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The impact of the inclusion of microbiology on expert conceptualization and public perception of geological disposal

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Publishable Summary

In comparison to other scientific disciplines, microbiology has received relatively little attention in the context of deep geological disposal (GD) research. Starting from this observation, this report illustrates how, in the European project Microbiology In Nuclear waste Disposal (MIND)[1], microbes, microbiologists, and microbiology are introduced in the international network around researching and implementing deep geological disposal facilities. Drawing on qualitative and quantitative social science methods, the study sheds lights on: (a) the ways in which project experts (MIND researchers, researchers, non-microbiologist experts, members of the MIND Implementer Review Board) and non-experts (e.g. citizens) present, receive, and understand the integration of microbiology into nuclear waste management; (b) based on findings elicited in (a), develops a communication approach to be used in order to support the informed decision-making of all stakeholders in RWM. The report seeks to enhance reflexive awareness among stakeholders about how they conceptualize and communicate the role of microbiology/microbiologists in nuclear waste management, and initiate debate among them on outstanding issues, challenges, and problem areas, such as safety, public communication, and uncertainty management.

Keywords: Communication, Geological disposal, Microbiology, MIND, Nuclear waste, Social sciences.

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1 Introduction

Scientific research on the role of microbes in radioactive waste is characterized by a considerable degree of exoticness, uncertainty, and ambiguity. Not only are the results of such research often undecided, they may also elicit mixed or even contradictory interpretations. Adding to this complexity are the various values at stake in microbiology research: technical and economic considerations unfold with concerns of safeguarding or enhancing public safety and trust, "good communication," and intergenerational solidarity to give a few examples. Accordingly, microbiologists, like many other researchers today, must work to meet the demand of generating scientifically sound research that is also socially and economic relevant (Rip, 2000). To do so, they must actively engage with funding incentives, a wide range of disciplines and technologies, and various stakeholders (Schröder, 2016).

Acknowledging the complexity of this research setting and how it is organized is important to scientists and all concerned stakeholders, as it facilitates understanding of the dynamic interplay between science, technology, and "the social". Many microbiologists acknowledge this interaction between research activity, value considerations, and incentives, and the various opportunities and challenges this gives rise to. To give an example, from the project outset several MIND project members conveyed to us that it is not always easy for microbes and microbiologists "to be taken seriously" by "the people that count in radioactive waste management". More recently, a few project members stressed that while there is "improvement", they still struggle to position microbiology in geological disposal and radioactive waste management. These frictions and struggles reside also in the MIND project itself and within the microbiology research community. For instance, one MIND member described to us that, "we want our research to be scientific but it also has to be fitted to the safety case". Whereas building a stronger "safety case" is presented as an overriding concern in the MIND project description (See: http://www.mind15.eu/about/), project members have on some occasions distanced themselves from the notion of safety all together, for instance by presenting their research as "pure science" which is "evidence based" as well as politically detached.

The aim of this report is to bring these observations to light, thereby opening a space to discuss the challenges and opportunities of introducing microbiology into radioactive waste management (RWM), with due attention for technical *and* social aspects – specifically (but not exclusively) communication aspects (see part B). In this way, the report seeks to improve our understanding of the processes of what is arguably a scientific discipline 'in the making' and of developing new research and policy directions in relation to RWM. It will be of interest not only to MIND researchers but to all actors involved in science and technology development and policy making, including end users, policy makers, regulators and concerned publics.

2 Methods and approach

To gain a better understanding of these challenges and how experts sought to tackle them, we adopted a grounded, inductive approach that observes how these actors process new data and insights, and resolve challenges. Drawing on semi-structured interviews with actors in the MIND project (MIND researchers, researchers, non-microbiologist experts, members of the MIND Implementer Review Board), on techniques of participant observation, and documentary analysis, we ascertained how the integration of microbiology in nuclear waste management elicits or affects: (i) new topics and processes, (ii) knowledge gaps and uncertainties; (iii) priorities and opportunities; (iv) future outlooks. The semi-structured interviews with experts and our notes from participatory observation allowed us to identify the abovementioned issues (i-iv) and the strategies actors deploy to discuss and manage these issues (e.g. the development of intermediary languages using models, scenarios, calculation cases), as well as justify the role of microbiology/microbiologists in nuclear waste management. We also drew on relevant public statements, authorizing statutes, MIND documents, etc. to facilitate interviewing and draw out responses from experts. Various data of the communicative interactions

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(interviews, group meetings, conference presentations) were collected using a digital audio recorder, and thereafter transcribed and analysed using NVIVO software. All data have been fully anonymized to ensure research subjects' privacy.

