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A nuclear real-world experiment: Exploring the experimental mindsets of radioactive waste management organisations in France, Belgium and Canada

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ABSTRACT

Following the theoretical approach of Herbold (1995), Gross and Krohn (2005), and Van de Poel et al. (2017), this article argues that nuclear waste management is a real-world experiment. Based on this first assumption, we examine how radioactive waste management (RWM) organizations conceive or organize their experiments. Through three illustrative case studies in France, Belgium and Canada, we highlight how the RWM organizations obliged to participate in complex networks and unable to completely control the experimental process, adopt two different attitudes: an "open" or "closed" experimental mindset. We argue that these mindsets provide different answers to the questions: which main variables to focus on, how and who should design them, how to deal with conflicts and unexpected events, what are the justifications for participation and expert analysis, and what are the expected outputs and outcomes. The findings underline that although some RWM organizations have -at least since the participatory turn- had some 'open' mindset moments in some cases, they quickly revert to a closed mindset. We conclude by emphasizing the need for practitioners and scholars to further examine and evaluate the virtues of the open mindset when the experimenter assumes the program has a real-world experimental status. This status recognizes the limits of control over experimental conditions, allows for more substantial moral considerations when making technical choices before wider audiences and allows for collective sharing of responsibility, knowledge production and trade-offs over such a long-term and controversial program.

1. Introduction: Nuclear waste management as a Real-World experiment

How to manage waste for decades, centuries or even a thousand years? Among different types of waste, nuclear waste management remains a wicked and crucially important problem to study. To begin with, technically, there is no final long-term repository for high-level radioactive waste (HLRW) currently in operation in a nuclearized country [1,2]. The nuclearized world is still watching, and waiting for, its effective implementation in Finland – one of the nuclear countries most advanced in its long-term plan for the implementation of the Onkalo final repository. In the same vein, Sweden, the other well-known illustrative case of a nuclear waste management success story [3], is facing new legal challenges, as the Swedish Radioactive Waste Management (RWM) organization has yet to prove how long-term safety can be guaranteed and how human beings and the environment can be protected from radiation for centuries. If among the vast majority of RWM organizations across the world deep geological disposal is still presented as the main and the only option to deal with such waste, not all countries (especially those with small national territories) have the appropriate geological conditions for such disposal. With no shared international solution [4], several national technical and geological uncertainties about this option persist [1].

Secondly, the suggested nuclear waste solutions are not only extremely challenging from a technical point of view, they are also highly political. Procedures for siting nuclear waste repositories regularly face deadlocks resulting from endless conflicts due to strong local and national opposition and the polarized positions of the stakeholders [1,5–7]. Selecting a site is also closely connected to social, economic and environmental constraints [8,9]. Variables such as regulatory structures, legal frameworks, societal acceptance (or the lack thereof), or the type of management, for example "non-transparent top down approaches", can the influence nuclear waste implementation processes [1,8,10].

Thirdly, the sociotechnical challenges associated with nuclear waste management occur in a context of uncertainty concerning the future energy mix coupled with a heightened climate change debate where nuclear energy regularly resurfaces as the potential energy of the future [11–14]. Scholarly opinions regularly diverge on the added value and pitfalls of nuclear energy futures [15]. Recent comparative studies highlight the fact that nuclear waste futures remain strongly dependent on nuclear energy futures and *vice versa* [16].

Lastly, these sociotechnical challenges are taking place in a particular and very unusual timeframe. Managing nuclear wastes is

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necessarily widely encompassing, as it concerns many different (present and future) societies, far beyond human imagination. This temporal regime therefore implies multi-generational strategies [17,18].

To sum up, on a daily basis, political representatives, public administrations and waste producers must deal with the sociotechnical unknown and unexpected [19]. Their job is to make decisions "facing uncertain situations" [20]. Amidst this ocean of interconnected uncertainties, in the past two decades, several RWM organizations have reflected on new managerial practices and many cross-national projects have been funded to improve the governance of nuclear waste management (see for instance ENTRIA, MoDern, MoDern2020, InSoTeC or COWAM projects). Among other things, these projects suggest improving managerial practices by resorting to an array of new deliberative procedures with experts and potentially affected publics and stakeholders [2,6,21–23].

If some scholars have called this momentum of the early 2000s the "participatory turn"[24], others, especially in environmental studies and science and technology studies, have recently stressed that the participatory turn in American and European countries extends beyond the participatory turn as a "long-standing experimental practice" [25,26]. Instead, they speak of an "experimental approach" in which society becomes the main experimental site [27]. Among these scholars, several scrutinized nuclear technologies in particular. They suggest that nuclear waste management is a particular form of "real-world experiment" where every national nuclearized country responsible for the nuclear waste produced on its territory is the laboratory [28–31].

This paper follows those authors' assumptions and scrutinizes an important, but neglected, component of nuclear waste management processes as real-world experiment: the role of the principal investigator. The question is, if nuclear waste management is a real-world experiment, how do RWM organizations conceive or organize their experiments? How do they address their audiences – the different publics (scientific or not) who "witness" the experiment, when the laboratory boundaries are the national territory? And more generally, how does considering radioactive waste management as a real-world experiment affect and modify our perceptions and practices as analyst, manager or affected stakeholder in such a controversial program?.

RWM organizations are one of the oldest actors and remain key players in the development and implementation of long-term nuclear waste programs. Analyzing and comparing their positions as principal investigators makes it possible to emphasize power relations between them and the audiences of such social experiments. Even if new actors appear in the process, power asymmetries remain; environmental associations [32], affected local publics [10], leading newspapers [33], new consultative bodies [7], nuclear waste management agencies or nuclear industries do not have the same resources and knowledge to influence the program.

Some authors consider that recognizing the experimental nature of governing waste could, in the coming years, fundamentally change the way in which actors (including nuclear engineers, social scientists and policy-makers) perceive and assess their roles in the art of governing controversial objects [27]. This paper brings social science and Science Technology Study (STS) concepts into productive conversation with natural and engineering sciences concerned with nuclear energy issues. First, we stress that assuming the particular experimental nature of the HLRW program means also considering the other instruments with which the experimenter and the audiences have to deal. Second, there is also a need to assess how an open experimental mindset – here defined as a way of looking at, thinking about, and acting on the experiment – confronts sociotechnical uncertainties. Both statements can differently illuminate the logics and assumptions upon which nuclear waste practitioners and engineers have rested historically.

