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ADVANCED REVIEW

Technical and social problems of nuclear waste

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Despite decades of effort, the nuclear industry does not yet have a working solution for managing spent fuel and high level waste, the most radioactive products generated by nuclear power plants. Although many scientific and technical bodies have endorsed geological disposal as the preferred solution to this problem, there remain significant uncertainties about the long-term performance of repositories and behavior of the nuclear wastes to be stored in these facilities. Apart from a minority of countries, most countries have not chosen any sites for a repository. Further concerns about the long-term safety of repositories arise from the experiences of failures and accidents at pilot facilities. One reason for the absence of operating repositories decades after they were first proposed is widespread public opposition to such facilities. Polls have revealed that substantial majorities of people consider nuclear waste with dread and do not approve plans to dispose of radioactive wastes near them, or, often, far away either. Nuclear power advocates have typically dismissed public concerns as resulting from a lack of understanding of scientific facts but this explanation does not withstand scrutiny. Technical approaches to dealing with nuclear waste, such as reprocessing of spent fuel, mischaracterize the social concerns and therefore do not help gain public acceptance. Concern about radioactive waste has contributed to the failure of the propaganda effort by the nuclear industry to market nuclear power as a solution to climate change. The absence of a solution to waste negatively affects the future expansion of nuclear energy.

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1 | INTRODUCTION

Nuclear waste is controversial. Many consider it highly dangerous, "the least acceptable of hazardous wastes" in the words of a group of researchers who have been at the forefront of research on public attitudes towards risks of all kinds (Flynn et al., 1995, p. 8). Many also see the problem of dealing with it as negating any benefits that nuclear energy might produce. As one activist put it, "Electricity is but the fleeting byproduct from atomic reactors. The actual product is forever deadly radioactive waste" (Kamps, 2016). There is also an extensive literature that highlights various ethical problems associated with nuclear waste (Andren, 2012; Hannis & Rawles, 2013; Shrader-Frechette, 2000; Taebi, 2012).

Public resistance has halted multiple proposals to set up sites to bury nuclear waste in several countries. The United States and Germany actually constructed repositories for disposal of weapons-related radioactive waste, and low and intermediate level waste respectively, only to have them shut them down (temporarily in the U.S. case) due to accidents and leakages (Kallenbach-Herbert, 2011; Owen, 2010; U.S. Department of Energy (USDoE), 2015a); their attempts to set up a repository for wastes with higher levels of radioactivity have come to naught.[1] And at least three attempts to set up spent fuel repositories in countries without nuclear power plants have failed in the past (Feiveson, Ramana, & von Hippel, 2011). In combination with an ever-increasing stockpile of spent fuel around the world, these failures suggest that nuclear waste is a difficult, if not intractable, problem.

At the same time, advocates of nuclear energy consider radioactive waste to be an entirely manageable problem. The American Nuclear Society asserts that "the nuclear industry *has* found a solution for its waste challenges. Radioactive wastes must be managed and disposed of properly", with the recommendation that the disposal solution for "transuranic and high level wastes" be storage in a deep repository (American Nuclear Society, 2016). The International Atomic Energy Agency highlights "significant progress" on disposal plans in countries such as Finland and Sweden (Henriques & Quevenco, 2015). And, indeed, in November 2015, the ruling center-right party in Finland became the first government to grant a construction license for an underground repository to manage radioactive spent fuel from commercial reactors (Rosendahl, 2015). The state Royal Commission in South Australia went so far as to say that nuclear waste "presents an *opportunity* that *should* be pursued"(Scarce, 2016) (our emphasis).[2]

Given this welter of conflicting narratives on nuclear waste, what is one to make of the challenge of dealing with this material? This paper explores some of the technical and social challenges associated with radioactive waste management and disposal, arguing that there are unique characteristics of nuclear waste that render the problem of managing it in the long term all but intractable. Although this paper does not discuss the institutional challenges, it is worth noting here that managing nuclear waste and siting repositories is a problem that is going to involve, inter alia, the nuclear industry, regulatory and other government agencies, as well as political officials faced with electoral pressure. The complex interplay between these multiple groups makes it very difficult to deal with nuclear waste.