Examples of guiding questions for experts in the early stages of the MIND project included the following: Why is it important to study microbial processes in relation to nuclear waste disposal? How will microbes affect the evolution of a repository? How can microbiology make a contribution to radioactive waste management? Does taking microbiology into account contribute to a more complete and realistic safety case, as the MIND website suggests? In which ways? Why is this important? What are the biggest challenges you and your colleagues face in this research field? When will the MIND project be a success?

The questions were meant to invite reflection on the rationales and motivations that inform the MIND project, including the project's premise that MB deserves a more prominent role in GD research. They elicited additional reflections and considerations on the role of microbiology in GD and RWM, enabling us to identify recurrent challenges and opportunities in how experts make sense of, and communicate, their research to colleagues and non-experts. The identified themes were followed up through document scoping, additional conversations with research participants, participant observation and group discussions.

A detailed description of how these themes were discussed among MIND project members and other stakeholders is provided below, along with a summary of a participatory workshop held in Mol (Belgium) in 2018 with local residents, among other public stakeholders. The themes are not exhaustive but indicative of issues (e.g., interdisciplinary collaboration, public communication, uncertainty management) raised time and again in and beyond the MIND project. They are meant to sensitize MIND stakeholders to their own research concepts and practices, including the value all stakeholders, without exception, ascribe to public communication – particularly as research on the role of microbes in radioactive waste is characterized by a considerable degree of exoticness, uncertainty, and ambiguity.

In addition, we investigated a communicator, an audience & channels of communication in a particular social context. For this, document analysis, media analysis, interactions and a dedicated workshop have been applied. Table 1 provides an overview of the different methods used, focusing upon the data gathered.

Method	Data gathered from
Document analysis	Radioactive waste research & strategic policy documents, MIND documentation (reports, websites, papers, media articles, multimedia etc.)
Interviews	Scientists, implementers and regulators
Group discussions	MIND participants and others
Participant observation	MIND events in Granada, Prague, Mont Terri etc.
Open-up your mind discussion	Advanced training course in geomicrobiology (Mol, Belgium)
Public value workshops	Local residents, life scientists, a member of the Belgian waste management organization NIRAS/ONDRAF
Online Survey	Experts, public and students

Table 1: methods used

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3 Microbiology, microbiologists and microbes in geological disposal research: expert conceptualisations (Part A)

In this section we shed light on the manifold ways in which project experts (MIND researchers, non-microbiologist experts, members of the MIND Implementer Review Board) and non-experts (e.g. citizens) present, receive, and understand the integration of microbiology into nuclear waste management. These findings give rise to challenges and opportunities and serve as inputs for part B, which provides communication guidelines for experts on how to communicate among themselves and with wider audiences about microbiology in the context of geological disposal projects.

3.1 Background

After decades of dedicated research worldwide, today the international consensus seems to be that GD research is mature enough and that the time is right to move towards implementation. To this aim, the Implementing Geological Disposal of radioactive waste Technology Platform (IGD-TP) was launched in 2009, bringing together European waste management organisations (i.e. the organisations in charge of national RWM, further referred to as 'implementers') and other bodies concerned with the implementation of deep geological disposal facilities. The vision of the IGD-TP members is that it is "time to proceed to licence the construction of deep geological repositories" and, more concretely, that "by 2025, the first geological disposal facilities for spent fuel, high-level waste and other long-lived radioactive waste will be operating safely in Europe" (IGD-TP, 2009). To this aim, a Strategic Research Agenda (SRA) was developed, identifying remaining challenges that need to be tackled to achieve the IGD-TPs vision (IGD-TP, 2011). The IGD-TP thus is "dedicated to initiating and carrying out European strategic initiatives to facilitate the stepwise implementation of safe, deep geological disposal of spent fuel, high-level waste and other long-lived radioactive waste" (https://igdtp.eu/).