2. Material and methods

2.1. Theoretical framework: The two mindsets of the experimenter in a real-world experiment

In this paper, the theoretical focus is on the concept of "real-world experiment" [34], which designates an experiment that revolves around the passage of a technology or method from the confined laboratory-controlled conditions into the outside world, in which technologies are tested in real-life settings.

Real-world experiments share three characteristics with scientific or technological experiments in natural science: instrumentation, demonstration, and uncertainty [35]. Firstly, any kind of experiment is based on a series of instrumented interventions relying on material devices and knowledge that are more or less formalized. Secondly, an experiment is always associated with various forms of "demonstration"[36], proofs that imply audiences (scientific or not) who "witness" the experiment, criticize it, encourage it or give it their approval. Lastly, the outcomes of an experiment are always partially uncertain. In any kind of experiment, there are important questions at stake such as mastering the space in which an experiment takes place, identifying who is authorized to conduct the experiment or witness its demonstration [37] or defining who can either approve or oppose it [38].

Beyond similarities with 'traditional' scientific experiments, the first particularity of the real-world experiment is taking place "outside", amidst society, in an open and "non-scientific" environment. The laboratory space is therefore delimited at a very large scale [39]. Because the experiment is conducted at real-life scale, the experimenters have less control over the experimental conditions (e.g. containment is impossible [39]) and the consequences are indeed harder to assess and to manage. Consequently, the experimenters have to deal with greater risks and potentially irreversible effects [31] that are subjected to more substantial moral considerations [40]. The second particularity is that the demonstration takes place in front of a larger audience. Audiences who "witness" the experiment are indeed multiplying. The decision-making power is no longer solely in the hands of scientists, decisions are also up to policy makers and newly introduced actors (for instance, citizens or non-governmental organizations) who are henceforth included in the experimental system. In addition to material devices and knowledge production, the experimenters need to interact with additional instruments: policy instruments that can sustain or constrain the experimental conditions.

In a real-world experiment, scientists are just one actor among others, involved in a setting in which they are obliged to participate [40]. As Gross and Krohn [41] summarize: "With this type of experiment going on, […] the experimenter is bound to participate in complex networks of actors embedded in institutional and natural environments that the actors cannot completely control".

To face the particular conditions of real-world experiments, experimenters may adopt two different mindsets [42]. A mindset is defined here as a way of looking at, thinking about, and acting on the experiment. It refers to an experimenter's acceptance of contingency as well as the ability to live with ambiguity and to accommodate uncontrolled or unexpected events. Contingencies and ambiguities are not new, but in a real-world experiment, coping strategies shift from attempts at control and the confidence that it brings, to ironical, practical, skeptical or radical positions and actions. This is a challenge for nuclear waste managers and policy-makers, since they need to maintain their legitimacy by undertaking actions to make a difference. As further explained below, a mindset can be "closed" or "open". In both cases, what matters is the way the real-world experiment is managed and its variables are controlled. Yet, both mindsets present crucial differences that require a brief explanation.

The "closed" mindset is one that aims at controlling the outputs and the outcomes of the real-world experiment. This mindset is characterized by the will to control the maximum number of variables and the

unexpected effects of the experiment. The experimenter visualizes a particular outcome and adopts rigid planning to achieve it. In this mindset, the aim is to apply a pre-established protocol and to foresee and contain any possible conflict or obstacle [43] that may arise during the course of the experiment. Conflicts and unexpected effects are seen as a something to be solved, and two types of instruments are used to settle any conflict: scientific expertise and participation [42]. In this mindset, the call on scientific expertise is intensified, presented as the best way to provide appraisals that are "objective and independent". When a scientific expert's involvement is not sufficient to put an end to controversies and conflicts, procedures for broader consultation and participation are set up as "an option for pacification" [42]. In this case, expert and participatory procedures generally focus on reaching a consensus. Regarding the decisional model associated with this approach, policymakers expect the experts and the public to work together and produce simplified, straightforward, decisions enabling them to choose one option over another [42]. The decision model related to this first attitude, to echo the words of Stirling [22], tends to prefer governance dynamics that favour "closing down" by suggesting policy appraisals and commitments in favour of the "best" solution, the single or definite result. It can provide prescriptive recommendations, as it is indeed about finding the priority issues, identifying salient knowledge and recruiting the appropriate protagonists to determine the best output.

On the contrary, the "open" experimental mindset consists in fully acknowledging that total control of the experiment and its effects is neither possible, nor desirable. Rather than trying or wanting to control all the variables, experimenters are ready to integrate any element of surprise as additional variables in the experiment [27]. This mindset is not just a state of awareness of novelty and surprise, it also assumes that the actors will agree to be "flexible" depending on how the experiment unfolds and to adapt their roles and their tasks accordingly [42]. With this mindset, the experimenter accepts and welcomes the unknown and does not shy away from sharing it with the audiences of the experiment: "Such consultations are not the norm in many projects that deal with known unknowns, since the official rhetoric is still that science delivers fully reliable results. This also means that all the actors involved must communicate their own ignorance, but this is not understood as a failure but as a normal way of dealing with the unknown" [27]. It is thus not a question of identifying a truth, of agreeing on the result to be achieved, but rather, through this approach, one of facilitating the conditions enabling "broader learning" through the unexpected and the uncertainties [27]. The management protocols that come with this open mindset are not set in stone. On the contrary, they require constant revision and long-term reflection "to prevent the ossification of habit or the entrenchment of narrow self-interest" [44]. The decisional model associated with this second approach implies more "opening up" governance dynamics. It reveals the open-endedness, contingencies of technological choice. Marginalized perspectives, contending knowledge or ignored uncertainties can be examined [22].

It is important to stress that the strategies of the experimenters are not fixed once-and-for-all in a particular mindset: the experimenter's mindset may evolve over time, in a particular context, and according to the stage of advancement of the process. An open experimental mindset can help include a wider range of inputs and to consider neglected uncertainties whilst a closed experimental mindset or "closing down" moments are also necessary to reduce complexity [45,46]. The key analytical question associated with this theoretical framework thus concerns the moments and the situations in which an "open" or a "closed" experimental mindset would be desirable. In so doing, it questions the foundations of management itself and how the control of an ongoing sociotechnical program is/should be applied over time. In the following sections, we characterize the experimental arrangements in HLRW programs in their context, describe the experimental mindset each RWM organisation adopted over time and compare the results of the different approaches.