This paper will also briefly discuss some of the implications of the connection between nuclear energy and nuclear waste, which goes beyond the obvious technical fact that nuclear reactors produce radioactive waste. In particular, the absence of an acceptable solution to the problem of nuclear waste contributes significantly to public attitudes towards nuclear energy (Whitfield, Rosa, Dan, & Dietz, 2009, p. 426), and has led countries to rethink their policies about this source of electricity. One illustration of this rethink is Taiwan's decision to phase out nuclear power; while that decision was largely related to safety concerns, it was also influenced by concerns about waste management.[3]

Several surveys have found that public acceptability of a nuclear power expansion would increase significantly if the waste storage problem could be more effectively solved (Ansolabehere, 2007). In the words of a Canadian activist, "To advance [the nuclear industry's] expansion ambitions they want to be able to say that they've solved their biggest problem, which is nuclear waste. The industry's end goal is to have a community say 'yes' and then say 'look, the problem is solved'" (Cornwell, 2012). Conversely, a decision to phase out nuclear power would make it easier to dispose of the waste stockpiles that have already been produced because at least some of the opposition to waste repositories is from activists who see such opposition as a way to force governments and nuclear utilities to stop expanding reactor construction and shut down existing ones, a strategy that has been termed "constructive procrastination" (Darst & Dawson, 2008).

2 | TECHNICAL BACKGROUND

Nuclear waste is not a singular category. Different kinds of radioactive products are produced in nuclear reactors as well as in various steps of the nuclear fuel chain. Among the most potent of these is the irradiated fuel, which is also called spent fuel, produced in all operating nuclear reactors. The spent fuel contains all the radioactive fission products that are produced when each nucleus of uranium or plutonium breaks apart to produce energy, as well as those radioactive elements, including plutonium, that are produced when uranium is converted into heavier elements following the absorption of neutrons and subsequent radioactive decays. This paper largely deals with spent fuel and the waste forms produced by processing it.

The spent fuel has to be stored underwater for periods ranging from a few years to decades to deal with the high levels of heat and radiation it emits. In some countries, this spent fuel, once it is cool enough, is transferred to dry casks for storage on site or in a centralized facility. Most countries have accumulated large inventories of spent fuel (see Table 1), most of it stored at reactor sites.

A few countries practice what is called reprocessing where the fuel is subject to a chemical process that separates out the plutonium produced through transmutation as well as the uranium that is not fissioned (International Panel on Fissile Materials, 2015). The idea, although it is not always implemented, is to use the resulting plutonium and uranium as fuel in

TABLE 1 Spent fuel inventories from nuclear power plants in select countries

Country	Spent fuel inventory (tons of heavy metal)	Inventory date	Source of information
Canada	54,000	June 30, 2016	Garamszeghy (2016)
China	4,367	December 31, 2013	China Atomic Energy Authority (2014)
Finland	1,934	"End of 2013"	EC (2017)
France	14,146	"End of 2013"	EC (2017)
Germany	8,397	"End of 2013"	EC (2017)
Japan	17,838	June 2017	Takubo
Russia	21,362	January 1, 2014	Rosatom (2014)
South Korea	14,620	"End of 2015"	Kang (2017)
Sweden	6,296	"End of 2013"	EC (2017)
United Kingdom	5,329	"End of 2013"	EC (2017)
United States	69,682	December 7, 2015	U.S. Energy Information Administration (USEIA) (2015)

Note: In some cases, country totals include spent fuel inventories from different kinds of reactors (e.g., South Korea), with different levels of radioactivity, and so the figures might not be directly comparable.

reactors. [Plutonium can also be used to make nuclear weapons (Mark, 1993; USDoE, 1997), and that is a major concern with reprocessing, but this paper does not deal with that problem.)] Reprocessing also results in a variety of waste streams; the one with the highest concentration of radioactivity is called high-level waste. The high-level waste is, typically, vitrified, that is, converted into solid form by mixing with a glass-like substance and cooled.

The key technical characteristic that makes dealing with spent fuel and high-level waste so difficult is that the presence of radioactive substances with extremely long half-lives. In the case of spent fuel, for example, it takes several hundreds of thousands of years for the radiotoxicity of the contents of spent fuel (under hypothetical ingestion) to become less than that of the natural uranium (including its associated decay products) from which it was derived (Hedin, 1997). This is graphically illustrated in Figure 1.

Since radiation is hazardous to health, even at low levels, exposure to these wastes will be harmful to people and other living organisms as long as the wastes remain radioactive. Thus, they have to be isolated from human contact for periods of time that are longer than anatomically modern *Homo sapiens* have been around on the planet. Such a need for stewardship is unprecedented in human history.

