radionuclides. In this way, it might be obvious that technology and geology are integrated as resources for the anthropocentric project of disposing of HLW—a project initiated by humans as members of nuclear societies that are increasingly confronted with the amounts of waste they have produced over the past decades.

At second glance, this field-immanent differentiation provides a perspective on two collaborative spheres that are accumulated in order to develop a concept for a disposal system in which technology and geology are both involved but also treated differently according to their particular challenges and potentials: while technical components of a disposal system have to be developed by humans, geological formations are basically not human productions or human interventions. Hereafter, these geological entities integrate their own affordances into the task of disposing of HLW depending on their specific constitutions that humans and their sociotechnical conceptualizations have to react to in certain ways. Neither technology as part of a human culture nor geology classified as a material nature solely determine the concept of disposal systems in deep geological formations. Rather, both spheres are addressed together in their respective challenges, complexities and potentials to complete each other. In this view, geology and technology, nature and culture have to work together and therefore enter into a collaboration, here with regard to disposal concepts, in order to face a long-term problem caused by humans and their technologies that finds its goal in preventing an uncontrolled dispersion of radioactivity.

Following this differentiation between technical and natural in the field of nuclear waste management might be an inspiration to broaden the perspective: while sociotechnical approaches in their ambitions to overcome technical determinisms and, furthermore, dualisms (such as technology vs. society) often tend to frame nature as a useful resource for technical interventions and developments or as an environment for but outside the sociotechnical system, here geology and technology, nature and culture are addressed as two different but equal spheres depending on the grade of human influence. In this way, the suggested sociomaterial perspective might also include materials that are not defined as technical in the field of nuclear waste management itself with respect to the natural scientific (here, geological) differentiation between technical and natural.

The alliance of sociomaterial collaboration as outlined above could be transformed into a triadic system in which three spheres of collaboration become identifiable while at the same time they are interwoven with each other: the sphere of human-based practices (socio), the sphere of technical and therefore human-related material productions and procedures (techno), and the sphere of natural and therefore non-human-related processes of rock formations (geo) collaborate in order to face the toxic object named HLW. The following visualization illustrates this triadic alliance of multiple sociomaterial collaborations.

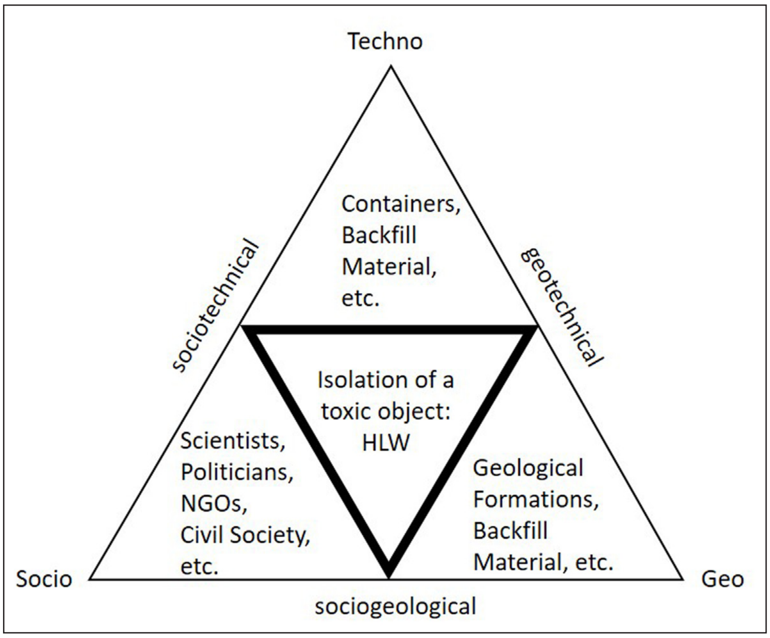

Figure 3 Three spheres of sociomaterial collaboration to dispose of HLW. Source: Christiane Schürkmann.