2.2. The Cases, data collection, and analysis

We illustrate our theoretical framework empirically through the temporal description of three case studies: France, Belgium and Canada. These three nuclearized western countries were selected based on their similarities concerning three criteria: first, in all three countries, their respective RWM organizations (the Canadian NWMO/SGDN – Nuclear Waste Management Organisation, the French ANDRA – *Agence Nationale pour la Gestion des Déchets RAdioactifs* and the Belgian ONDRAF/NIRAS – *Organisme National des Déchets Radioactifs et des matières Fissiles*) all support deep geological disposal (with or without reprocessing of spent fuel) as the main option to manage HLRW. Second, the three countries, like many others, faced strong public opposition when their RWM organization attempted to implement its program in a defined territory (siting process). Third, facing the strong opposition, all three RWM organisations took a "participatory turn" [24] as they decided to include different publics and experts in their nuclear technology assessment processes.

As researchers belonging to the interpretivism paradigm, we consider that actors' attitudes, preferences and discourses must be understood in particular technological and political contexts. In our methodology, we combine different qualitative methods to ensure in-depth analysis and the triangulation of data collection [47]. Each case study relies on extensive qualitative data collection and we use both primary and secondary data.

The secondary data includes press archives, legislation, official reports, official websites of nuclear waste management organizations. To gather the primary data, in France and Canada, participatory observations were conducted at expected future sites for radioactive waste in Bure, France, in 2014 and 2018, as well as at four volunteer municipalities in Canada (Manitouwadge, Nipigon, Schreiber and Ignace) potentially concerned with HLRW repository in 2015. Being physically on site allowed us to take into account the distances from place to place, the isolation of the municipalities and the way opposition (where it exists) and RWM organizations are located both symbolically and physically in the areas concerned. In Belgium, our data come from a 11-year run of almost uninterrupted observation and assessment of participatory events on nuclear waste management, including public and expert engagement.

In addition, a total of 87 semi-structured interviews were conducted between 2012 and 2019 and some of the key informants were interviewed up to three times. In France, 32 interviews were conducted in 2014 and in 2018; in Canada, 17 interviews in 2015; in Belgium, 38 interviews between March 2012 and June 2019. In France, most interviewees were local committee actors (13) but also included national-level representatives from consultative bodies (7), safety authorities (4), HLRW experts (3), journalists (2) and the ANDRA (3). In Canada, the interviewees included representatives of local committees (8), safety authorities (1), federal consultative bodies (2), policy-makers (2), the NWMO (2) and HLRW scientists (2). Most Belgian interviewees represented the ONDRAF/NIRAS (21), safety authorities (6), waste producers (6), HLRW experts (3) and the administrations concerned (2).

In this data collection, two limitations must be acknowledged that should inspire further research. First, due to limited time spent on fieldwork, important choices had to be made and it was not always possible to interview informants again later to see if and how their opinions had changed over time. Second, to make it possible to maintain control over data collection, national environmental associations (for or against nuclear power) and cross-border publics were not included in the list of respondents.

In order to analyze the complexities associated with each case study, two writing strategies were used. The first was a full chronological description of each case study, condensed from the main scientific reports and articles [21,46,48–50]. To this end, we used the opening up and closing down framework of Stirling [22]. This first strategy allowed us to "understand the case studied in itself" and to restrict ourselves to

the description and historical contextualization of the case [51]. Interviews were systematically categorized and tagged with Mosaiq software in order to understand the extent to which HLRW assessments and commitments were open or closed.

Based on these extended descriptions, the second writing strategy consisted in adopting an approach based on "thematic entry points". In this paper, the results of the case studies are described in terms of an explicit theoretical framework (considering HLRW management as a real-world experiment) in order to illustrate a theoretical point (the importance of exploring the role of the main experimenter, the RWM organization) [51]. We focused in particular on the type of actions and discourses of RWM organizations and how these were perceived by other stakeholders.

To compare the narrative of the case study analysis in the following sections, we use two successive phases that are common to all HLRW programs: conceptualization and operationalization. The conceptualization phase is generally associated with the adoption of the *generic and strategic* long-term program without targeting a specific territory. It encompasses what RWM experts call "policy" and "planning". Even if site selection, construction, operation, post-closure and monitoring are already addressed at the generic level or in underground laboratories at this stage of the program, the latter is usually "placeless" [52]. During the operationalization phase, RWM organizations further develop and adapt the program to one or more specific territories or sites. Partly related to the "siting" phase in RWM jargon, the policy and planning towards monitoring phases focuses on selected areas.

3. Exploring the mindsets of RWM organizations in France, Belgium and Canada

The following sections discuss three distinct types of real-world experiments in the governance of high-level radioactive wastes in France, Belgium and Canada. For each phase (the conceptualization and the operationalization phases), we highlight how the mindset of RWM organizations evolved over time, depending on the interferences of policy instruments and audiences that may be active, reactive or passive.

3.1. Closed mindset of the ANDRA in France?

In France, both conceptualization and operationalization phases have faced, and still face, strong local opposition.

The opposition started in 1987 with the publication of the ANDRA report that supported deep geological disposal as the main option and identified four potential sites to host the final repository [53]. After three years of violent conflicts between the ANDRA and the local population, the French Prime Minister decided to suspend the program for one year [54,55], asking the ANDRA to temporarily halt its search for sites [56]. In so doing, the government admitted that the ANDRA's manner of regulating and controlling the real-world experiment had not been successful in legitimizing the conceptualization phase it originally promoted for the management program. It required the intervention of a new Parliamentary Office (OPECST – Parliamentary Office Technology Assessment) to assess the suggested HLRW program and act as a mediator between civil society and the ANDRA experts [56]. OPECST suggested a new conceptualization phase and suggested new information and dialog procedures, as well as the exploration of new nuclear waste management options. OPECST entering the scene dramatically changed the context of the real-world experiment. ANDRA became just one actor among many other institutions. For each aspect, each problem encountered, a group, committee or organization was asked to organize one or more consultations to evaluate and propose a solution for one or several dimensions of the HLRW program. As a result, the situation became even more complex, each actor following their own protocols and operational rules and having a broad initiative capacity in their field of competence [57]. Nevertheless, a first legal instrument, the Waste Plan Act of 1991, was passed that maintained the exploration of new research options for HLRW management. In parallel, the number of expert and public national consultative bodies multiplied, and the Local Information and Oversight Committee was created to initially inform and monitor the HLRW research program. During the following fifteen years, numerous experts and public national consultative bodies contributed to the conceptualization phase.

