Deep borehole disposal of nuclear waste: trust, cost and social acceptability

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Abstract

Globally, radioactive waste governance has been subject to a participatory-deliberative turn. Increasing the opportunities for public involvement is presented as a means to build trust and to alleviate siting conflicts over facility construction. However, a move towards community partnership and voluntarism in site selection belies a lack of social control over technology choice, given the oft-repeated claim of a settled global scientific consensus on the safety and efficacy of waste disposal in a mined geological disposal facility (GDF) 450-800m below the surface. Consensus on the GDF concept is critiqued as a form of 'sticky knowledge' and path dependency within a socio-technical regime that began in the 1960s to the exclusion of alternatives. One contemporary alternative is the deep borehole disposal (DBD) concept. DBD emplaces spent fuel, plutonium or higher-activity wastes in boreholes to a depth 5km below the surface. In this paper DBD is subject to socio-technical analysis extending to six inter-related considerations concerning: *cost, land use, decision-making scale, trust, geographic distribution and temporality.* DBD is presented as a preferred solution to a GDF because it ameliorates the challenges associated with inflexible megaproject development–project size and scale, timing and cost over-runs limit the social acceptability of mined repositories at the community scale. DBD, by contrast, is an incremental technology strategy. A DBD-focused solution lowers public costs and decision-thresholds, localizes waste disposal by reducing transportation, and shortens the timeframe from decision-to-implementation. Together these factors encourage communities to take an active role in the decision-process, maintaining "vigilant mistrust" and accountability in ways that are not possible for a multi-generational, national-scale GDF. DBD is therefore proffered as a means to improve the overall social acceptability of higher activity radioactive waste disposal siting processes.

Keywords

Radioactive waste management, deep borehole disposal, incrementalism, vigilant mistrust, socio-technical analysis

Introduction

The long-term management of radioactive wastes is a 'wicked' and intractable policy problem for many nuclear energy-producing countries. Policy authorities have sought to ameliorate social conflict within radioactive waste governance by implementing public engagement and voluntary site selection processes to build community trust, social acceptability and public accountability. The participatory turn in radioactive waste governance is now an institutionalised norm of decision-making (Chilvers 2007; Di Nucci and Brunnengräber 2019; Cotton 2017). However, as Ramana (2018) argues, the development of long-term solutions for managing the most highly radioactive products – spent fuel and high level waste (hereafter HLW)– remain elusive. Although technical actors and institutions have endorsed deep geological disposal as the preferred solution to this problem, significant uncertainties about the long-term performance of waste packages within geological repositories remain; and evidence of failures and accidents at pilot facilities have eroded public trust in these solutions. The persistent challenges of complexity, residual risk and perpetual uncertainty (Landström and Bergmans 2015) pervade nuclear waste governance for such a high cost "megaproject" approach. Moreover, the emergent scientific consensus on deep geological disposal as the preferred technological option has "closed down" public deliberation on the *socio-technical* nature of radioactive waste management solutions (see for example Stirling 2004; Lehtonen 2010), and has steered deliberative processes towards issues of geography, environmental justice and governance within planning and construction of deep geological disposal facility programmes (Cotton 2018; Krütli et al. 2012; Jenkins and Taebi 2019). This paper therefore attempts to reopen policy dialogue on technology alternatives–specifically the deep borehole disposal (hereafter DBD) concept that has re-emerged as a feasible socio-technical solution in recent years. The paper discusses DBD through socio-technical analysis and the capacity of the technology to disrupt the settled consensus on the deep geological disposal of higher-activity radioactive wastes through mined repository construction (referred to as a geological disposal facility– hereafter GDF).

The analysis has three parts. Firstly, the limitations of resolving the radioactive waste facility siting contestation through mechanisms to improve public participation and foster public trust in GDF siting are assessed. Secondly, the settled scientific consensus on geological disposal in mined repositories is critiqued through socio-technical analysis. Thirdly, a normative argument is presented favoring the deep borehole disposal (DBD) to ameliorate the limitations of a centralised GDF siting process, discussed in terms of six inter-related considerations: *cost, land use, decision-making scale, trust, geographic distribution and temporality*. The paper concludes with discussion of the desirable features and limitations of a DBD-focused waste policy platform.

The limitations of the participation in radioactive waste governance

The issue of radioactive waste management has shifted from a solely technical and engineering problem, to one that incorporates assessment of social and institutional values relating to risk communication, trust, aesthetics, ethics, perceptions of safety and environmental justice (Di Nucci and Brunnengräber 2019). Nuclear waste governance was traditionally dominated by assessment of risk and risk-mitigation in transport, package design, and in the engineered and geological barriers to radionuclide migration. Since its inception the nuclear sector promulgated a policy *framing,* articulated by Teräväinen, Lehtonen, and Martiskainen (2011), as a 'technology-and-industry-know-best' model. Policy-making consequently became largely *technocratic* across Europe and North America (Espluga et al. 2018; Malone 1991; Krütli et al. 2010). The technocratic approach (sometimes referred to as *decide-announce-defend*) commonly stimulated social conflict and public distrust in radioactive waste management organizations (RWMOs), characterized by place-protective action (i.e. protest, direct action and political campaigning) amongst affected residents, community activists and local government to halt planning and construction activities within localities; the upshot of which has been near-universal planning failure, disruption or delay (Lawless, Whitton, and Poppeliers 2008; Whitton et al. 2015; Lidskog 1992; Blowers 2016).