Hereafter, social, technical and geological collaborators are assembled and entangled in order to regulate and to isolate a critical toxic object. While collaborations between socially organized procedures and technical developments are categorized as sociotechnical and collaborations between geological formations and technical processes are established as geotechnical, relationships between society and nature (here, in the sense of geological formations) can be described as *sociogeological collaborations*. These collaborative relationships raise issues about how societies 'acquire' host rocks, how they produce knowledge and non-knowledge (e.g., Groß 2016) about them and furthermore how they integrate them into their political and legislative processes (here, into processes of site selection and disposal concepts). At the same time, these collaborations ask questions in how geological materials effect scientific knowledge production and processes of decision-making, as well as in how far geological conditions become relevant as determinants for disposal projects.

It should be mentioned that collaborative relationships associated by the task of isolating HLW are not always effective and functional, but rather are quite unruly and unpredictable both within any particular sphere and between the different spheres: humans struggle for strategies of governance and participation as well as with possibilities and limits of developing reliable technical solutions in the sense of Technical Assessment—and last but not least with the possibilities and limits of modelling long-term developments of geological barrier effects together with ambitions of Geosphere and, particularly, Biosphere Assessment in order to calculate 'hypothetical radiation exposures to humans, plants, and animals' (Ialenti 2020: 76). Not only human-related societies but also materials classified as technical (produced under human influence) and natural (formed without human influence) isolate and struggle against migrating radionuclides. Therefore, this alliance of multiple sociomaterial collaborations is not always well-functioning; it rather includes conflicts and challenges emerging inside and between the three collaborative spheres in and between their socio-, techno- geo-logics.

3. COLLABORATIONS IN PRACTICE AND PROCEDURE: VULNERABLE HOST ROCKS AND MIGRATING PLUTONIUM—EMPIRICAL INSIGHTS INTO THE PROCESS OF SITE SELECTION IN GERMANY

In Germany the functionality of the future repository is to be delegated to host rocks after a certain amount of time: the repository should be definitively sealed after 500 years and is supposed to work without any human influence through the insulation capacity of host rocks with regard to repositories built in clay rock and rock salt. The legal anchoring of how to dispose of nuclear waste and the establishment of a legal procedure of site selection has a contested history characterized by conflicts and tensions (Radkau & Hahn 2013). Protests against the politically planned disposal center Gorleben by the end of the 1970s, in combination with a strong anti-nuclear movement, are only one example of the potential controversy of the disposal question. In order to avoid such conflicts, the procedure of locating a site had to be reworked: from 2014 until 2016, the Commission on the Storage of High-Level Radioactive Waste (Kommission Lagerung hoch radioaktiver Abfallstoffe) developed recommendations for establishing a procedure that was to include the participation of the public and scientific knowledge beside political competences of decisions-making (Commission 2016). Based on these suggestions, the site selection law (Standortsauswahlgesetz, StandAG) was revised in 2017. In the current version of the law, the procedure of site selection is sectioned into phases and tasks, respectively, in chapter 2 StandAG: while in the first phase, sub-areas are to be identified based on geological data (chapter 2, section 13 StandAG), the second task is to determine regions within the identified sub-areas in order to start with further overground explorations (chapter 2, section 14). The law also defines potential host rocks for HLW: 'rock salt, clay rock and crystalline rock' (section 1(3) and 23(1) StandAG).

In order to unfold the developed sociomaterial perspective empirically, I will focus on documents (laws and reports) (Atkinson & Coffey 2011; Prior 2011) published by officially involved organizations (e.g., Federal Ministry of Justice [Bundesjustizministerium], Bundesgesellschaft für Endlagerung [BGE]), ethnographic protocols based on participant observations (e.g., Atkinson et al. 2001; Emerson et al. 1995) of the Conference on Sub-areas supported by the Federal Office for the Safety of Nuclear Waste Management (Bundesamt für die Sicherheit der nuklearen Entsorgung [BASE]) in February 2021, and ethnographic data gathered in a nuclear chemical laboratory at one German University equipped with its own research reactor.