During the conceptualization phase, the ANDRA observed the progress of the real-world experiment from a distance. The agency was officially commissioned to study two research options (surface storage and deep geological disposal), with a mandate to assess only the technical aspects of these options. OPECST members suspected the ANDRA of preferring the research option it has long favored: deep geological disposal [58]. The alternatives to deep geological disposal studied were still considered inadequate (transmutation-separation was a utopic solution but too costly and storage on the surface was only to be envisaged as a transitory solution on the way towards the deep geological disposal [58,59]. In the ANDRA's opinion, this option had the advantage of presenting variables that could be controlled, with management stages that could be planned. The alternative of surface storage was historically "under-researched" considered as "less interesting for scientific programmes" (personal interview with ANDRA representative, March 23, 2015). The ANDRA kept its closed experimental mindset, which prevented it from deviating from the trajectory to which it had hitherto committed. This position was reinforced over time by other institutional bodies who rallied to the deep geological disposal option – including OPECST and the scientific expert of the National Assessment Board [60–62].

Yet, if the ANDRA managed to continue with closing down appraisals around deep geological disposal, the outcomes of the many publics' and experts' consultations forced them to accept some compromise. One crucially important but unexpected output of the conceptualization phase process was the addition of the reversibility principle to this research option, defined later as 'the capacity, for successive generations, either to continue the construction and then the exploitation of successive tranches of a repository, or to re-evaluate the choices previously defined and to change the management solutions' (Law of 25 July 2016). Parliament validated this principle and confirmed the future host territory at Bure in the Planning Act of 2006. This legal instrument of 2006 marked the beginning of the operationalization phase.

During the operationalization phase, the role of the ANDRA became more visible at the local level: the organization received from the government the mission to identify a restricted area to host the future final repository. Based on its previous geological research, ANDRA identified a geological zone with several scenarios for surface facilities and consulted the Local Information and Oversight Committee. Although the latter demanded that the geological zone and its location first be discussed, ANDRA explicitly limited the discussion to surface facilities [63]. For a member of the Local Committee, ANDRA considered the underground to be purely scientific matter (Personal interview with Local Committee representative December 2, 2014). In this way, ANDRA ascribed specific roles to active local audiences. After a series of other legal consultations, a new governmental decision approved ANDRA's suggestion in 2010: a zone called ZIRA (for *Zone d'Intérêt pour la Reconnaissance Approfondie*) was delineated in order to extend and confirm, among other things, the previous results of the underground laboratory at Bure [64].

At the national level, RWM also continued negotiations on the industrial project design with the nuclear industries behind closed doors as this was a "sensitive issue" (Personal interview with ANDRA representative, October 17, 2014). OPECST denounced "the lack of transparency" in the choices made between ANDRA and the nuclear industries that "limited Parliamentary control" [65]. The conclusions of the National Public Debate Commission responsible for organizing and opening the HLRW programme to public deliberation in 2013

underlined the same concern: the updated cost assessments of the project were “unavailable” to the public [66]. Economic and scientific trade-offs were *de facto* beyond the scope of the public debate and therefore did not allow the public to fully evaluate all aspects of ANDRA’s demonstration. Currently, the ANDRA is working on site characterization, preventive archaeology and environmental monitoring [67]. At the local level, public and expert opposition has never stopped [68]. The local opponents have declared the future host zone to be an ‘area to defend’ [69], an area once defined and identified that is literally occupied by the project’s opponents.

We stress that once the Planning Act of 2006 and the deep geological disposal was validated, the relevant ministers, the waste producers and the ANDRA took control of the program in the exact same way that had led to the undermining of the legitimacy of the program in its original conceptualization phase. ANDRA, with the support of waste producers and relevant ministers, controlled what information was available to whom and the preferred option(s) for financial support. They regulated the way in which the debates were framed and indirectly, what roles were expected from the public. They planned the financial and technological design of the HLRW program in a restricted context, following the pre-established experimental protocol of 2006 and adopting a clear-cut decision-making process. Particularly in the operational phase of the real-world experiment, the ANDRA gave the impression, to paraphrase OPECST’s statement, that the implementation of a management option was exclusively a techno-scientific and economic issue to be negotiated among experts [65,70]. Consequently, we conclude that ANDRA and other associated nuclear actors never changed their closed experimental mindset concerning the governance of HLRW. They have continuously positioned themselves outside the ongoing real-world experiment. The operational phase of the French HLRW management program can be seen as the affirmed continuation of the former regime of experimental practices that tend to control and regulate all variables of the real-world experiment and in which the experimenters position themselves outside the experiment underway. Once the program entered its operational phase, the decision-making power remained in the few experimenter’s hands (the ANDRA, the ministries concerned and the waste producers) [21].

Nonetheless, the decision validated by the Planning Act in 2006 favoring the deep geological disposal was not the exact replica of the one proposed by ANDRA in the 1980s. Although alternatives to the long preferred option of deep geological disposal became less attractive, one big change did take place: the notion of reversibility was introduced [71], thereby questioning the design of the deep geological disposal and raising important sociotechnical challenges. This notion opens up a new space for negotiation in the operationalization phase, a potential new foothold for audiences of the real-world experiment to take a more active part in it, which may lead to a deeper revision of the recommended solution. How to technically conceive and organize the retrievability of wastes? How to organize active safety (i.e. ensuring safety with human action as opposed to the passive safety, which means safety without human action [72]), for how long? In other words, this condition triggers new uncertainties in the ongoing experiment, which comes with its own technical and political challenges. We conclude that reversibility enacted by Parliament in 2016 could become a key element that threatens to inflect the closed experimental mindset of the ANDRA toward greater openness. As an unintended consequence, the seemingly harmless condition of ‘reversibility’ will put nuclear actors’ experimental mindset to test, which may breach their reluctance to integrate surprise, to address any unknowns regarding the consequences of future experiments and to acknowledge the great technological and social complexity of HLRW governance. Speaking about reversibility of scientific and technical choices opens a space for debate, a possibility to ‘unlock’ a scientific and technical trajectory that, so far, had been successful in excluding all the others. In the long term, the notion of reversibility may be envisaged as an instrument for real-world experimentation that facilitates the progressive adaptability of the decision-making process and reinforces the need to take society into consideration in the ANDRA experimental protocol.