3 | GEOLOGICAL DISPOSAL

There is in fact a technical solution to this problem that is on offer: bury the radioactive wastes underground. The idea of building a geological repository for radioactive wastes is old, and the U.S. National Academy of Sciences proposed the concept as early as 1957 (NRC, 1957). Over the decades, support for the idea has grown and the U.S. Department of Energy cites a "consensus in the scientific community" to advocate for geological repositories, which it characterizes as "the safest

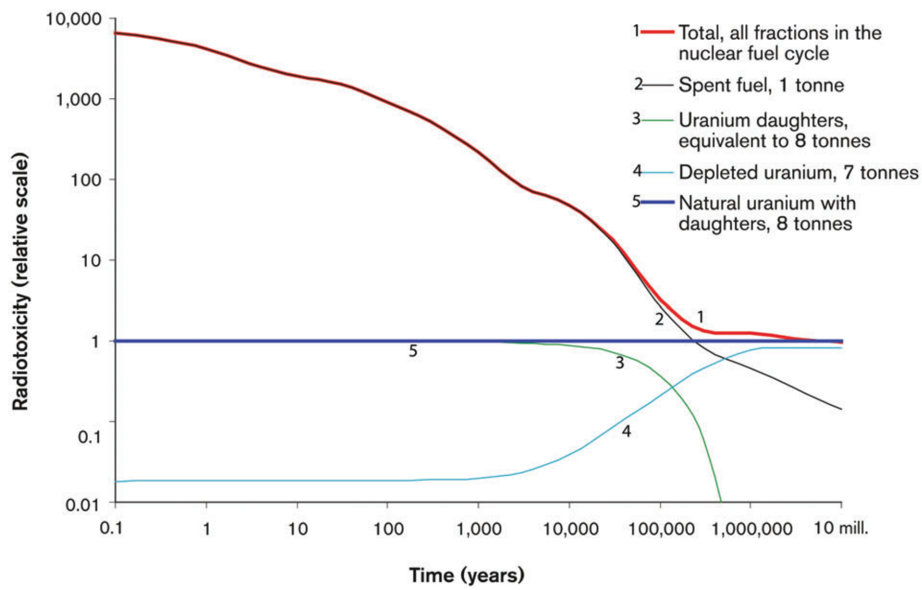

FIGURE 1 Relative ingestion radiotoxicity of uranium ore, of the spent LWR fuel that could be derived from it, the toxicity of the uranium decay products that are separated in the uranium mill, and of the depleted uranium that is stored at the enrichment plant. Source: Hedin (1997)

and most cost-effective method for permanently disposing of spent nuclear fuel and high-level radioactive waste" (DoE, 2015b).

In such a repository, the waste would be packed in special containers and placed under the ground in some suitable geological medium. The problem with this method is that the wastes stay radioactive for hundreds of thousands of years and any container or waste package will almost definitely corrode within that long timespan. Therefore, it is only a matter of when, not if, radioactive materials will escape into the biosphere and contaminate ground water sources. How fast this happens is influenced by both the choice of geological media (e.g., granite, volcanic tuff, or clay) and the package in which the materials are emplaced (Ewing, 2011).

The hope is that if all of these choices are suitably made, and the repository is well-designed and executed, this could allow the nuclear waste to remain isolated from human contact for long enough for most of the radioactive materials to decay into stable substances. Nevertheless, there could be some remnant radiation releases. Humans could be exposed to radiation from these wastes through "two principal modes", which are, "1) small, concentrated releases produced by human intrusion (from digging a well either near or into a repository) that could result in large doses of radiation to a few individuals; or 2) the gradual release of radioactivity from the repository into ground water (and ultimately into drinking water or food supplies), leading to very small doses (compared to background radiation) to a large portion of the population" (OTA, 1985, p. 74).

Because models of how radionuclides behave in repositories over millennia suggest that the radiation doses will be low, some assert that this mode of waste management is safe. The World Nuclear Association, for example, states: "Safe methods for the final disposal of high-level radioactive waste are technically proven" (WNA, 2016). Such assertions raise an obvious philosophical question: given the empirical underpinnings of modern science, how can one "prove" anything about the behavior of a structure that is to last and function as designed for hundreds of thousands of years. Since there are no operational geological repositories that store large quantities of waste from commercial reactors, all that can be offered by way of proof is a theoretical case for why a hypothetical repository will be safe.

That, however, does not constitute proof because even in these theoretical safety cases, there remain significant uncertainties. The reliability of these safety cases becomes even more suspect when one considers the major failures that repositories have experienced within just a time span of a few decades of operations. We discuss these two aspects below.