3.1. MORE THAN FORMATIONS FOLLOWING FUNCTION: NATURE AS AN UNRULY COLLABORATOR

Following the path prescribed in the StandAG (chapter 2 procedure of Site Selection, in the original: Ablauf des Standortauswahlverfahrens), a primacy of geoscientific criteria becomes observable that predominates the procedure of site selection in a crucial way: where to dispose of HLW is neither addressed primarily as a question of technical possibilities or developments, nor as a question of societal acceptance and legitimation. First, it is addressed as a question of geological data and therefore geological conditions in order to locate areas and regions for further geoscientific investigations. In other words, one of the most important issues regarding the site selection process refers to the question of suitable rocks serving as host rocks. Against this background, the official project developer (in the original: Vorhabenträger, Stand AG Session 3), the BGE, published the *Sub-areas Interim Report* according to Section 13 StandAG in September 2020 in which the following statement is written:

> First of all, rock formations were identified which contain clay rock, rock salt and crystalline host rock types relevant to repositories. The minimum requirements refer to the hydraulic conductivity of the rock, the thickness of the effective containment area, the minimum depth of the effective containment area (i.e. its distance to the earth's surface), the assumed minimum area of the repository and the preservation of the barrier effect (BGE 2020 Summary Sub-areas Interim Report: 3).

In which way are rocks addressed in order to become an integral part for a disposal project initiated by humans within this excerpt of the interim report? Firstly, they are classified into different rock types according to their material properties and qualities. Furthermore, they are related to a set of requirements (minimum requirements) in the context of their geological prerequisites. In a way, the rocks embedded in special geological conditions are confronted with expectations of modern societies and their technologies, institutions, organizations and even their laws and legislation. In this functional view, rocks become resources of evaluating potentials and deficits concerning their qualities in order to retain radionuclides ('preservation of the barrier effect') and to store HLW far enough away from the surface of the earth and therefore from the sphere of human and other life ('its distance to the earth's surface'). Following this statement of the report, rocks in the sense of host rocks are addressed as natural objects that should serve a human-related society and its culture of safety. They are not reflected as rocks being confronted with a human-related project; instead they are taken for granted as a given nature in the sense of a resource that needs to be evaluated concerning how far it fits within preformulated sociotechnical demands. Therefore, the rocks are addressed in an ambivalent way: on the one hand, they seem to determine the procedure of site selection as a base for decision-making and technical developments in order to locate a site due to their 'productivity and resilience' (Coole & Frost 2010: 6); on the other hand, with respect to their different attributed advantages and disadvantages, they must match preconceived concepts of disposing of HLW. Hereafter, they are integrated as resources for a sociotechnical project.

The following argumentation presented by a participant and expert of the Conference on Sub-areas in February 2021 introduces an alternative way of addressing host rocks in the context of disposing of nuclear waste in deep geological formations and, therefore, introduces another perspective on addressing nature:

> The speaker, a geologist and social scientist continues his lecture held on the symposium of sub-areas in a panel focusing on clay rock. […] He argues: 'Clay has a number of disadvantages that depend directly on human interventions in the uninterrupted rock compound. When you construct a repository, you have to rupture the clay stone. On the one hand you bring in materials with chemical properties, which are reactive, which have radioactivity, which are particularly

> hot. You bring in heat. Then there is of course the risk of every underground waste disposal site: water. […] Then the reactivity of the waste. This is not only about reactivity with water but also with gas. […] Clay as a host rock has unbelievably good qualities but if you bring in the waste with the aim of long-term-storage then you will see the injuries you inflict and therefore serious problems. Here you can see [he refers to the slide] an overview over the repository configuration and the problems for both of the clay rocks.' After a short break he continues […] (Excerpt of a protocol based on participant observation of the first Conference on Sub-Areas, February 2021, i.o. German, translated by Sally Whitton).