An important activity to licence the construction of any deep geological repository – and to thus move from the research, development and demonstration phase to the implementation phase – is the preparation of a 'safety case'. A safety case is "a collection of arguments and evidence in support of the safety of a facility or activity" (IAEA, 2016, p.156). Put differently, it is "a formal compilation of evidence, analyses and arguments that quantify and substantiate a claim that the repository will be safe" (OECD-NEA IGSC, 2013, p.7). More concretely, "the safety case shows how the barriers in the disposal facility and associated host rock (the disposal system) work together, and how they fulfil their desired functions over time" (ICRP, 2013, p.34).

In this research policy context, microbiology has received relatively little attention compared to other scientific disciplines. In 2009, the Joint Research Centre (JRC), the European Commission's science and knowledge service, published a reference report which stated that "the potential importance of microbial activity for the evolution of the repository-relevant geochemical systems has long been underrated" (JRC-IE, 2009, p. 19) and that "overall the quantitative role of micro-organisms in repository development and far-field migration is not fully understood yet" (JRC-IE, 2009, p. 20).

These observations serve as entry points for analysis of the MIND project, as the MIND project is premised on the understanding that microbiology deserves a more prominent role in GD research and RWM. Although microbiological studies do have a longer history in RWM, dating back to the 1980s (see e.g. OECD-NEA, 1985), many scientific questions remain to be answered and several challenges remain to be addressed (Ahonen et al., 2016, p.16-17), including among others, "the multidisciplinary challenge to describe and model radionuclide migration in geological systems [starting from] simplified concepts" (Ibidem, p.17) and "the integration of different scientific disciplines and production of scientifically consistent models of the geological repository environment" (Ibidem, p.2). With these

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considerations come a range of broader socio-technical issues, such as how to safely dispose of nuclear waste to ensure the safety for future generations of humans and the environment in general.

3.2 Results

3.2.1 a) Expert conceptualizations

During our conversations with microbiologists in the initial phases of the MIND project (interview A, discussion group 1), it became clear that for many of them "microbiology is of course very important", but they are aware that "not everybody thinks the same". They felt they "have to fight to get the people who count in RWM in". The most important thing is not to publish good quality research, it was said, but "to be taken seriously by the people in charge of RWM" (discussion group 1). Before (and for some also still during) the MIND project, some had the impression that this was not really the case. An interviewee for instance disclosed: "When I started working with this, many years ago, a common reaction from the engineers and construction people and even geologists, was like 'oh microbes... oh that's cute'" (Interview C).

During the second year of the MIND project we further investigated this subject during interviews (interviews B&C) and a discussion group with researchers with an interest in MB from inside and outside the MIND project (discussion group 2). Illustrating that the network of actors involved in GD is constantly evolving, an actor active in the MIND project painted the following evolution during an interview: "When [implementer X] started, it was a company that only consisted of construction people and geologists. But they didn't really care about chemistry at all. So that was completely neglected. And then when we started studying the chemistry more and more, I think it was when one started looking at the water flows. […] And some of the chemistry that was found in the water could not be explained by chemical reactions, just like that. Some of the dynamics. So, they realised that there must be something else. And I think that was when they started talking to X about the sulphate reducing bacteria" (Interview C). Another person formulated it as follows during a discussion group: "As a MBist I sometimes have the feeling that MB is only considered when something does not fit what was predicted to be in chemistry. And then, when there is a problem, we try to fix it with MB" (discussion group 2).

In further discussing changing perceptions and appreciations of MB over time, technological development in the field of MB was also mentioned as one of the reasons. It was said that "in the 80ies, things went everywhere and things weren't as clear as they are today" (discussion group 1). "The brief argument that we raised writing the MIND application is that compared to the 80ies the development in technology and knowledge and MB has been extremely fast. We have so much better techniques and methods and knowledge about genetics today than we had in the 80ies. It was difficult to prove evidence in the 80ies. Today we have a way larger and better arsenal to explain and explore. That could be one reason, that MB now has the tools to show it's important" (Idem). An interviewee also explained that "microbiology is such a progressive science. There are so many things that you can do today, that you couldn't do previously. [...] Today we're not just taking out a sample and seeing what microbes there are. We can look at the DNA and then we see what can they do" (interview C). Some discussion group participants combined arguments, e.g. "In the 80ies everything was focused on inorganic chemistry and we didn't have very good thermodynamic databases. […] you first need development of technical and scientific knowledge and analytical capacities" (discussion group 2).