3.2. Open mindset of the NWMO in Canada?

Like in France, the beginning of the conceptualization phase of HLRW program, in the 1970s, was characterized by local opposition [73,74]. It started with the publication of two reports, the Hare report [75] and the Canadian Nuclear Research Center (Atomic Energy of Canada Limited – AECL) report [76] that supported the deep geological disposal concept, identified adequate geological areas and suggested a siting process located in Ontario Province [77]. In 1978 and in 1981, the Federal government and the Ontarian government mandated AECL to further study the deep geological disposal and permanent storage options and to organize “co-operation and consultation with the communities involved at all stages of the program” [77]. At that time, the development of the conceptualization phase was the responsibility of AECL, which reaffirmed its support for deep geological disposal. In 1988, the federal Minister of Natural Resources mandated an independent commission, the Environmental Assessment Panel (also called the Seaborn Panel after its Chairman), to review the conceptualization phase proposal for nuclear fuel waste management and the AECL disposal concept. The Seaborn Panel conducted several participatory experiments. Adopting an open experimental mindset, the Panel organized expert and public consultations over a period of nine years. The outcomes of their work strongly influenced the subsequent legal instrument, the Nuclear Fuel Waste Act of 2002. Indeed, Parliament decided to suggest a new conceptualization phase and to create a private not-for-profit company in charge of insuring the entire development of every phase of HLRW program, the NWMO. The Nuclear Fuel Act gives free rein to the private entity. As a result, unlike France, the capacity for expert and participatory initiatives was not multiplied and divided among several actors but concentrated in the hands of a single actor. Since 2002, as the exclusive experimenter, the NWMO has had considerable influence on the organization of the real-world experiment. Its initiatives directly affect the process and the content of the HLRW program. After its creation and for the following three years, new management options were considered and compared (deep geological disposal, storage at nuclear reactor sites and centralized storage either above or below ground) and new expert and public consultations were organized. The work undertaken by the NWMO can be analyzed as a continuation of the successful experiment undertaken earlier by Blair Seaborn and his colleagues. For example, at the start of public consultations, its strategy was to broaden the consultations to not only discuss the options to implement but also to any kind of issues they found relevant to the HLRW program. In this sense, the NWMO adopted an open mindset during the conceptualization phase.

Based on its data collection, in 2005, the NWMO submitted a report that endorsed the deep geological disposal concept with one condition, ‘the Adaptive Phase Management’, a progressive program combined with strong local support. The Canadian Government validated NWMO’s suggestion. The Canadian government established the broad principles for the real-world experiment but delegated and reaffirmed all power of initiative to the NWMO. The political commitments defined a light framework, a set of specifications for the missions to accomplish but without institutionalizing the practices or setting a pre-established protocol. In this sense, both policy decisions adopted at the federal level illustrate a more distanced commitment to real-world experimentation in nuclear waste governance. The Canadian legal instruments oversee the HLRW program, validate its principles, but do not specify the practices.

The beginning of the operationalization phase started when the NWMO invited experts and the general public to collectively design the operationalization stages of the HLRW program. This is a power that the NWMO chose to share with Canadian citizens during the design phase. Although the protocol is written exclusively by the NWMO, it

was repeatedly resubmitted to those who helped prepare it. Instead of focusing on the final product of the real-world experiment (the outcomes of the operationalization phase) the Canadian NWMO focused more on the protocol, the 'roadmap' composed of nine steps that was validated during the public and scientific inquiries, and then later by the Canadian government, as a NWMO representative explained: "[…] the even though we don't know what the outcome of that siting process would be, we have got a roadmap that we were in agreement that we could walk together on" (Personal interview with NWMO representative, June 8, 2015).

The NWMO officially started its site selection process in 2010. Twenty-two communities expressed interest in being part of the industrial project. As a result, the space for negotiating the variables of the real-world experiment has seen its contours identified, recognized and concentrated in particular places: this is where the volunteer local communities are geographically located, but without being definitive for two reasons. First, the host areas for the final repository need to be determined and technically studied in more detail. Second, the NWMO initially focused on volunteer municipalities before rapidly expanding the scope to "surrounding" [78] areas including the volunteer First Nation and Métis Communities and any community that may be interested in the future. In this operationalization phase, the NWMO has full responsibility for excluding communities that do not meet the previously established socio-technical criteria. Nevertheless, the NWMO also chose to share its right with the local collectivities as they could withdraw from the process at any time. Therefore, although nothing is imposed on the areas concerned, the real-world experiment is being conducted with the people who are directly concerned by the experiment. The actors affected by the experiment have the capacity to take the initiative but local audiences have been mainly passive. So far, criticism is neither controlled nor absorbed, but is more or less non-existent. The routinized and permanent participatory spaces have the tendency to 'devitalize' the effective deliberative participation [6]. Murphy stressed that one of the explanations could be the current 'placelessness' of the project [52]. Currently, the ongoing siting process is limited to two potential communities: Ignace and the already nuclearized South Bruce. The NWMO also thinks the populations concerned today will perhaps broaden. Indeed, (local) critics and broader interests could be stimulated at the next steps of the process when the implementation phase will effectively 'take place' at a particular site.

In this real-world nuclear waste experiment, we stress that the NWMO does not control; it organizes. Since its creation, it seems to have never stopped maintaining an open mindset. It does not attempt to convince others that it possesses all the knowledge needed to solve the problem or that it is capable of accomplishing the missions entrusted to it. Instead, it draws its legitimacy rather in the way the experiment is *collectively* organized (transparency, shared initiative, protocol to build, collaborative process, etc.).

The NWMO assumes that outcomes are undetermined. Aware that it does not have the capacity to control all the variables that make up the real-world experiment, it advances step-by-step thanks to a series of micro-decisions taken collectively with the audiences partaking in the experiment. The NWMO prefers talking about "adaptation" rather than "control" (Personal interview with NWMO representative, June 8, 2015). It perceives adaptation as a key ingredient in the success of a legitimate real-world experiment. The agency assumes its ignorance regarding the outcome of the siting process and when it faces present or future unexpected effects, it is thoroughly transparent as it appeals for new discussion with the partners involved.

Grasping the NWMO's approach is also the way to understand why the 2005 recommendation in favor of the deep geological disposal was not the exact replica of the one proposed by Canada's nuclear energy center a few years earlier. "Adaptive Phased Management" (APM) is the approach that legitimizes the closure of possible options in favor of the deep geological disposal because, at the same time, it opened a permanent negotiation space at each step of the process, fostered iterations and modulated the different decisions made. APM is a form of experimentation that involves both process and content. On the one hand, it can be seen as the NWMO's recognition of an open experimental attitude and as its formalization as a management principle. On the other hand, it tends to closely combine societal facets with technical facets; allowing the possibility that one can modify the other because they are both closely interrelated and interdependent.