In this statement, the host rock (clay stone) is framed as a naturally intact entity with special qualities that will only be injured by human intervention and therefore by the project of disposing of HLW and building a repository site that actively emits radiation and thus contaminates the materials surrounding it and brings in heat. Hereafter, clay stone is not a suitable host rock for HLW per se. Furthermore, it is turned into a host rock in order to bear and to endure this waste. In this way, the perspective is turned away from HLW as a problem for a human-related society: it is more marked as a problem for the clay stone and therefore for the environment or even nature itself. To explain it in a more metaphorical way, the material has to bear the imposed task to serve as a host for an uninvited guest. The consequence of this material-sensitive perspective is not only to focus on the suitability of host rocks in a one-sided way, but also to focus on the 'injuries you [humans bringing in the waste] inflict'. From this point of view, the suitability of the sociotechnical construction of the repository to the particular host rock becomes a central aspect: how far can injuries of the host rock be mitigated? How is the rock able to endure 'injuries' and 'attacks' in the 'best possible way'? Here, geology is not only addressed as a potentially suitable resource for a sociotechnical system. It is also reflected as a sociogeological collaboration in its own right, a collaboration in which vulnerable and fragile clay rock is forced to work for humans and their plans of constructing a disposal for HLW. Hereafter, the sociogeological collaboration between nature and humans is not only performed as a functional scenario dominated by humans. It rather emerges as a partnership of convenience or better: the injured clay rock is forced to become a partner in crime by joining the dirty mission of disposing of a critical toxic object. From this perspective, the deep disposal for HLW is a problem not only for humans, but also for the clay rock, even if it provides 'unbelievably good qualities' (see excerpt). In a certain way, geological formations, and therefore nature, are addressed as a vulnerable and *unruly collaborator* that refuse to follow a function (serving as a host rock) defined by humans. They rather integrate new challenges, problems and special requirements according to the material's ability to endure this forced collaboration.

3.2 MATERIALS AS SAMPLES: STUDYING THE BEHAVIOR OF PLUTONIUM

In autumn 2021 I had the opportunity to visit a nuclear chemical laboratory located at a German university in which projects are carried out in the context of nuclear safety research and deep disposal development. In this field I could observe collaborations between materials and humans on a practical level referring to experimental settings in which scientists investigate different materials and their qualities to retain radionuclides as components of HLW, for instance with regard to plutonium. This section will provide several insights into the practical research on interactions and migrations of plutonium as 'a major contributor to the radiotoxicity in a long-term nuclear waste repository' (Schönenbach et al. 2021). One great challenge the researchers face is developing sensitive methods in order to become able to observe and to interpret the behavior of radionuclides within various materials as technical, geotechnical and geological barriers. This material behavior or action is not perceivable by the human eye: technical solutions must be found to make it visible and measurable. For this purpose, nuclear chemists in this laboratory utilize means of mass spectrometry, or more precisely time-of-flight secondary ion mass spectrometry (TOF-SIMS), in combination with the more selective and sensitive method of resonant laser secondary neutral mass spectrometry (Laser-SNMS) with the aim to develop innovative methods for analyzing the behavior of plutonium, for instance. The combination of these two different types of mass spectrometry is used, for instance, to analyze surfaces of cement as a technical barrier and of bentonite as a geotechnical barrier and also to investigate heterogeneous materials, such as clay rock, for qualities to serve as a geological barrier.

The time-of-flight mass spectrometer (TOF-MS) (see Figure 4) is used for different experiments in the context of SIMS. In a very abbreviated form, this procedure operates in the following manner: A surface of a previously prepared or in a certain way radioactively contaminated sample (for instance, a slide of clay rock prepared with plutonium 239) is exposed to a primary ion ray in order to produce secondary ions. The detached ions are transported to a detector and separated during this time of flight according to their mass to charge ratio. Two types of experiments can be differentiated: the distribution of radionuclides *on the surface* of the sample is investigated with a focus on sorption (or in the simplifying words of a nuclear chemists talking to me as an ethnographer educated in sociology and not in chemistry, 'how much plutonium sticks to which