Decide-announce-defend has been criticized as a type of institutional arrogance (Löfstedt 1996; Atherton and Poole 2001) that leads to a pervasive *distrustful attitude* (Saunders and Thornhill 2004) within affected communities targeted for facility siting, which subsequently stimulates community contestation. Internationally, RWM policy authorities have responded to instances of social conflict by institutionalizing voluntarist site selection, public participation and shared governance through analytic-deliberative decision-making processes involving citizen representatives and civil-society stakeholders (Chilvers and Burgess 2008; Di Nucci and Brunnengräber 2019; Sundqvist and Elam 2010; Espluga et al. 2018) in order to rebuild community *trust as a process* (Möllering 2006) and subsequently build social legitimacy and community acceptance of waste facility proposals (Choi 2018; Carter 2015), and to avoid expensive policy failures such as those associated with the Yucca Mountain project in Nevada, or the rock characterization facility in a site near to Sellafield in the northwest of England.

Participation provides social scrutiny from engaged citizens and the evaluation of diverse values in policy design. However, even when participation is considered successful–in the sense of providing fair, competent and deliberative dialogue, and adequate public evaluation of policy options (see for example Charnley-Parry et al. 2017; Renn and Webler 1995), issues of cost, long-term safety over multi-millennial timeframes, stringency of regulatory approval, and the democratic processes of procedural fairness surrounding planning consent, have slowed or stalled action to construct GDFs in countries including (but not limited to) the USA, UK, France, Germany, Switzerland and Belgium (see for example Brunnengräber et al. 2018). Even in Sweden and Finland, two countries that have made significant progress in their respective siting processes (Lidskog 2004; Lehtonen 2010; Choi 2018); construction projects have been lengthier, more costly and politically uncertain than anticipated. Moreover, even when Swedish or Finnish participatory decision-making approaches are emulated, this is no guarantee of policy, planning and siting success, because the institutional context of community distrust of scientific or planning authorities and the consequent lack of deference towards scientific expertise (Bouchard 2016) (RWMOs specifically) differs from country-to-country and community-to-community. For example, the United Kingdom implemented a voluntary partnership process on GDF siting through a 'right to participate' that emulated Scandinavian voluntarist approaches, though this ended in rejection of a move towards further site investigation when proposals were voted down by Cumbria Country Council (Cotton 2018; Blowers 2014; DECC 2013). In Cumbria, histories of nuclear waste siting processes shape contemporary trust relationships and the interactions between local authorities and radioactive waste management organisations (RWMOs). The RWMO might have changed (in the UK case from the private company Nirex in the 1980s and 1990s, towards public bodies – the Nuclear Decommissioning Authority- and public private partnerships – i.e. Radioactive Waste Management Ltd), but the social memory of previous technocratic siting procedures remains a barrier to partnership relations and voluntary site selection (Bickerstaff 2012) because it fosters distrust in 'new authorities' tasked with building community relations in advance of site selection. Under such circumstance openness and participation can, counter-intuitively, build mistrust amongst participating communities (Laurian 2009).

Greater participation does not automatically lead to fairer outcomes for affected communities either. Reference to participation within siting processes for controversial energy technologies can often be a form of "deliberative speak" (Hindmarsh and Matthews 2008) – a policy rhetoric that emphasizes open communication without backing this up with citizen control over technology choice. Even when participatory methods are incorporated into siting process , they may not fully capture the complexity of diverse perspectives. Stakeholder responses to radiological risks, facility design and siting processes are socio-culturally and psychologically complex, and geographically and temporally dynamic. Successful RWM governance is fundamentally a relationship-building process; one that that takes time and sustained public resource. One off, or short-term participatory processes or consultation measures designed to gauge opinion or communicate technical information (e.g. opinion surveys, focus groups or exhibitions) are usually insufficient to build trust relationships; particularly given the long timeframes for facility development and construction which leave host communities grappling with persistent decision-making complexity, uncertainty and residual risk long after a decision has been made (Landström and Bergmans 2015). Given the psycho-social complexities of RWM governance, a deeper *socio-technical* understanding is necessary (Landström and Bergmans 2015) – whereby safety assessment, risk characterization and engineering design operate in concert with socio-psychological and ethical factors, such that decision-making becomes a cohesive package of assessment (Flüeler 2006; Landström and Bergmans 2015; Bergmans et al. 2015). A socio-technical approach may be facilitated by, but is not synonymous with, participatory processes.