3.1 | Uncertainty

Any assessment of the performance and behavior of geological repositories will be beset with uncertainties. What is being attempted is predicting how a complex system, undergoing numerous chemical reactions and a variety of physical changes, will behave in a medium that is going to be subject to multiple transformations over very long periods of time. Some of the complications include climate change, the potential for volcanoes, and changes in the behavior of various parts of the repository, including the intrusion of water, because of chemical changes (Macfarlane & Ewing, 2006, p. 394). The radioactive waste materials placed within the repository constantly generate heat, which also changes the behavior of the repository.

A further complication is that "the act of emplacement of the waste affects some of the fundamental properties of the surrounding rock. The construction of tunnels creates a disturbed zone of increased fracture, and pore waters move in response to the thermal pulse generated by the decay of radionuclides" (Ewing, 2015, p. 254). There are also some known unknowns, where the full impact of known threats to the integrity of the radioactive waste package are thus far not well understood; an example is the effect of microbial processes on the behavior of repositories.[4]

Adding to this technical complexity is uncertainty about how human populations will behave far into the future. How are we to know, for example, that in the 29th century, people might not be mining in the vicinity of the repository to obtain some mineral that has become widely used at that time? Efforts to try and communicate about the dangers of buried radioactive waste through millennia border on science fiction, and believing that the proposed design elements would deter human intrusion thousands if not tens of thousands of years into the future strains one's credulity (Galison & Moss, 2015). Similar uncertainties plague assessments of radiation doses to human beings from repositories because they have to necessarily make unprovable assumptions about characteristics of human populations over tens of thousands of years, for example, about how much groundwater would be used for drinking or in agriculture.

Just lavishing money on research will not solve this conundrum. As the U.S. National Academy of Sciences' Committee recognized: "not all… of today's uncertainties in predicting the future behavior of a repository system can be reduced or eliminated by further research and development" (Committee on Disposition of High-Level Radioactive Waste through Geological Isolation, Board on Radioactive Waste Management, National Research Council, 2001, p. 3). Thus, any decision making will have to be made under circumstances of not knowing fully well the future impacts of burying these long-lived wastes, and assertions about safety cannot be treated as definitive by any means.

3.2 | Accidents and failures

Given the sheer complexity of the behavior of a repository emplaced with radioactive waste, it should not be surprising that there would be accidents or failures of one kind or the other. Indeed, even the limited experience with existing repositories provides examples. In the case of the Asse repository in Germany, planners chose a poor location within a salt dome, the medium that was chosen because of its presumed ability to be dry, and ignored warnings from local NGOs about flooding (Kallenbach-Herbert, 2011, p. 48). There was, thus, both a failure of design and of the institution managing nuclear waste.

An example of an accident comes from the Waste Isolation Pilot Plant (WIPP) in the United States. For long, WIPP had been held up as a model for how radioactive wastes should be dealt with. As environmental lawyers Richard and Jane Stewart, wrote in 2011, "WIPP is functioning without major incident and is well on its way to safely disposing of the bulk of the nation's TRU waste" (Stewart & Stewart, 2011, p. 185). But, in 2014, a drum of transuranic waste exploded and released small quantities of plutonium and americium, which made their way to the Earth's surface (Editorial, 2014). The accident is among the costliest in U.S. history but the explosion resulted from a simple, seemingly minor, decision: to use an organic version of "kitty litter — used to blot up liquids in sealed drums" -- instead of a mineral one (Vartabedian, 2016).

The accident in turn is evidence of serious failures. Writing about this accident, three academics from Stanford University pointed out that the "failures were wide-ranging: in safety assessments, control of drum contents, installation and maintenance of equipment, and preparation for an accident" (Tracy, Dustin, & Ewing, 2016, p. 150). Even the official Department of Energy analysis of the WIPP accident concluded that organizations that were involved in managing the facility had allowed safety culture "to deteriorate within pockets of the organization" (DoE, 2015a, p. ES-17). The more important lesson for the purposes of evaluating the safety case for proposed repositories is "how difficult it is to predict potential failures of such a disposal system over millennia" (Tracy et al., 2016, p. 150).

One could go further. Because of the possibility of "unknown unknowns", it is simply impossible to predict all potential failures. Further, if such failures have already been observed within such a short period, how can one be confident about safety claims, that no such failures would not occur during the many decades it would take to construct and load hundreds of tons of highly radioactive waste into a geological repository?