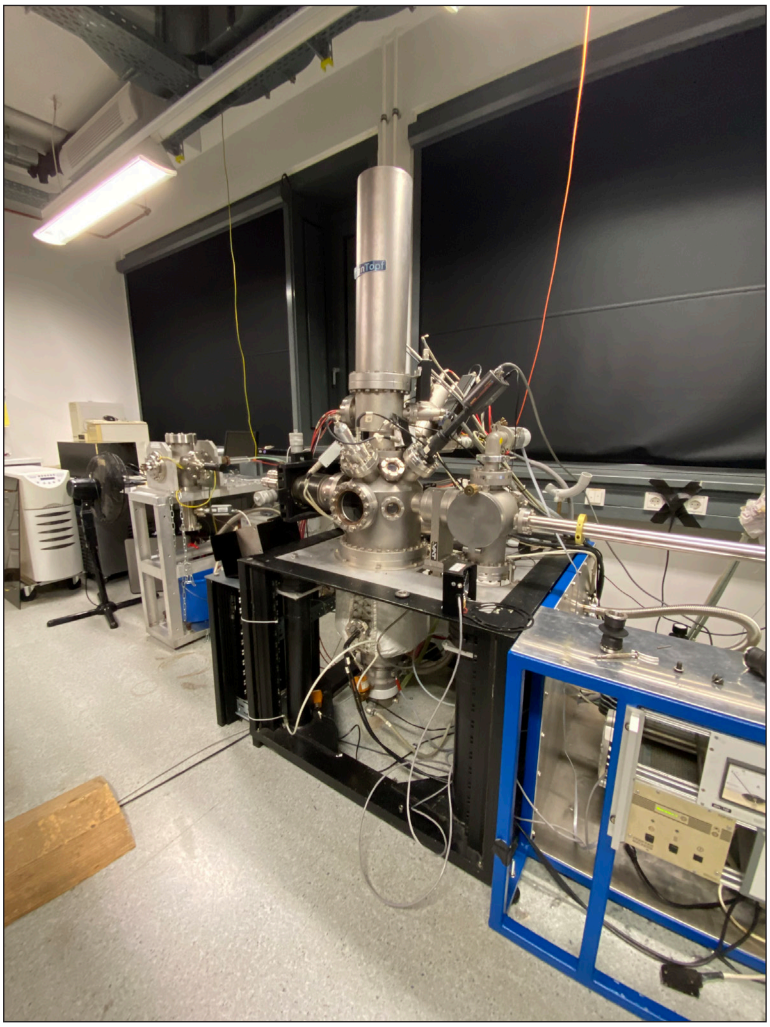

Figure 4 Photo of a time-of-flight mass spectrometry in a nuclear chemical laboratory (TOF-MS). Source: Christiane Schürkmann.

components'); the migration of radionuclides *inside the sample* is in the center of the analysis in diffusion experiments. Scientists working with such methods exercise caution due to a reflexive attitude toward the capacities and error susceptibility of SIMS with regard to the possibility of so-called matrix effects caused by the procedure itself. TOF-SIMS and Laser-SNMS then provide data in the form of mass spectrograms and images that become a resource for the scientists' interpretations, accompanied by educated guesses in order to identify the behavior of relevant components based on their measured masses.

Within such experimental settings, geological formations and their materiality do not appear as nature far away from humans. Rather, they are translated into material samples becoming preparable and ready for use in the laboratory practice (Knorr Cetina 1999: 26ff; Latour 1995). In this way, materials that are relevant for repositories by providing barrier effects get involved in sociomaterial collaborations (here, in scientific practices related to TOF-MS, lasers, detectors, computers, software and scientists). Therefore, fragments of rocks, such as clay rock, are brought to the surface, sent to the scientific institutions and prepared to become a resource for different experiments. They are cut into slides or pieces and brought in contact with radionuclides, such as plutonium as one relevant component of HLW. The intentional contamination of the produced samples with radionuclides simulates the leakage of radionuclides over time. By simulating ageing processes of the used materials (for instance by changing the ph value of cement) it is possible to generate a scenario in which the used material sample might be hundreds of years old. Karin Knorr Cetina (1999: 43) has argued, 'Laboratories recast objects of investigation by inserting them into new temporal and territorial regimes'. Here, the project of long-term nuclear waste management and disposing of HLW in deep geological formations is transferred into scientific laboratory experiments located in the present with the aim of getting closer to a far-away future by analyzing material behavior on a level of micro- and nanometers. But even the laboratory practice produces its own materials by transforming nature (geological formations) into explorable artifacts in order to create 'epistemic objects' (Rheinberger 1997), scientists working with these materials sensitively acknowledge their fragility, dynamics and complexity, referring to their state of being pristine. The following excerpt based on an ethnographic protocol might illustrate this sensitivity.