The settled consensus on the geological disposal of radioactive wastes

As Bergmans et al. (2015) note, participatory-deliberative RWM heavily emphasizes the "social" but is generally poor at integrating the "technical". With the notable exception of the UK's Committee on Radioactive Waste Management's governance of the Managing Radioactive Waste Safely program (MRWS 2003-2007) which included participatory assessment of the technical options of radioactive waste management (Wallis 2008), for most historic and contemporary RWM policies it is technical expertise that is drawn upon to define the problem and its potential technological solutions. Citizen-stakeholder actors are more commonly brought in to assess and influence the *geography* and *social acceptability* of the proposed solution (i.e., where a facility is placed and the conditions under which a community will accept this placement). As Gregson (2012) argues, participation has reframed radioactive waste as a matter of *human-centred politics* – how to manage waste has once more become the preserve of expert technical knowledge, leaving community actors to coalesce around how to site a future GDF, due to a settled scientific consensus that this provides the "best and safest solution" (Swift 2017).

Consensus on the GDF 'gold standard' is enshrined in the shared policy platforms of the EU. The 2009 Vision Document of the Euratom-funded Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP), by the European Commission's Joint Research Centre and also the Radioactive Waste Management Committee (RWMC) of the OECD's Nuclear Energy Agency (NEA) state that *geological disposal* in a mined repository represents the best overall safety case for higher activity wastes (Falck 2009). The consensus declared by the Joint Research Centre (JRC) and other key scientific bodies is primarily based upon 'road maps' towards implementing the GDF approach in Finland and Sweden (Falck 2009; European Commission 2009). As Wallace (2010) argues, the JRC favored the IGD-TP because assessments over several decades had considered alternatives – e.g. launching into space, ocean dumping, disposal under continental glaciers, sub-seabed disposal and long-term supervised storage–but found poorer environmental and public health outcomes when compared to geological disposal. Though the aforementioned UK MRWS program did seriously consider alternatives to deep geological disposal it is notable that CoRWM similarly concluded that safe interim storage and eventual geological disposal presented the best of all currently available options at the time of assessment (CoRWM 2006).

The settled consensus on a GDF approach is relevant to a broader understanding of the networks of trust built between industry, academic and public scientific institutions close down technology assessment processes such that one technology concept is agreed to be the agreed outcome. As Stirling (2008) argues, the discursive deference towards participation is countered by linear, scientistic and deterministic approaches to technology choice. Consensus raises questions about the role of trust in the so-called science-policy interface. Trust between nuclear knowledge producers (industry/academic scientists), knowledge brokers (lobbyists, research councils and consultancies) and knowledge users (policymakers, RWMOs) on the GDF concept is clearly established–they have, to adopt Hotes and Opgenoorth's (2014) terminology, struck a balance between mutual trust and control mechanisms such that a settled consensus has emerged and conflict between scientific policymaking networks is negligible.

Settled scientific and technical consensus encourages "low friction" policy movement on key environmental management issues across multiple scales, with climate change being the most obvious example (Pearce et al. 2017). However, it is important, when solutions to environmental problems are proposed, that we understand that the network of trust within a science-policy network can create new risks (Lacey et al. 2018). Providing greater input into technology choice from 'the outside' (i.e. mistrustful citizens) who are not embedded in nuclear science knowledge networks) provides an element of *civic vigilance* (Laurian 2009) through which citizen-stakeholders can hold scientific elites to account. Indeed, in circumstances of high levels of public trust in scientific elite, such trust implies willingness to delegate power to technocratic institutions and thus acquiesce to settled consensus without further social scrutiny (Tait 2011; Lehtonen and De Carlo 2019; Lehtonen, Cotton, and Kasperski 2021). Maintaining an "open" (Stirling 2008) and ongoing technology assessment process through civic vigilance of the material politics of radioactive waste (see Gregson 2012) is therefore necessary to maintain social choice, political accountability and environmental justice.

Disrupting settled consensus on geological disposal requires both scientific and sociological critique, and mistrustful civic vigilance of RWM is proffered by outsider analysis of the GDF approach. Wallace (2010) notably raises several concerns. These include the risk that the copper or steel canisters in which spent nuclear fuel or high-level radioactive wastes are packaged might corrode more quickly than expected under high temperatures and that the build-up of gas pressure as a result of the corrosion of metals and the degradation of organic material might damage the engineered barriers providing a root for radionuclide migration; that the unidentified fractures or faults in host rock may lead to the release of radionuclides faster than expected; or that future glaciation or seismic activity (including man-made seismic activities such as those caused by hydraulic fracturing of rock for oil and gas exploration) could cause faulting of the rock and the penetration of surface water or permafrost. Wallace argues that consensus on the GDF concept is a means to achieve policy expediency on *siting*, and that broader examination of the potential drawbacks and alternative options has been lost. Indeed, many RWM experts in the engineering and physical sciences consider the problem of radioactive waste as simply one of social acceptability rather than of *technical* feasibility (North 1999), and so emphasis has shifted away from the development of new disposal/management concepts towards the political apparatus needed for the implementation of the GDF solution–the human-centred rather than material-centred politics that Gregson (2012) identifies.