3.3. Closed mindset of the ONDRAF/NIRAS in Belgium?

Based on its previous experience with a low-level radioactive waste program, the Belgian RWM organisation proactively launched a participatory phase for HLRW during the conceptualization phase in the early 2000s. In 2004, the relevant ministers requested a comparative study of all the available options (called Strategic Environmental Assessment) and recognized, as the ONDRAF/NIRAS had previously underlined, the need for the public consultation. The ministers also explicitly asked the ONDRAF/NIRAS to suggest a Waste Plan for HLRW. Although it had been considering the deep geological disposal option for several years, the first consultation with key stakeholders in 2009 was more open, as it addressed the appropriate method of consultation to be chosen and the questions to be asked. Next, the Belgian RWM organisation collectively created the agenda for the HLRW program. The agency started from a blank page, with no pre-established protocol; it did the same during subsequent participatory dialogs and at the interdisciplinary conference [46,48]. From 2006 to 2009, it also delegated the inventory and evaluation of technical options to nuclear expert analysts connected with the nuclear industry. In this context, the ONDRAF/NIRAS organized more than it controlled. But when the evaluation committee composed of social scientists criticized the fact that the ONDRAF/NIRAS was the main and only organizer, the agency decided to delegate the next participatory event (Citizen's Conference) to an independent organization, the King Baudouin Foundation. It accepted the 'risk' of not being able to control the outcomes emerging from the conference, which attests to their open experimental attitude. During this period, we can say that Belgian RWM organization proactively adopted an open experimental mindset.

However, when the final version of the Waste Plan was under preparation, ONDRAF/NIRAS adopted another approach that sought to control the produced outcome. At that moment, it forcefully suggested what it had long considered to be the best option: passive deep geological disposal. Whether or not intentional, this shift organized a hierarchy of social and technical dimensions and narrowed the debate from a technical point of view.

More precisely, among the likely options to consider for HLRW management, looking at the breadth of results produced by the Belgian Nuclear Research Center (SCK-CEN) over the past 35 years and those of the public consultations (2009–2011), the ONDRAF/NIRAS clearly positioned itself in favor of one particular outcome. Retrospectively, we can conclude that the broader participatory consultations did not modify the technical management program originally envisaged by the ONDRAF/NIRAS. Studying all available options from 2006 to 2009 resulted in the confirmation of what the ONDRAF/NIRAS already considered and previously supported: it seems there is no other appropriate alternative to deep geological disposal. The various consultations helped reinforce the long-favored technical option. The Waste Plan certainly underlined the importance of taking the project's social dimensions into account, but the very structure of the Plan showed that this dimension was still clearly considered as distinct from the techno-scientific aspect of the project. For instance, the ninth chapter discussed the project's societal dimension and was completely separate from the discussion of the deep geological disposal and its technical aspects [79]. When the ONDRAF/NIRAS technical report included certain conditions emerging from the public consultations, such as the controllability or reversibility of the system, these conditions could only be considered as relevant in the priority framework of the

repository's passive safety concept, as envisaged by the technicians and engineers working on this issue. Presented in this way, the Belgian RWM organization tended to control all the variables and anticipate the potential effects of outside requests by placing emphasis on its concept of long-term passive safety. In a way, the ONDRAF/NIRAS limited the uncertainties inherent to a possible integration of the societal dimension in the scope of its deep geological disposal project.

While waiting for a political decision on the conceptualization phase for almost a decade, the Belgian RWM organisation has progressively shifted to a closed experimental mindset. The topicality of maintaining the legal public consultation during the COVID-19 crisis and the Belgian lock-down situation (April–June 2020) is a good illustration. In the absence of a clear political framework on HLRW program, the ONDRAF/NIRAS has chosen to no longer work proactively, especially in the realm of public consultations.

We argue that one explanation for this shift is the repeated perception of powerlessness of the ONDRAF/NIRAS representatives in the face of the lack of governmental support for the HLRW program they suggest. It is a variable the agency cannot control. The Belgian RWM organization, as a public interest body, has less margin for action than the Canadian NWMO. For example, experiments entailing consultations could not be conducted or extended without the agreement of the relevant ministries. Belgian ONDRAF/NIRAS' initiatives are subject to Government oversight even if it benefits from considerable autonomy in its decision-making and management capacities. Secondly, although the agency wields considerable influence, the ONDRAF/NIRAS has failed to convince the political authorities that its choice of deep geological disposal is the only option. The Belgian RWM organization has to deal with a state of political uncertainty concerning the option to be implemented and for continued funding of the associated research and development programs.

Nevertheless, it would be a mistake to think that the Belgian RWM organization positions itself outside the experiment it aims to control. Quite the contrary, the body is fully aware that it is an integral part of it. For instance, the Belgian RWM organization fears that its proactive actions could be badly interpreted by the local and regional actors who may be included in later phases of the process. On this subject, the agency considers that the political decision about the conceptualization phase will give social and legal legitimacy to its recommended option. According to some ONDRAF/NIRAS representatives, its actions will be legitimated and recognized by civil society through its elected representatives, especially the Government. But the recent (absence of) ONDRAF/NIRAS actions have already created several tensions: the public potentially concerned (at the local level and across borders) have expressed negative opinions about the process and the content of the ONDRAF/NIRAS project. The ONDRAF/NIRAS is thus waiting for a pre-established protocol to be designed by the national political representatives. They seem to expect a legal instrument supported by policy-makers that would provide the official outlines of future experiments.

Compared to the two other countries, the HLRW program in Belgium is at a crossroads. It is the only country studied where the conceptualization phase remains uncertain. Indeed, even if the ONDRAF/NIRAS strongly supports the deep geological disposal option, Belgian federal authorities have not officially validated any option. At most, there have been political declarations in successive government statements promising to make a commitment but the national HLRW management policy remains to be defined. There is no operationalization phase yet and the long-term project remains lost in 'placelessness' (Table 1).

4. Discussion: Assuming the experimental status of real-world and its consequences

Following the illustrative cases of France, Belgium and Canada, the aim of this section is to launch a debate on the challenges of considering the HLRW program as a real-world experiment and on the importance of experimental mindsets in such a context.