> After a few minutes, L. returns holding a fragment of clay rock in his hands that is wrapped in plastic. His colleague F. takes a pair of disposable gloves from a box while saying: 'In many chemical laboratories it is possible to work without gloves. We actually always work with gloves. Here (pointing in the direction of the fragment of clay rock), this shouldn't get greasy.' He further explains that clay is a layered silicate with a very heterogenous structure – he says: 'At one point it is this way, a few units besides it already looks very different'. He continues: 'It is also important to use them under anaerobic conditions, they should not get in contact with oxygen' (Excerpt of a protocol based on participant observation in a nuclear chemical laboratory at a German university, September 2021, i.o. German, translated by Sally Whitton).

Following the everyday practice of wearing gloves in the laboratory in combination with F.'s statement, disposable gloves not only are used to protect the scientists against alpha radiation of the used plutonium, but also are rather primarily relevant for keeping the materials clean—materials that will be used as samples for experiments. Such samples should stay untouched by humans who could contaminate them with grease from their touch and therefore influence their qualities, which in turn might lead to mistakes in the context of the experimental arrangement. With regard to their natural sources, these materials furthermore may not get in contact with air in the sense of elements of a sphere 'they do not know'. This means to handle them under anaerobic conditions in order to simulate their original habitat or 'dwelling' (Ingold 1993): they exist in depths where no oxygen or, more generally, air can be found. Such protection practices might be characterized in the sense of 'purification' (Latour 1993: 14): a non-human-produced and therefore natural material (here clay rock) is integrated into an experimental setting including humans and their technology (the laboratory practice with its machines, technical devices and scientists), but the two spheres should not get mixed in an uncontrolled way in order to create an epistemic object. Technology and scientists collaborate with geological material that has to be preserved in its natural conditions. The following illustration visualizes this alliance of sociomaterial collaborations in the laboratory.

In the context of this experimental setting in the laboratory, humans, technology and nature are collaborating united by the joint task of creating an epistemic object by investigating the migration of radionuclides on material surfaces in the context of developing deep disposals. Even material classified as natural has been removed from its natural surroundings and is manipulated and prepared to become usable as a material sample for experiments, its natural state is protected with respect to preserving its qualities, dynamics and structures in order to be able to approximate and represent (Coopmans et al. 2014; Lynch & Woolgar 1988) real conditions inside the further repository. This also includes prudence and a careful treatment of the used materials. It might be stated that the laboratory customizes not only its materials, but also its practices to the affordances of the used materials, here with regard to their natural origin. In this way, even in such a highly artificial setting, nature becomes addressable as a sphere of collaboration beside humans and technology.