Disrupting consensus – the deep borehole disposal concept

Research on the technical and scientific dimensions of RWM is extensive and alternatives to geological disposal in mined repositories have been a feature of the research landscape since the 1960s (see for example Saling 2018, for an up to date review). However, much less research funding, testing and political attention has been directed towards an alternative geological disposal approach termed *deep borehole disposal* (DBD) concept, which are considered here.

Though DBD has gained recent attention in the technical literatures on RWM disposal techniques (Beswick, Gibb, and Travis 2014), it is not, strictly speaking, new. As Brady et al. (2017) argue, disposal in deep boreholes may be more ready than disposal in mined geologic repositories because humans have greater experience operating small deep holes (i.e., boreholes) than big shallow holes (i.e., mines). In the 1950s a review of RWM techniques included discussion of injecting liquid HLW into boreholes (Hess et al., 1957), followed by the "very deep hole concept" (O'Brien et al., 1979). DBD concepts have remained under scientific scrutiny (Bates et al., 2014), though have been largely excluded from mainstream policy dialogue on RWM governance. The DBD concept involves the emplacement of small quantities of highly active radioactive wastes in boreholes up to 5km (3.1 miles) below the surface. There are multiple deep borehole disposal (DBD) concepts that cover a range of higher activity waste products. These include the disposal of surplus weapons-programme related plutonium, the disposal of vitrified HLW (immobilised in glass) or cemented wastes, the disposal of spent fuel assemblies, and the melting of host rock to encapsulate heat producing HLW (Bates et al. 2014)..

From a technical perspective, wastes would be stacked inside a drill casing (either fuel assemblies or vitrified glass canisters) and then lowered and emplaced, using off-the-shelf oilfield and geothermal drilling techniques, into the lower 1-2 km portion of a vertical borehole, followed by borehole sealing (Brady et al., 2009). Depending upon the waste stream, some contemporary DBD concepts involve using the heat from the spent fuel to melt the rock, holding it in place (CoRWM 2019). Well construction would likely use existing technology, as geothermal operations can create large diameter holes in crystalline rock (Polsky et al. 2008). The geologic environment and seal systems for the borehole are the primary barriers to prevent radionuclide migration back to the surface, and so shielding is reliant upon the thickness of the natural geological barrier. Groundwater salinity, the temperature and the rock stresses increase with depth whereas the hydraulic conductivity decreases. Therefore, at the proposed 5km depths, water movement is extremely low and the risk of radionuclide migration to surface water is negligible over timeframes exceeding 1 million years (Chapman and Gibb 2003; Beswick, Gibb, and Travis 2014).

From an environmental protection standpoint, DBD has a number of advantages. Conflicts between environmentalists and specific institutionalised distrust of RWMOs amongst citizen-stakeholder networks is rooted in *intergenerational equity* concerns that the safety of future generations is sacrificed when seeking expediency in siting waste products that result from nuclear-powered electricity that only benefits current generations (Cotton 2013; Shrader-Frechette 2000). Geological disposal has been critiqued on the grounds of intergenerational equity because this method of disposal necessitates societal stability to provide guardianship/stewardship of waste sites (Ahearne 2000; Brook 1997; Damveld and van-den-Berg 2002) against anthropogenic or natural changes to the geologic environment (i.e. intentional or unintentional intrusion, and geohazards such as seismic activity). Guardianship necessitates long-term monitoring of waste sites (Flüeler 2020; Landström and Bergmans 2015) and an effective governance/security response if adverse events arise (Macfarlane 2003; Lidskog 2004). To ensure long-term guardianship of waste sites, this in turn is based upon future society's ability to understand risk messages over multi-millennial timeframes (Jensen 1993; Nolin 1993). DBD ameliorates many of these intergenerational risk governance and equity concerns because wastes are emplaced far below oil and gas fields, mineral deposits or other potentially valuable natural resources (and are less likely to be accidentally disturbed). There is no facility to which a potential intruder might venture. Moreover, the geologic environment is more stable and the movement of water slower than at shallower depths. As Kristopher Kuhlman, a hydro-geophysicist at Sandia National Laboratory states: "If we want to put waste where we'll never see it again… it should go at the bottom of a deep borehole." (cited in Voosen 2016).

Despite these potential benefits, DBD has had comparatively little traction within RWM policy communities. In 2006 when the UK CoRWM gave recommendations to government, despite a commitment to deep geological disposal in mined facilities, it included one recommendation pertaining to DBD (CoRWM 2006, 11):

> Recommendation 5: The commitment to ensuring flexibility in decision making should leave open the possibility that other long-term management options (for example, borehole disposal) could emerge as practical alternatives. Developments in alternative management options should be actively pursued through monitoring of and/or participation in national or international R&D programmes.