We have seen that the instruments mobilized to produce knowledge, the forms of demonstration, the roles of different audiences and the expected outcomes are modified when they evolve in an open and "non-scientific" environment. We argue that assuming the experimental status of such a program may affect our ability as an analyst or practitioner (manager, controller, or committed stakeholder), to examine and reconsider the underlying assumptions and management practices that drive a particular program. If all RWM organizations and other stakeholders (including regulatory bodies) embrace the uncertainties inherent in the HLRW program, their mindset fundamentally changes the way in which these uncertainties are managed and communicated. Their mindset also influences the choices of instruments, the type of demonstration, the roles of experimenters and audiences they expect.

We consider that there are three issues that need to be addressed systematically by any analyst or practitioner wishing to be part of, or to evaluate, a radioactive waste management program:

- Concerning recognition of the experiment: Do the experimenters recognize the experimental status of such a program? Do the audiences do the same? Why (not)?
- Concerning the potential of instruments: How does using (new) instruments such as law change or affect the experiment?
- Concerning the type of control: In a context of high uncertainties, what is controlled or what should be controlled (according to whom)?

First, acknowledging or refusing the experimental status of a nuclear waste management program may be strategic. The actors responsible for the experiment and the audiences of the experiment (no matter who they are) may resist, refuse and oppose the status of the program being qualified as a 'real-world' experiment. Their aim may be to 'close down' the experiment, refuse to name it as such, or to only accept the status as temporary, until a final solution is found. By contrast, actors may adopt another position, which is to acknowledge the experimental nature of the HLRW program, to envisage it as a new hold on the governance of radioactive waste. This position considers the experimental nature of the program as the permanent and normal course of action. This first distinction is fundamental. Indeed, in the former case, actors tend to see and position themselves 'outside' the real-world experiment. They issue a diagnosis from the outside and then formulate a response that tends to produce effects that are beyond their control. Anything beyond their control is subsequently considered as a 'challenge', something that must be overcome and fixed in order to arrive at a situation that is an improvement according to the stated objective or the previously established result to attain [80]. In the latter case, the actors responsible for the experiment see and position themselves as acting from inside the permanently ongoing real-world experiment. Along with the other actors, they take action in order to modulate, not control. The experimental process can be the object of permanent or temporary instrumentalization, supporting the ideological interests of the actors – whether these are activists opposing a deep geological disposal concept or nucleocrats – and reinforcing their positions.

With regard to this first question, a distinction needs to be made between the experimenter(s) and the audiences of the experiment (the direct or indirect target of the program). It concerns their capacity to insert themselves, whether consciously or not, in the ongoing process. Several scholars stress that for nuclear waste experiments, audiences are not always explicitly seen or recognized as such [31,40,81]. Consequently, the actors affected by an experiment may not even be aware of their status as experimental subjects. The experimental site can also become structured and the protocols can come into play without, for instance, really considering the potential host territories and their inhabitants. This raises several ethical and social challenges, as already

Table 1
Comparison of the process of real-world experiment on high-level radioactive waste management in France, Canada and Belgium.

Process of real-world experiment	France	Canada	Belgium
Conceptualization phase	***Open mindset*** of OPECST Invisible role of ANDRA	***Open mindset*** of the powerful NWMO	***Open mindset*** of the powerful ONDRAF/NIRAS
Selected outputs	***Reversibility principle*** (supported by Government decision in 2006)	***Adaptive Phase Management principle*** (supported by Government decision in 2007)	/(No government decision)
Operationalization phase	***Closed*** mindset of powerful NWMO. (supported by policy framework that strictly ***constrains experimenter's roles and practices)***	***Open mindset*** of the powerful NWMO (supported by policy framework that strictly ***constrains experimenter on HLRW principles)***	***Closed mindset*** of the powerless NWMO (with an unchanged policy framework)
Siting phase Audiences' reactions	Host territory ***(one preselected site, Bure)*** Strong local opposition from concerned audiences	Host territories ***(two potential volunteer sites)*** Local Support/Disinterest from potentially concerned audiences	Host territories: ***(none)*** Disinterest from potentially concerned audiences

mentioned by Felt et al. [82]: 'we are in an unavoidably experimental state. Yet this is usually hidden from public view and public negotiation […]. If citizens are being enrolled routinely without negotiation as experimental subjects, in experiments which are not called by name, then some serious ethical and social issues would have to be addressed'. But do the embedded actors agree that we live in an experimental state? Why (not)?

Second, the analysis of our three case studies underlines the fact that in the real-world experiment, new devices or instruments including legal instruments may be mobilized. Their initial objectives, their long-term roles, their effects (irreversible or not) and the way in which the different actors mobilize them needs to be analyzed in more detail. What should be the role of law? We have seen that the Belgian RWM organization considered it as a way to validate the program and to plan the next steps of their suggested research agenda accordingly. In France, the successive laws that were passed were instrumental and binding in the organization of the roles and practices of actors and the continuation of the HLRW program. In Canada, the law seems to sustain HLRW principles giving the NWMO more freedom to organize its scientific and consultation process. Three potential uses of legal instruments can be identified. On the one hand, legal devices can validate new practices *a posteriori,* once stabilized. They can also plan and define in detail the next practices to adopt. In these two cases, the law can also rigidify future actions. But legal instruments can also be used as tools that define a minimum to be reached or that validate the main management principles to be respected during the ongoing process. As Barthe and Lindhart [42] point out, a new debate must be reformulated on the implicit hypotheses and biases of the adopted policy: "It is a question of the way to formulate policy that definitively realizes the impossibility of settling all matters once and for all. This would fully assume the observation that any form of intervention, any "solution" is nothing more than the relaunching of a continued process of transformation and revisiting of what poses a problem". Lastly, in some cases, like in Belgium, we add that the absence of legal instruments may also be seen as an opportunity to innovate and to further experiment.

Third, concerning the question about what is it that should be controlled, two different framings are possible depending on the experimental mindset of the organization in charge of managing the experiment. We highlighted two kinds of experimental mindsets in our three case studies. They both provide different answers to the question of the main variables to focus on, how and who should design them, how to deal with conflicts and unexpected events, what are justifications for participation and expert analysis, and what are the expected outputs and outcomes.