3.3 | Failed plans to construct repositories

Although geological disposal is widely accepted as the appropriate solution to radioactive waste by nuclear industries and regulators around the world, no country has so far constructed and operated any such repository for storing waste from nuclear power plants. Some countries have made significant progress, but there is still no operating site that holds high-level waste from commercial nuclear reactors. Almost all countries that have tried to site repositories have experienced one or more failures. In most cases, the failure stemmed from the adoption of a process that involved site selection by technical personnel with no involvement from the public at the early stages. As elaborated by academics Gordon Mackerron and Frans Berkhout, the policy in the United Kingdom can be "described as 'decide, announce, defend' (DAD), meaning that Government, the nuclear industry and selected scientists would develop policy in a closed environment, then announce it and finally seek to defend it against the tide of opposition that always ensued. Given the UK Government's unwillingness to force radioactive waste management sites on resistant local populations, this also meant that the word 'abandon' had to be added to DAD – DADA was a fair representation of two decades of policy failure" (Mackerron & Berkhout, 2009, p. 997). Similar DADA sequences occurred in other countries as well.

Attempts to site repositories that accept spent fuel or high level waste from other countries have also experienced failures (Feiveson, Ramana, & von Hippel, 2011; Holland, 2002; Silverstein, 1997). Typically, such proposals have involved countries that have no nuclear power plants themselves. Rather, these countries tried to describe themselves as attractive for one reason or the other (remoteness or low population density, for example). The latest such proposal was the one to set up a repository in South Australia (Scarce, 2016), which ended in failure due to widespread public opposition (Australian Broadcasting Corporation, 2016; Green, 2016). In addition to the record of failures, there are normative problems with the idea of exporting nuclear waste, including the environmental injustice inherent in the exports of such hazardous materials, and the ethical argument that those enjoying the benefits of nuclear power should also incur the costs (Dawson & Darst, 2005; Marshall, 2005).

Faced with such failures, some countries have started seeking community consultation and verbal commitment to voluntary participation. In practice, however, many of these countries have just focused on finding a relatively powerless community to site the geological repository, portraying the waste management project as a major investment that would bring large amounts of money, jobs, and taxes to local governments, and, if necessary, dealing with any opposition through some combination of undemocratic decision-making at local levels, bribery and force (Burrows-Taylor, 2017; Gosden, 2014; Hannis & Rawles, 2013; jas, 2011; Simpson, 2016). These pay only lip service to democratic and ethical principles.

In Canada, the ethical principles that underlay the plans for setting up a repository in consultation with local communities morphed to, in essence, the offer of an expensive carrot, namely a multi-billion-dollar project, with associated jobs and tax flows, to various impoverished communities (Ramana, 2013). But the focus on small poor localities is likely to emerge as a problem because decisions on final resting places for radioactive waste also necessarily involve larger regions, namely the state in which the repository will be sited, as well as locations along transport routes. Historically these larger areas have opposed waste repository siting for obvious reasons: people living in the larger surrounding areas bear a significant risk, at least in their perception, but they obtain little financial benefit from the presence of the repository.

4 | PUBLIC RESISTANCE

Why has there been such a divergence between theoretical confidence in geological repositories as a solution to nuclear waste and real-life impossibility in setting up a repository? The overwhelming reason is public resistance to siting such repositories. Most countries that are looking for specific repository sites are faced with sustained opposition, for example, in France (Oroschakoff & Solletty, 2017), the United Kingdom (RT, 2015), Japan (Ryall, 2017; Suzuki, 2017), and South Korea (Richardson, 2017). Even in countries that have chosen specific sites, namely Sweden and Finland, there is a history of opposition (Sjoberg & Drottz-Sjoberg, 2009; Swahn, 2011; Vira, 2006).

Underlying this opposition is the negative attitude that a large fraction of the global public have towards nuclear waste and repositories to store them. This is revealed by numerous polls. An example is a 2008 poll of citizens in the 27 Member States of the European Union that found that 72% of those interviewed were in agreement with the statement: "There is no safe way of getting rid of high level radioactive waste", even though they felt responsible for the waste (as evidenced by 93% agreeing with the statement "A solution for high level radioactive waste should be developed now and not left for future generations") (EC, 2008). Since the preferred "way of getting rid of high level radioactive waste" is by constructing a repository, it follows that a majority of the public would not associate repositories with a "safe way" of waste disposal. Similarly, in China, nuclear waste was identified by a significant fraction of people polled as one of the main risks associated with nuclear energy (Sun, Zhu, & Meng, 2016). A 2015 poll in Churchill County is an illustration of the majority sentiment being against siting a repository at Yucca Mountain in the United States (Churchill County Nuclear Waste Oversight Office & Churchill County High School, 2015).