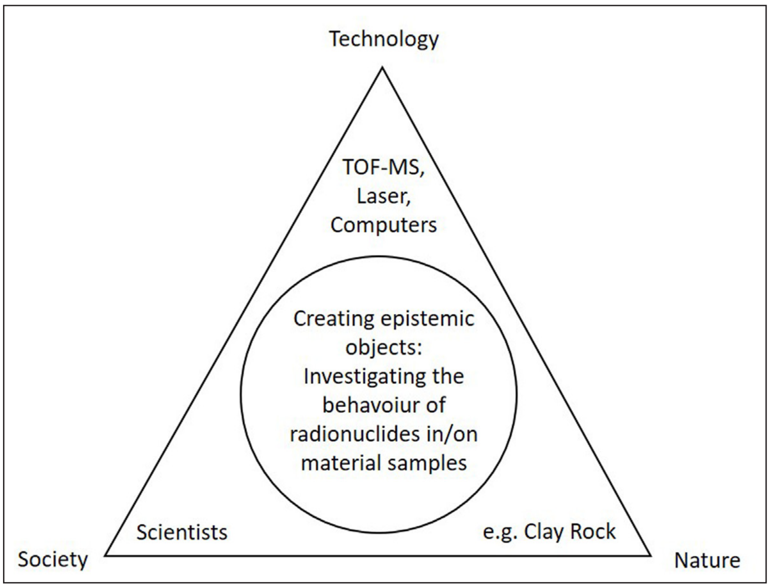

Figure 5 Three spheres of collaboration to investigate the behavior of radionuclides. Source: Christiane Schürkmann.

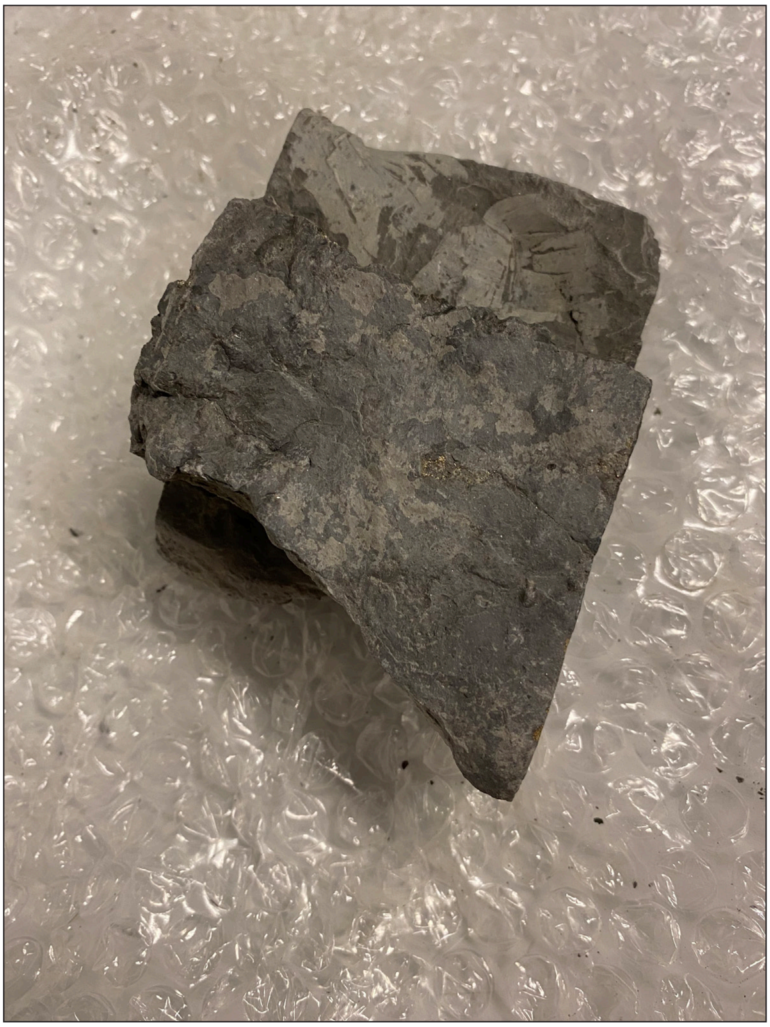

Figure 6 Photo of a clump of clay rock imported into a German nuclear chemical laboratory. Source: Christiane Schürkmann.