Further exploring these evolutions, some participants in the discussion group expressed the opinion that research develops in waves: topics come and go, appear, disappear and reappear. Many factors are at play here, it was pointed out: you can see research as linear and incremental, but often it is also about individual interests and what is popular at a certain moment in time (discussion group 2).

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In line with this reasoning, some microbiologists disclosed that they may have not communicated the relevance of their research "in a very strategic manner" in the beginning, as from the start a link was made between microbes and corrosion and how this may impact the SC (Interview A). "All focus was on microbial induced corrosion that would have detrimental effects on containment. Whereas I think more recently when we've considered things like consumption of gases and breakdown of organics, that there are many effects that MB has" (discussion group 2). Following this reasoning, another participant wondered whether MB may also not be welcome because it may suggest a need for costly adaptations of the GD system design (e.g. thickening the canister) (discussion group 1). Other actors identified an opposite effect of highlighting of potential negative effects of microbes: "He showed some examples that really looked very badly corroded. And then people jumped very quickly: 'look at the sample, it is very badly corroded, and they included bacteria and the implementer has not looked at that'. And this kind of pushed the implementer into looking at this issue again" (interview B).

One actor also explained how media coverage about the positive effects of microbes helped to bring MB to the foreground. "Of many articles in newspapers about RWM, the only positive one was about microbes" (PAM Prague). This helped to mobilise attention and funding, it was said.

In line with seeing research as developing in waves, other researchers identified a change or evolution in focus in GD research, notably from the long term and the far field to the shorter terms and the nearer fields. Especially in the more initial phase the role of MB is important, it was pointed out. It was highlighted, however, that this also influences the evolution scenarios and thus requires to also review the studies on the long term and the far field, as microbes may cause multiple bifurcations in evolution scenarios (discussion group 2).

The role of individual personalities in agenda setting was also pointed out in an interview with an actor active in the MIND project. "Up to now I haven't heard people worrying too much about MB. With the exception of country X, but this is somewhat related to person Y who, well, it's kind of normal, he is a MBist, he has his company" (interview B).

Networking in action: the MIND project

MBists knew that they would have to address the IGD-TP to overcome the hurdles "of not being taken seriously" in high-level RWM research. They explained how, after 3 years of intense discussions between MBists and the IGD-TP, MB was included in the 'key topics' of the SRA of the IGD-TP (interview A). The MIND project proposal was based directly on this part of the SRA. By aligning itself with the IGD-TP the project got funding via H2020, addressing the Euratom 2014-2015 Work Programme topic NFRP 6 – 2014: Supporting the implementation of the first-of-the-kind geological repositories (http://www.mind15.eu/about/).

Studying the MIND project proposal, we can see how the MIND researchers formulated strong statements aimed at inscribing MB, microbes and MBists into the network around supporting the SC and the implementation of GD internationally. "The objectives of the project target key technical issues, involving microbial processes, which must be addressed to facilitate safe implementation of planned geological disposal projects in the EU. The knowledge of system-dependent microbial processes that affect repository safety and performance is incomplete because current safety assessment concepts either ignore microbial processes, or adopt a simplified approach to assess the performance and processes occurring in the waste form, backfill, buffer and host rock systems" (MIND grant agreement, p.6, own italics). Both the presence and activity of microbes are highlighted: "Despite the ambiguity related to the possible presence of an indigenous microbial population in the host rock, microorganisms will be ubiquitously present in the repository as it will not be possible to build a repository in a sterile manner. It has been shown that those communities can survive and be metabolically active, hence they have to be considered when radioactive waste will be disposed"

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(Ahonen et al., 2016, p.26). We can thus say that the existing SC and implementing GD network at large was entered by establishing a common mission ("to facilitate the safe implementation of GD projects") and by highlighting the de facto presence of microbial processes in RWM, for which MBists would have to act as spokespersons.