The recommendation to "leave open" the option of DBD is significant (it is notable that CoRWM shows some recent support for the option, though they highlight that numerous technical design challenges remain: CoRWM 2019). Though as Chapman (2019) argues, RWMOs have largely dismissed DBD due to a lack of practical experience of borehole research when compared to the decades of in situ testing associated with conventional GDFs. The reason for this is grounded in the socio-technical history of RWM–at the point at which nuclear waste became a salient policy issue (generalized here as around the late 1960s and early 1970s in France, Germany, the UK and the USA), contemporary drilling and emplacement technology was not sufficiently advanced to make DBD feasible – thus funding, research and policy effort was geared towards the GDF concept instead (Gibb 1999). This is an example of *socio-technical path dependency* - technical authorities within the science-policy networks of the nuclear sector affect change less than might be expected and thus constrain technological advancement (Suddaby, Foster, and Mills 2014). Path dependency is often driven by bounded rationality (in which decision-makers seek satisfactory rather than an optimal solutions) (Simon 1959), cautious decision-making and failure to learn from policy mistakes, and the cost implications of larger-scale changes to an established system (Peters, Pierre, and King 2005). Path dependency can create *lock-in* within a technological 'regime' – such that technological research and advancement is directed through the belief systems of engineers - not just of *how* to solve the problem of RWM, but indeed of *what* problems there are to solve (Nelson and Winter 1977). Under conditions of technocratic governance in RWM during the 1970s and 1980s (as briefly discussed above), technological transformations became 'sticky' (Clausen, Göll, and Tappeser 2017) in the sense that they were driven by existing expertise, routines, and social/behavioural norms within the industry, rather than by innovation in socio-technical system design. The sticky knowledge problem of an established science-policy network that favours deep geological disposal therefore leads to path dependency - the GDF concept 'flourished' whilst the DBD concept remained a niche engineering concern (more of less confined to research at Sheffield University, MIT, and most recently at Sandia National Laboratories: Driscoll et al. 2012). However, recent drilling technology advances in other sectors (notably within the oil and gas sector as a result of deep-sea drilling and ‘unconventional’ drilling onshore) have since turned DBD into a feasible option using adaptations to current technology. The question of why this is not explored further by RWMOs can therefore be explained by path dependency and knowledge stickiness – the GDF may not, in fact, be “the best” solution for higher activity wastes, but there is little civil-society policy scrutiny of the DBD alternative.

The socio-technical dimensions of deep borehole disposal

The argument presented here is that as DBD has become a plausible technology option for RWMOs. It is an approach that requires greater social scientific as well as technical scrutiny, as an option to complement or replace either existing technology choice for geological disposal in mined repositories or interim (or permanent) surface storage of waste materials. The socio-technical dimensions of the DBD concept are discussed in relation to six key features of RWM governance: *cost, land use, decision-making scale, trust, geographic distribution and temporality*. These are then used to structure a discussion of the potential advantages and limitations of the DBD concept in contemporary RWM policy.

The costs associated with a GDF are considerable. For example, in the United Kingdom the Nuclear Decommissioning Authority (NDA) calculates a fixed cost of £4.401 billion for the construction of the GDF plus a cost of £398,300 per canister of spent nuclear fuel or HLW (Sellafield Ltd. and Nuclear Decommissioning Authority 2020). The cost estimate is based upon the assumptions that a GDF is constructed at 650m depth in a high strength rock, with no restriction on land footprint, and excludes the costs of reprocessing (the UK’s nuclear fuel reprocessing is a the time of writing on the ‘last lap’ of Magnox reprocessing to begin reducing the final 1% (538 tonnes) of fuel left since reprocessing began in 1964 of packaging of wastes (including the cost of the waste container) and of the transport of wastes to the GDF (ibid.). The NDA’s scenario assumes that the total land footprint of a GDF accommodating spent nuclear fuel alongside all the other legacy higher activity wastes, would be just over 5 km^2 and the disposal costs indicate a total undiscounted GDF cost of £12.3 billion (NDA 2012). Similarly, until the disposal policy was halted under the Obama Administration, the estimated cost of the Yucca Mountain geological disposal concept in Nevada was $96.2 billion in 2007 dollars (World Nuclear News 2008). It is in this sense that the GDF can be understood as an *inflexible technological system* (Collingridge 1980): a high-stakes, high-cost project that requires specialist supporting infrastructure. The GDF as an inflexible technology of this size is a megaproject–one that not only carries a multi-billion pound/dollar cost, but takes decades to build, requires multiple scales of agreement and cooperation from heterogenous and often conflicting public and private interests, and will impact upon millions of people either directly or indirectly (Flyvbjerg, Bruzelius, and Rothengatter 2003; Lehtonen, Joly, and Aparicio 2016; Genus 2000). DBD, by contrast, uses a small area of land–the footprint of an individual borehole is tiny (less than 1m). Gibb et al. (2012) use heat flow modelling high heat-generating waste to show that boreholes can be placed a few tens of metres apart and making multi-borehole arrays a possibility. The DBD programme could therefore involve a number of small sites with only one or a few boreholes each, such that individual nuclear power plants could dispose of their own wastes on or near site (assuming that there is suitable geology nearby) (Beswick, Gibb, and Travis 2014). Such an approach would reduce environmental and public health risks associated with waste transportation, and is is much cheaper by comparison (circa $40 million per borehole with costs falling as drilling technology improves) (Arnold et al. 2011). It is estimated that entire Yucca Mountain spent fuel inventory could be emplaced in ~550 boreholes thus the potential cost and land footprint savings are significant (less than a tenth of the cost per unit of waste compared to a mined GDF) (Brady et al. 2017; Brady et al. 2009). It is in this way that one can conceptualize DBD as a flexible, incremental, or pay-as-you-go model. Inflexible technological systems create sociotechnical lock-in – by their very nature they are path dependent because the cost of reversing a decision involves considerable waste of public-private investment; DBD is favored precisely because it provides much needed flexibility to the policy process.