The first one a 'closed' experimental mindset that aims to control the outputs and the outcomes of the real-world experiment without considering any kind of opening up moments. In the case of HLRW management, this means considering a particular outcome, deep geological disposal, with pre-established design and advanced planning, and assuming that all stakeholders will share the same vision of how to technically and socially achieve the expected outcomes, regardless of any uncertainties that may arise. This used to be the case in France, Belgium and Canada before the so-called 'participatory turn'. To a lesser extent, it still is the case in Belgium when the ONDRAF/NIRAS refuses to take repeated public requirements seriously, or in France, when the ANDRA promotes one particular design of the deep geological disposal based on what OPECST called "opaque" financial and technical choices. Audiences are excluded from certain technical and financial negotiations and cannot witness the full demonstration. In these cases, the aim of producing scientific knowledge is to demonstrate how uncertainties can be anticipated and how the program favoring the deep geological disposal concept can respond to those uncertainties. For instance, in France the ANDRA wants to demonstrate that Bure is and will remain the best host site for the project. The main focus on the demonstration is on the desired outcome and how to ensure that the provided solution is safe enough based on the original plan. This strategy remains the most common one [27].

The second mindset is the 'open' experimental mindset that integrates the element of surprise and complexity. With this mindset, we highlighted that additional variables (such as reversibility or adaptative phase management conditions) can raise substantial sociotechnical challenges. In the case of HLRW management, it means partially recognizing that the final version of the envisioned outcome (deep geological disposal) beyond the conceptualization phase is not yet known. Rather than aiming at full control over the program, efforts target the modulation of the long-term project and its design according to possible future uncertainties. Here, the aim of scientific knowledge is to demonstrate how the HLRW program can absorb uncertainties and how the deep geological disposal concept can be modulated accordingly. Our analysis has shown that the Canadian NWMO modulates the HLRW program according to the successes or failures that occur during the process (e.g. the withdrawal of one local municipality or the inadequacy of a local underground territory).

5. Conclusion: Open mindset as the only way to deal with nuclear Real-World Experiment?

For radioactive waste managers, experimenting in the 'real-world', implementing or controlling a sociotechnical program on a particularly difficult object remains extremely challenging. Outside the confined space of a laboratory, experiments take on another dimension: every initiative of the experimenter is likely to have irreversible consequences and lead to strong lock-in. Experimental conditions are no longer completely under control, uncertainties are a sort of 'default mode' but are at the same time technical, political, societal, environmental and economic. In this paper, we have shown that the Belgian, the Canadian and the French RWM organizations are fully embedded in the experiment and that they must deal with complex networks and tough constraints. Operating on bounded site(s), their national territory, they also have to demonstrate their capacity to manage the unknown and the

unexpected in front of larger audiences, some of whom are very skeptical, to say the least.

In search of sustainable solutions in the face of current sociotechnical uncertainties, the experimenter's mindsets in HLRW management or, more generally, in the management of contested technological objects, are crucial. First, because experimenters such as RWM organizations often appear to be the most powerful actor. Even in the 'open air' laboratory, the experimenter usually remains the leader of the experiment and endorses multiple roles of primary importance: taking the initiative, having the main funding support, having the power to delegate the consultation processes if needed, and occupying a particular spot in the policy room. As the experimenters mainly in charge of conceptualizing, managing, and operationalizing the long-term HLRW program, the RWM organizations in France, Belgium and Canada deal differently with uncertainties that arise in their management programs. Here, we have highlighted how the RWM organizations all tend to control particular program parameters such as their preferred research and development programs, the technical and safety aspects of it, or who they consider to be relevant actors to influence the program.

We stress that the different forms of real-world experimentation in France, Belgium and Canada vary because of the contrasted experimental mindset of the actors involved in the experimental HLRW program. We suggest that we gain analytical purchase by viewing RWM organizations' mindsets as more or less open or closed. These two mindsets aim to deal with uncertainty, ambiguity or the unknown, but with different entry points. They both differently influence the key variables to focus on at first glance, the underlying premises of the end result and its design, and the relevant people to demonstrate or witness the HLRW program. The two mindsets provide different spaces for conflict and unexpected events and mobilize different justifications for expert participation and analysis. As a result, the power of the audiences who wish to shape the HLRW program is not the same and the resulting outputs and outcomes are modified accordingly.

The closed experimental mindset concentrates above all on controlling the final result of the HLRW program, its design is fixed in advance according to a strict schedule. With this mindset, the ongoing process aims to achieve and justify the desired result at all costs: the experimenter must demonstrate that the initial protocol can address the problems and avoid any kind of surprise. Conflict and unexpected events have to be resolved. Public participation (if necessary) and expert analysis are used as a "pacification" tool to help close appraisals and commitments (in the sense of Stirling). With a closed experimental mindset, there seems to be an expectation that the public is more passive in validating the program predefined by the experimenter.

By contrast, with the open experimental mindset, the primary focus is on quality control of the process and the design of the final outcome is considered to be changeable and adaptive. With this mindset, the experimenter recognizes that it is impossible to control all the variables. Therefore, planning is flexible and the protocol includes the possibility of surprises and unexpected events. The rationales for public participation and expert analysis are rather "normative" tools because they are used to *collectively* design opening up appraisals and commitments. Here, the experimenter asks for more proactive audiences: not only do they validate the experimenter's results, but they expect to generate knowledge and feed the HLRW program.

For decades, a 'closed' mindset has been the norm for some RWM organizations. With the participatory turn, active audiences have forced them to adopt at least some 'open' mindset moments. But our illustrative cases also highlight the fact that in some cases, the RWM organizations quickly revert to a closed mindset, thereby limiting the role of the audiences. The variations from one mode to another over time, the reasons for these changes and their consequences for HLRW programs should be studied in more detail in the coming years.

More importantly, one question remains: regarding the real-world experimental status of the HLRW program, should the open-mindset be the only way to deal with nuclear waste in a real-world experiment? We emphasize that assuming the real-world experimental status of the controversial program means two things to the experimenter: recognizing the limits of control over experimental conditions and considering more substantial moral arguments when making technical choices before wider audiences. Decision-making power is no longer solely in the hand of the RWM organizations and should not be. Faced with the impossibility of controlling all the variables in these timeframes, responsibilities, knowledge production and trade-offs have to be shared *collectively* as do the potentially greater (unexpected) risks with irreversible effects and financial responsibilities will *de facto* be a "common good". Sociotechnical issues and ignorance need to be communicated more systematically and to be considered as a normal way of dealing with uncertainties. In particular, a more comparative exploration is needed to identify the virtues and potential pitfalls of the open mindset in a controversial energy program.

Considering HLRW management as an ongoing 'real-world' experiment and assessing how open the mindset is on these issues is an invitation to analyze and act differently on waste management programs. Taken seriously, it offers opportunities to embrace uncertainties with humility and collectively rather than simply pretending there is a way to control them completely.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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