Just association of an area with nuclear waste creates such a negative image that it leads others to shun or avoid the area, which some have termed stigma (Bassett, Jenkins-Smith, & Silva, 1996; Gregory, Flynn, & Slovic, 1995; Slovic, Flynn, & Gregory, 1994). When the United States was considering the Yucca Mountain location in Nevada as a disposal site for high-level radioactive waste, nationwide surveys showed that a majority of people felt that a repository would reduce the desirability of Nevada as a state to move to, and could deter them from visiting for a vacation or a convention (Flynn & Slovic, 1995). Thus, regardless of whether or not nuclear waste poses a threat to the health of humans, it does have economic impacts. In addition to such adverse economic effects, it has been argued that "social, psychological, and cultural impacts are often at least as significant and merit greater attention from policymakers and researchers" (Gregory & Satterfield, 2002, p. 347).

The public could carry this opposition to the ballot booth. In the United States, a national level poll in 2015 found "63 percent of voters saying they would be less likely to vote for a candidate running for federal office who supported building a nuclear waste storage site in their state, compared to 13 percent who said the opposite" (Burroughs, 2015).

Nuclear waste invokes strong feelings of dread, and psychometric researchers using opinion polls and other ways of studying attitudes have long realized that it is in a special category in terms of how the public views it. For example, a two country study that surveyed public perceptions of risk in the United States and Japan showed "that people in both countries have the highest level of dread toward nuclear waste disposal, nuclear accidents, and nuclear war, greater even than their dread of crime and AIDS" (Hinman, Rosa, Kleinhesselink, & Lowinger, 1993).

4.1 | Misdiagnosis

There is a tendency to dismiss opposition to waste storage as a "not in my backyard" (NIMBY) phenomenon. However, such a pejorative characterization hides more than it reveals about the underlying source of opposition. Although polls suggest that people typically express less opposition to nuclear facilities located anywhere than to one that would be constructed close to where they live, a substantial fraction, often a majority, of those opposing a facility express opposition even if the proposed waste project is considerably further away, far enough not to be considered one's backyard. For example, the national level 2015 poll in the United States mentioned earlier showed that 77% of those polled said they would not live within 10 miles of a nuclear waste storage site, but 63% said they would not live within a 100-mile radius either (Burroughs, 2015). Their opposition evidently stems not just from a desire to avoid personal harm, but also from the ethical conviction that no community should be subjected to such risks. In other words, the sentiment might be better characterized as a "not in anyone's backyard" opposition. NIMBY, in contrast, suggests that people think of nuclear waste repositories as socially necessary but just that the facility should not be situated in their vicinity—which is far from the truth.

Rather, the inconvenient truth for those who think that the nuclear waste can be managed is that opposition to waste is not just from members of the local community. There is a much wider constituency, cutting across local, regional, national, and international lines, that opposes not just the siting of these facilities but the whole idea that one can "solve" the waste problem.

4.2 | Lack of trust

Organizations involved in managing nuclear waste are not often trusted by members of the public. In one national survey from as early as 1989, 68% of Americans disagreed with the statement: "The US Department of Energy can be trusted to provide prompt and full disclosure of any accidents or serious problems with their nuclear-waste management programs" (Slovic, Flynn, & Layman, 1991, p. 1604). The reasons for a lack of trust, not just of the Department of Energy but of the general effort to site a repository in Yucca Mountain, included a site selection process that was perceived as unfair, attempts to coerce the state of Nevada, manipulation of regulatory criteria to make them fit the chosen site, and treating the public as if their concerns were irrational (Tuler & Kasperson, 2010). In Japan, trust in the organizations involved in nuclear power, including waste management, dropped dramatically in the aftermath of the Fukushima accidents, and this has changed people's attitudes towards setting up a repository (Gallardo, Matsuzaki, & Aoki, 2014). Once lost, trust is extremely difficult to regain – a characteristic that has been termed the *asymmetry principle* (Slovic, 1993).

5 | THE SOCIAL AND THE TECHNICAL

Public concern about proposals for nuclear waste disposal is often dismissed by members of the nuclear establishment as not being based on scientific or technical facts [for example, (Peterson, 2017)]. The underlying implication is that "technical" assessment of risk is rational and objective while "social" perception of risk is driven by subjective factors. However, there are sound reasons for doubting the validity of the technical assessments for "social" reasons, both because of the historical experience of how technical assessments err far more often on the side of underestimating rather than overestimating purely "technical" risk factors, and because of the biases inherent in the institutions that generate the technical assessments of risk.