Due to the nature of the technology as both expensive, specialized, and constructed and operated over multigenerational timeframes, it becomes deeply challenging for local governmental administrations to accept the political risks associated with high capital intensity projects like the GDF for their respective communities. This is, in part, related to the networks of trust that need to exist between scales of government. Local authorities need to trust central government authorities, while RWMOs and associated scientific and technical bodies have to trust that the uncertainties over impacts to the local economy, health and natural environment associated with radionuclide migration, transport and infrastructure impacts, the land footprint, and the potential stigmatization of the community as a 'waste dump' over decades can be ameliorated or compensated for. Moreover, communities must have institutional trust that agreements will be respected and honored in the future (and not changed to a system that is more coercive with a change of government, for example). Given the bounded rationality of local politicians and community partnerships which limits their capacity to make decisions under conditions of high environmental, political and financial risk and uncertainty, and the *scale* of the GDF decision, these factors become barriers to successful policy implementation (as seen in notable examples in the UK and USA discussed above). This leads to the second advantage of DBD, that by reducing the scale of decision-making around RWM, the larger problem (a national stockpile of wastes) is reduced to a series of smaller-step decisions based upon a site-by-site analysis of locally-produced waste volumes, local planning considerations and community engagement processes. In essence, it "re-localises" the risk within a local/regional governance frame (see for example Beck 2013). DBD does this by increasing the *incremental* nature of radioactive waste management decision-making that, in turn, scales down the political risk for communities and their representatives in such a way that would more likely lead to successful implementation of policy, planning, site selection and community acceptance (Cotton 2017), and by reducing the movement of waste packages across space towards a centralized GDF facility..

The current and expected construction and development costs associated with the DBD concept are much lower than for a GDF; but there are also other factors of the social control of technology that make it a desirable option to both radioactive waste management organisations seeking to site a waste facility, and to communities that host them. One major problem associated with the GDF concerns place-based differentiation of risk messaging and risk tolerance – a problem sometimes described as an insider-outsider problem (see for example Baxter 2009) when it comes to accepting waste within host communities. Most national programmes for the disposal of spent fuel are centralised, usually to a single location; or else are multi-national in scope involving waste transportation across borders to a single site (Jenkins and Taebi 2019). The reasons for centralisation are to capture the economies of scale – one large GDF is cheaper to build than two (or more) smaller ones, and to minimise post-closure hazards by reducing the range of potentially affected sites once the repository is sealed. However, given the distributed nature of the waste problem across multiple regions (for countries with large and dispersed nuclear power programs), centralised RWM has been politically controversial. For example, networks of co-ordinated direct-action campaigns against RWMOs in the 1980s and 1990s emerged due to the threat of exporting English wastes to a centralised Scottish GDF (the Scottish Campaign to Resist the Atomic Menace - SCRAM: Blowers, Lowry, and Solomon 1991). We see this effect and other spatial justice concerns raised in other cross-border/multinational waste repository disputes (Rabe et al. 1994; Jenkins and Taebi 2019). As assessment of the so-called not in my backyard (NIMBY) phenomenon suggests (Welsh 1993; van der Horst 2007; Schively 2007) there is a socio-psychological difference between a community motivated to deal with "its own" waste as a matter of environmental stewardship, and one motivated (or compelled) to accept "other people's" wastes. The former is a moral duty, and the latter is an supererogatory act – one that is good but not morally obligated; i.e. accepting elevated risks from an influx of waste is an act that is *more than is necessary*, when another course of action—involving less risk—would still be an acceptable (Heyd and David 1982; Hansson and Peterson 2001). The moral incentive for communities to accept waste is therefore different for centralised than for decentralised disposal plans. One of the challenges, therefore, for using a participatory approach towards planning for a centralised, national-scale megaproject such as GDF siting, is that democratic control of technology, community trust in RWMOS, place and cost are interwoven. Trust in democratic accountability and fair outcomes is grounded in the notion of a shared community interest. Politics (in particular that which relates to participatory-deliberative decision-making) is increasingly grounded in the language and thinking of the *civic* and the *social* (Williamson, Imbroscio, and Alperovitz 2014) and so decisions about technological risk must therefore be embedded in the context of families, neighbourhoods and communities if they are to be successful. Decision-making 'success' is therefore defined by the extent to which RWM governance can be captured within community or municipal politics (for example Krannich, Little, and Cramer 1993; Petersen 2001), as reflected in the move towards community partnership and voluntarism as 'normal' components of policy. However, centralising waste storage as a local solution to a national-scale (or indeed international-scale) problem stimulates conflict between multiple scales of decision-making governance which can lead to unjust outcomes (Cotton 2018) – a disparity between local-and-national that cannot be resolved simple by increasing the type and variety of public engagement methods used.