Next to aligning their overall discourse with the vision of the IGD-TP, the MIND project proposal furthermore outlines how MIND researchers will directly address topics identified in IGD-TP SRA as "high urgency" and "high importance" (IGD-TP, 2011) (MIND Grant Agreement p.8). MIND researchers thus realised further enrolment into the network by developing their objectives in collaboration with the IGD-TP members, focused on "improving the safety case knowledge" (MIND Grant Agreement p. 4 – 5). "These objectives have been developed with consultation of waste management organizations (WMOs) and are thus targeted at specific remaining issues concerning geological disposal of intermediate and high level radioactive wastes" (MIND Grant Agreement, p.5).

In the second year synthesis report, we can again clearly recognize different networking actions. "Microbiology In Nuclear waste Disposal (MIND) is a multidisciplinary project with the goal of addressing key microbiology technical issues that must be tackled to support the implementation of planned waste disposal across the EU. Whilst it is widely acknowledged that microorganisms are capable of transforming materials within nuclear waste and under the conditions of waste disposal, our understanding of what impact these processes will have in situ remains tenuous. The project is designed to tackle a number of topics identified in the Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP) Strategic Research Agenda (SRA) as "high urgency" and "high importance" (Mijnendonckx et al., 2017, p.1, networking phases added).

MBists thus take up a spokespersons' role for microbes, presenting them as undeniably present and influential, and thus as an obligatory passage point in the implementing GD and SC network. It is highlighted that "our current understanding of the impact of microbial metabolism on the safety of geological repositories remains tenuous, even though microorganisms may have controlling influences" (MIND Grant Agreement, p.5). Put differently, "the main question is not whether microorganisms are present but to what extent they will impact the safety case" (Grant agreement p.8), because "by excluding microbial processes […] uncertainties and technical issues remain that could undermine the repository safety case" (MIND Project Proposal p.4).

Further networking is also foreseen in the MIND project proposal. Work package 3 of the project proposal is specifically focused on integrating microbial processes in the conceptualization and performance assessment of geological repositories, and on communicating and disseminating conclusions and results as widely as possible. MIND thus aims to broaden the network by distributing its results "to a broad audience, including students, professionals, the scientific community, stakeholders and the lay community", through training and education (courses and an exchange programme) and information exchange (website, newsletter, peer reviewed papers, open meetings, …) (http://www.mind15.eu/work-packages/wp-3/). "In addition, possible synergies of the MIND program and consortium will be identified and cultivated with ongoing research lines of European laboratories and institutes outside the MIND consortium" (Idem).

We investigated MIND's networking activities among others by discussing the question "When will MIND be a success" in discussion groups. The following elements were brought forward: "if we can get WP3 to fulfil its intentions to communicate and spread the word, including education and training to a larger audience, then it's a success. Even more important than good laboratory work and science, is that we can translate the science we do into something that is understandable to a larger audience" (discussion group 1). Another person added: "It's not only a matter of communicating, but also of making sure that all the results we have are useful for going further into something like performance

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or safety assessment. So not only doing science for the science […] but really making a difference and making it into future performance assessment" (Idem).

Networking also took place throughout the MIND project by the installation of the Implementer Review Board (IRB), aimed at ensuring a link with the established network throughout the duration of the MIND project. The IRB consists of representatives from 10 implementers of the IGD-TP. Other organizations that officially followed the project are two technical support organisations (TSOs, i.e. research entities that support the implementer) and one regulator (MIND Newsletter 5, April 2018).The purpose of the IRB is to "advice the project with critical evaluations con¬cerning research quality and significance of outputs" (MIND Newsletter 5, April 2018). It "evaluates the progress of the MIND project by following the project on the webpage, reviewing and participating in discussions of the outcome at the yearly project meetings (PAM)" (Idem).