The related problem is that the kinds of technical or scientific analyses that are carried out, and how problems are framed in the first place, do not start from public concerns. As a group of social scientists arguing for the intake of "social science input into acceptable solutions" articulated it, "Although scientific and technical analyses are essential, they will not, and arguably should not, carry the day unless they address, both substantively and procedurally, the issues that concern the public" (Rosa et al., 2010, p. 762). Further, what constitutes an adequate level of safety cannot be a technical issue but is necessarily a social and political decision.

5.1 | Reprocessing

One example can illustrate the mismatch between the nuclear industry's responses to the problem of radioactive waste and public attitudes. The technical proposal that is most often articulated to be a solution to nuclear waste is to subject the spent fuel to reprocessing (Barbat & Liberge, 2013; Kakodkar, 2012; Kok, 2013; Ling, 2009; Shughart II, 2014). Reprocessing frames the waste problem as one to be tamed through volumetric reduction: instead of disposing of spent fuel as it is, the idea is to concentrate most of the radioactivity contained in the spent fuel into what is called high level waste. Although the latter still requires a repository, its proponents focus primarily on the reduction in volume of the waste. For example, the French nuclear corporation Areva, which operates the largest reprocessing plant in the world, states on its website that "the volume and radiotoxicity of the waste is reduced, compared with the storage of unprocessed spent fuel" (Areva, 2016).

What this assertion misses out is that the rate of heat generation, not the volume of the materials being disposed, determines the necessary area for the repository. In turn, how much heat is generated is dependent primarily on the radioactive content. Further, when one includes what is needed to dispose of the plutonium that has been separated and used as fuel in reactors, the repository area increases further. In all, there is at best a marginal benefit from reprocessing on the required repository area (Feiveson, Mian, Ramana, & Von Hippel, 2011, pp. 15, 151).

More important, even if there were to be an advantage in terms of the size of the repository needed in the case of reprocessing, that does not solve the problem of nuclear waste. As argued elsewhere, the "public's concern about repositories is not that they will be too big, but that they simply are being built and will remain hazardous for millennia. Thus, a smaller repository does little to address the underlying concern" (Ramana, 2017).

The reprocessing idea also misses a second characteristic of public concern, namely that much of the public is quite concerned about the waste streams that have low concentrations of radioactivity. This is why, for instance, there is widespread concern about the relatively low levels of radioactive contamination from the Fukushima accidents detected off the West Coast of the United States, or about a Canadian utility's proposal (ultimately abandoned) to ship steam generators from decommissioned nuclear reactors to Sweden (Iype, 2011; Sherwood, 2014). At reprocessing plants, because low level waste is produced in extremely large volumes, nuclear establishments find it is too expensive to store them. Therefore, around the world, reprocessing plant authorities simply release these low level waste streams into the environment after some treatment, which can be detected far away from the source (Baburajan et al., 1999; NRPA, 2002). The public's concern also extends to this waste form and the contamination of the environment.

Finally, thinking of reprocessing as a way to solve the nuclear waste problem misses out on the fact that reprocessing facilities might well be opposed by members of the public too, in part because there is the risk that an accident at these might release large quantities of radionuclides and these might get dispersed over vast areas (Ramana, Nayyar, & Schoeppner, 2016; Thompson, 2014). The protests in 2016 over the proposed reprocessing plant in Lianyungang in China, because of the health and safety concerns of residents (Hornby, 2016; Hornby & Lin, 2016), leading to the cancellation of the project, offers an illustration of public concern about reprocessing facilities. Thus, in these many ways, offering reprocessing as a solution to nuclear waste mischaracterizes the nature of the public's concern about the problem in the first place. Reprocessing as a cure for the growth of spent fuel inventories is worse than the problem, whether viewed in technical or social terms.

6 | CONCLUSION

In 2015, Yukio Amano, the director general of the International Atomic Energy Agency, stated: "Waste disposal is often cited as one of the major problems facing nuclear power. In fact, the nuclear industry has been managing waste disposal for more than half a century. Dozens of facilities for low-level and intermediate-level nuclear waste are in operation throughout the world. As far as the management of high-level radioactive waste and spent fuel is concerned, good progress has been made in recent years, especially in Finland, Sweden and France… The first deep geological repositories for nuclear spent fuel are likely to become operational after 2020. The progress that is being made in this area deserves to be better known" (Amano, 2015). In other words, we know how to deal with high-level nuclear waste and spent fuel and the solution will be apparent to all quite soon.