DBD is potentially advantageous to the process of *localising* RWM decision-making to the municipal/regional scale because it makes decentralised waste management feasible for higher activity wastes. This feasibility is a function of the technology and geological/hydrogeological nature of the disposal solution. DBD is relatively 'placeless'. GDF siting is only successful if there is hydro-geologically suitable host rock. In the first instance, this requires a desk-based assessment of the geological make-up of the host-rock, followed by site characterisation and testing. This can be scientifically controversial. For example, in the 1990s when the former RWMO NIREX investigated the Borrowdale Volcanic Group in West Cumbria, criticism was raised of the choice due to concerns over rock fractures that would allow water intrusion over relatively short timeframes (Nirex 1997; Stirling 1996). In the DBD concept waste canisters disposed at depths of 5 km are emplaced in crystalline rock; with the upper 3 km of the borehole filled with protective layers – first, of the steel casing, as well as concrete, crushed rock, bentonite, or asphalt to fill the borehole and isolate the waste package(s) from the biosphere over geological time. There is less reliance, therefore, upon host-rock suitability to ensure long-term environmental safety because the waste is emplaced deep in the brine-saturated zone far below aquifers in a geologic zone sown to have been isolated from the surface for exceedingly long times; its depth provides safety against inadvertent intrusion, earthquakes and near-surface perturbations (Muller et al. 2019). Moreover, at the 5km depths proposed, the only mechanism for radionuclides to reach the biosphere is through slow aqueous diffusion – a process that would (hypothetically) take millions of years (Freeze, Stein, and Brady 2019). This opens up a greater range of geographical locations suitable for borehole disposal when compared to a GDF. In political terms, these two facets are related. The DBD concept would allow communities that host stored spent fuel or HLW to dispose of their waste locally, for lower cost and over shorter timescales. As Chapman (2019) argues, DBD could form an attractive:

> "…'boutique' solution—handling small volumes of waste in one or two boreholes, at or close to the site of waste generation. Where this site is a major, historical nuclear legacy facility undergoing extensive remediation, then this approach seems potentially realistic."

As policy discourse theorists such as Hajer (2005) have shown, the technology allows the reframing of both the nature of the *problem* and the range of acceptable solutions within political discourse – it allows RWM governance to move away from a framing of "waste dumping" (for example: Blowers 2010) from the influx of "outsider wastes" through centralisation, to active local community social control and environmental stewardship through decentralisation and localisation. The impact of a change in framing on social acceptance could be tested empirically, and it would behove RWMOs to explore the social science of DBD concepts further at community/host site-scales.

The development and deployment of a GDF is a multi-generational project lasting long beyond the lifetimes of the communities that make a decision to host it (from scoping to closure >100 years Pescatore and Vári 2006; Department of Energy & Climate Change 2014). Conversely, the investigation requirements for rock at circa 5km-depth are much simpler. The DBD safety concept works with a dense, ancient, and highly isolated deep groundwater system that moves very slowly – it requires far less detailed characterization and assessment. Unlike a GDF, constructing a borehole, emplacing waste and sealing can therefore be done in 1-2 years, and a DBD facility does not need to remain operational until a further borehole is required – as Chapman (2019) states, these elements make the DBD concept suitable for modular operation through much shorter campaigns (i.e. the incremental, 'pay as you go' approach mentioned above).