4. CONCLUSION

The article provides a sociomaterial perspective on nuclear waste management by combining the investigation of sociotechnical with geotechnical relationships and therefore taking into account sociogeological relationships in a triadic alliance of collaboration in which society, technology and nature are assembled. From such a perspective, nuclear waste management will be more than technical, social or societal and, therefore, more than a sociotechnical task if we consider the dominant role of geological formations classified as nature in developing and locating sites for deep disposal. In the field of nuclear waste management, geological formations are not addressed as technical but rather as natural in the sense of a non-human sphere, while technology is characterized as a product of humans or human-related societies, respectively. In this way, nuclear waste management can be described as a complex of *socio-, techno- and geo-logics* entangled in a triadic system of sociomaterial collaborations.

From such a perspective, nature (here, materialized in rock formations) becomes relevant as a further, and at the same time central, collaborative sphere. The identified spheres characterize the assumptions of the field itself, including its participants. With regard to nuclear waste management, these spheres are premised on field-immanent differentiations between a human-related society focusing on procedures, especially with regard to legislation, participation and legitimation, a human- and material-related technology as hybrid functional creations and constructions and a material-related nature (here, geological formations) in their attributed provided long-term-stability. The integration of nature enables studies of waste management to investigate relationships between societal procedures, technical developments and, depending on the particular fields of investigation (here, nuclear waste management), geological, chemical, biological or physical activities collaboratively with natural scientific knowledge productions. While sociotechnical collaborations are already the focus of social scientific research on nuclear waste management and geotechnical collaborations are intensively investigated by the natural sciences, the suggested sociomaterial perspective unfolds a ‘third knowledge space between nature and society’ (Bogusz & Holtappels 2021) by opening up a further field of research that centers around relationships between societies and nature, societies and bedrocks and, therefore, sociogeological relationships (here, in the sense of sociogeological collaborations referring to the task of long-term disposal of HLW).

With a view on challenges of nuclear waste management, the potential for collaborating with nature, or more concretely, with geological formations, lies in the necessity of operating with time scales beyond social, technical and sociotechnical orders. While technology is always embedded in and dependent on situated states of knowledge with several changes and dynamics, geological formations are attributed as stable manifestations by societies. As the empirical sections have illustrated, they are addressed as *bedrocks of hope* and are prominently integrated into laws as paths based on geoscientific knowledge. They are also addressed in their fragility as epistemic objects of investigations and in their vulnerability and distinctiveness in scientific lectures apart from single-sided reductive functional and exploiting views. With respect to the ethnographical insights into the scientific practice in a nuclear chemical laboratory, furthermore, it becomes obvious that materials taken from their natural (here, geological) habitat implement their own dynamics and requirements not only with regard to future scenarios of repositories but also to the epistemic practice itself. They are transformed into samples used for experiments in the context of studying their behavior in interaction with released radionuclides in order to forecast far away futures in the sense of 'deep time reckoning' (Ialenti 2020) and long-term designs for *posthuman vaults*. They become the fundament for vaults in which natural materials will serve as protective shields even if distant future generations will no longer be operators of such repositories and even if technical barriers will no longer retain the implemented active waste in motion. In this way, nature (here, in form of geological formations) is addressed as a compensator to countervail potential sociotechnical shortcomings and uncertainties.

With regard to the field of nuclear waste management and the development of deep disposals, it might be stated that from such a sociomaterial perspective nature is not only a passive environment for sociotechnical interventions contaminated and polluted by anthropogenic waste productions. Furthermore, it is not reducible to an extension or a prothesis of a produced sociotechnical system. Nevertheless, nature becomes visible as an unruly sphere of purification we relate to in multiple ways in order to separate our waste from ourselves. In the case of nuclear waste management, it is addressed as a thick and long-living collaborator to countervail possible shortcomings of developed sociotechnical systems in order to create and design long-term perspectives beyond social orders, political periods and dynamic technical developments.

NOTE

1 At the end of the twentieth century the question of how to include nature in sociological approaches had increasingly been discussed accompanied by criticizing constructivist positions, which tend to reduce nature to a human-centered cultural and social construction (e.g., Grundmann & Stehr 2000; Woodgate & Redclift 1998).

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COMPETING INTERESTS

The author has no competing interests to declare.

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