For all the reasons discussed earlier, this picture is misleading and hides more than it reveals. First consider the cases highlighted by Amano as displaying "good progress". France is still battling fierce opposition from protestors (Burrows-Taylor, 2017; Oroschakoff & Solletty, 2017). In Sweden and Finland, the waste disposal concept rests fundamentally on the use of copper canisters and there remain important questions about their reliability (Swahn, 2011). Indeed, in January 2018, Sweden's environmental court ruled that there "is still uncertainty about the ability of the capsule to contain the nuclear waste in the long term", which complicates plans to construct a repository (Karagiannopoulos, 2018). And, of course, there could be failures even with repositories that are constructed—as has happened at WIPP and Asse—that lead then to the project being abandoned. Finally, the process through which the sites for geological repositories in this special group were chosen is not reproducible in all other countries.

In sum, isolated and partial successes do not amount to a robust way to manage nuclear waste. The histories of arbitrary imposition of sites and sustained public opposition make it very difficult to obtain voluntary acceptance among communities living near potential repository locations. Therefore, dealing with these hazardous products will continue to be a nearly intractable problem for most countries and programs.

What, then, is to be done? One, perhaps obvious, first step is captured by a quote that has been attributed to, among others, American humorist Will Rogers: If you find yourself in a hole, stop digging. In the context of the subject of this paper, the import of that aphorism is straightforward: stop producing more nuclear waste.

The problem that some might have with this recommendation to stop producing nuclear waste is that it also automatically implies stopping the generation of more nuclear energy, not to mention the construction of more nuclear plants. In turn, ceasing to produce nuclear power is seen as a problem because its proponents have worked hard at rebranding the technology as an important solution to climate change (Diaz-Maurin & Kovacic, 2015; Doyle, 2011; Stoett, 2003). But it is becoming increasingly clear that phasing out nuclear power does not have to result in an increase in emissions of carbon dioxide because of the drastic reductions in the costs of renewables, and their rapid growth in countries around the world. Nuclear power's substantial limitations have also become more apparent in recent years (Ramana, 2016a, 2016b; Schneider & Froggatt, 2017; von Hippel, 2010), which implies that there need be few regrets about phasing out the technology.

Nuclear power is also not seen as a desirable solution by members of the public, even among those very concerned about the dangerous impacts of climate change. By and large, efforts to change public attitudes towards nuclear power by stressing its potential role in reducing carbon emissions have not been very successful, leading at best to reluctant support (Bird, Haynes, van den Honert, McAneney, & Poortinga, 2014; Pidgeon, Lorenzoni, & Poortinga, 2008). Further, studies of public opinion suggest that "people who did not think that nuclear power can help to prevent climate change were also those who are most concerned about the environment and about climate change" and that "enduring issues over radioactive waste disposal and pollution mean that nuclear energy is unlikely to ever gain the status of an environmentally benign technology" (Spence, Poortinga, Pidgeon, & Lorenzoni, 2010, pp. 399, 401).

A particular concern with using nuclear power to mitigate climate change is that it implies having to tolerate the production of long-lived radioactive waste. In a study conducted in the United Kingdom, "survey respondents were more concerned about radioactive waste: 28% were "very concerned" about climate change and 39% were "very concerned" about radioactive waste" and "radioactive waste was far less acceptable to people overall with 63% saying it was very or fairly unacceptable compared with climate change where only 44% said it was very or fairly unacceptable" (Bickerstaff, Lorenzoni, Pidgeon, Poortinga, & Simmons, 2008).

For those unwilling to give up nuclear power despite the presence of alternatives and the many problems afflicting that technology, including nuclear waste, the only option is to continue with the present state of affairs, in the hope that someday there will be a path forward. For reasons discussed above, that day will not come anytime soon.

CONFLICT OF INTEREST

The author has declared no conflicts of interest for this article.

NOTES

[1]In the United States, the Department of Energy under the Obama administration launched a consent-based process to site a waste repository but the official website (https://www.energy.gov/ne/consent-based-siting) for that effort now says "Thank you for your interest in this topic. We are currently updating our website to reflect the Department's priorities under the leadership of President Trump and Secretary Perry" (as of January 5, 2018).

[2]But citizens rejected this logic and the Royal Commission's proposal to construct a multinational repository.

[3]As a senior Taiwanese official told a standard trade journal: "Due to Taiwan's active geophysical character, it will be next to impossible to find a suitable repository or method to deal with spent fuel and other nuclear waste so it would be best to create as little radioactive waste as possible … We have therefore chosen to adopt the path of energy transition to reduce carbon emissions and reduce our impact on climatic change" (Engbarth,).

[4]See for example (Little & Wagner, ; Meleshyn,).

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