Importantly, DBD can be implemented within a single electoral cycle (once the feasibility of the borehole concept, waste packaging design and safety assessment can be demonstrated – a nontrivial issue that requires further research and development), thus avoiding the not-in-my-term-of-office problem that plagues vital but long-range policy planning. In the context of promoting trust in RWM governance, *demonstratable* success – where a small number of waste packages are disposed of successfully within an "assessable" timeframe, is beneficial for promoting what is referred to as *vigilant mistrust* within host communities (Lehtonen and De Carlo 2019). If an RWMO can demonstrate successful implementation of a small-scale, modular DBD project, then this established a positive track-record, and moreover will allow post-implementation scrutiny amongst a network of "evaluators" across scientific institutions, central and local government policymakers, and community partnership organisations (Pinto 2013; Nutt 1983). This could, in turn, potentially generate support for future projects (whether this is further DBD or GDF projects) because the technology is then open to scrutiny through means of audit, assessment and regulation. The institutional distrust that communities have in RWMOs is wrapped up in future uncertainties surrounding the modelling of hypothetical risks for GDF. DBD, by contrast, moves the social assessment of RWM from hypothetical future uncertainties to active systems of monitoring and accountability for an *in-situ* waste disposal solution and subsequent auditing, and environmental assessment. This would reduce the need for community institutional trust in RWMOs based upon their promises of long-term safety, because rather than planning for a hypothetical future GDF, communities can monitor, evaluate and assess an existing waste solution as it is implemented. In short, they don't need to trust in a future solution, rather they can assess a contemporary one, monitor outcomes and assess adjustments – what Guston and Sarewitz (2002) term a 'real time technology assessment' that demonstrates, monitors and adjusts socio-technical policy options through an incremental approach, thus benefiting both environmental safety from long-term radioactive waste management implementation, and ensuring stronger procedural environmental justice for affected 'host' communities.

Conclusions

Radioactive waste management (RWM) governance *can* become fairer through processes of voluntarism and participatory-deliberative decision-making, though these facets alone do not guarantee environmental justice for affected communities, nor do they guarantee successful the siting of a centralized radioactive waste facility. There are a number of problems with the status quo. Firstly, decision-making over *technology choice* is closed-down by a global scientific consensus on the geological disposal facility (GDF) (a mined repository 450-800m below the surface) as the 'best option'. The GDF consensus is a form of sticky knowledge – it gained traction in research and development in the 1970s primarily because the drilling technology for DBD was not sufficiently advanced. The path dependency of expertise, technology and scientific testing for mined repositories has led to a belief that this is the safest option, to the exclusion of DBD from mainstream policy and R&D and so it remains a niche concern. However, given recent developments in deep borehole drilling and encasement from the oil and gas industry, the argument presented here is that it *should* now become part of the mainstream policy discussion, overcoming the lock-in within the GDF socio-technical regime. Secondly, the psychosocial dimensions of decision-making over risky megaprojects (including financial and socio-cultural, as well as environmental risks) are related to problems of decision-making scale, the centralization of waste, and the framing of such projects (and the communities that accept them) as dumps for other (outsider) people's waste. These dimensions should not be ignored, and the current GDF solution exacerbates these concerns.

The arguments presented are intended as a provocation, to spur technology assessment of DBD alternatives to the GDF, and "open up" technology choice. DBD does however, have limitations, and should not be understood as the panacea to all radioactive waste management problems. Though DBD has a number of desirable safety features from a socio-technical perspective, it is still a form of geological disposal, which remains controversial for many environmental advocacy actors irrespective of the depth of the emplacement (Voosen 2016). Public skepticism is a common feature of nuclear waste politics in part because citizen-stakeholders make decisions about geohazards in an information-poor environment (Rosenbaum and Culshaw 2003). The extent to which opposition groups would differentiate between temporal and spatial risk horizons for DBD compared to a GDF is a matter for further empirical social research, and it is worth exploring this dimension in future waste policy planning. The DBD concept is limited to only small-volume high-activity wastes, and so for large producers of intermediate and low-level wastes, a mined facility, near surface disposal or on-surface storage would still be necessary for high volume-lower activity wastes. DBD would remain suitable as a complementary or *parallel* option.

Despite the current technical limitations, DBD remains an important consideration for long-term HLW and spent fuel disposal, one that has a number of potential implementation benefits over the GDF concept. The primary benefit is the depth of waste emplacement (Gibb 1999;

Freeze, Stein, and Brady 2019). DBD provides geological and hydrological stability across timeframes exceeding 1,000,000 years, and a greater geological barrier between the waste and the biosphere, with benefits to intergenerational environmental justice as a result. DBD is favorable due to the cheaper cost, shorter timeframes to implementation, modular nature of the method (which allows incremental rather than *threshold* decision-making), smaller land footprint, and greater potential for localized/municipal radioactive waste disposal. By lowering the stakes of RWM through shortening cost and timelines for disposal, it allows greater opportunity for *vigilant mistrust* to emerge – citizen-stakeholders can assess RWM based upon accountability for project implementation, environmental monitoring and audit of wastes in situ, rather than relying upon trust relationship-building though participatory methods to "convince" communities that the waste facility will be safe in the future. Thus, the *incremental* nature of DBD can ameliorate political deadlock by reducing the barrier that distrust plays in shaping RWM policy outcomes.

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