Preliminary discussion of the success of MIND's networking activities

Some actors in and around the MIND project seemed to agree that that the interest in MB is making a 'catching up move' and gaining ground (dinner discussions at the Mont Terri meeting, 2017) and that successful networking has thus taken / is thus taking place. As an interviewee expressed it: "I think we are making progress. [...] I'm sort of comparing what we had in the past. So for me now, it feels quite easy. It's much easier for me to convince people that we have to take those microbes into account. It was so much worse ten years ago when you got those comments like 'they're cute', or 'do you really think that those small things would have any impact on the chemistry or the...'? […] Luckily people have so much more knowledge about microbiology today. And they find it very interesting" (Interview C). The interviewee concluded "the fact that we actually got this project MIND, shows that the opinion has changed. […] If we would have tried to submit an application like ten years ago, it would have ended up in the trash bin. But now there are lot of people or organisations interested in following the MIND project. And they are both scientists and waste managers, which I think is remarkable. […] This project […] it has become famous. […] It's a first. […] I'm still in shock that we have this huge interest" (Interview C).

Others, however, disagreed and continued to disagree throughout the MIND project that MB had become accepted and valued in GD research today. "I still don't see […] I feel people are open and say it's important, but personally I don't see that a priori, by design, on prediction, on an experiment, MB is taken into account" (discussion group 2).

We indeed perceived the signals about the impact of microbes on the SC and the implementation of GD as mixed, ranging from a negative to a positive impact on the SC, from 'highly influential' to 'no real impact', from 'more research is definitely needed' to 'the disposal project will not be delayed for it'. Some illustrative citations are the following:

- "we are not saying that what you are doing is not important, but you have to take into account general physics. We say this with hindsight, issues that were once thought as highly important and then appeared to be rather irrelevant. It is important, but don't be too extreme with your assumptions" (plenary discussion PAM Prague).
- "For us, the host rock is the most important barrier and if we can prove there that microorganisms, that there are space restrictions, if we can find arguments that microbes won't be active, then at least for the main retention barrier, the problem is more or less solved, to be very short" (discussion group 3).
- "MB is 1 scientific discipline among other that you have to include in the SC. You got to show that you understand what microbial processes do to a certain concept design". "There is no question that it cannot be left out if we really want to develop system understanding" (discussion group 2).

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- “Well, they are certainly relevant. […] But it is not so decisive. It is an issue that we also have to look at, like a variety of other issues” (interview B).

There was no agreement on the fact that taking MB into account would lead to a more ‘realistic’ SC, especially taking into account complexity and context dependency. But there seemed to be agreement on that it would contribute to a more ‘complete’ SC (e.g. interview B). “In any case you need to study MB in order to make a case for whether or not it belongs to the SC. It’s wrong to dismiss it” (discussion group 3).

Researchers, implementer and regulators

We already explained how the MIND project was set to aim “to contribute to a more complete and realistic safety case and to communicate the effects that microbiological processes will have on the geological disposal of intermediate and high level radioactive wastes” (http://www.mind15.eu/about/). As such, it aligned itself with the IGD-TP vision and SRA to “target key technical issues, involving microbial processes, which must be addressed to facilitate safe implementation of planned geological disposal projects in the EU” (MIND research Grant, p.6). When addressing the question ‘when will MIND be a success’ throughout various discussion groups and interviews we did, various accents were nevertheless discernible.

One discussant explained that “there is a difference for success for scientists and for [implementing] agencies. The fact that we are sitting here together and exchanging information is a success for science. […] But GD is commonly accepted as the best solution. […] No one discusses this anymore. So what is a success? Science will always go on. But we must be realize that there is an endpoint for MIND and that is when we decide that we can dispose nuclear waste in a geological layer in a safe way” (discussion group 1, own addition between square brackets).

Another participant shared the following opinion: “our [implementing] agency just wants us to prove that microbial activity will not be happening. So on the national scale we only get projects in which we have to prove that consolidation will stop activity, heat will stop activity. So from our point of view we cannot really talk about corrosion, it’s really difficult. […] It will be difficult to get the money” (discussion group 1).

The presence of multiple interests was further discussed during another discussion group, where one participant explained the following: “We ignored the MB issue in putting our license case together. And this caused many engineering changes in the design of the repository, was very costly and was all needlessly so. It was a lack of data that caused all these problems. We have since gone back and reinvestigated MB much better, understand it much more, and we realized that all of these things we did were not needed. They actually weren’t impacted. We just didn’t have good data”. Against this background, the discussion group participant highlighted the need to focus: “Once you get entrenched in a concept in a regulatory process, it’s extremely hard to change it. So it’s important to get it right, right from the start. […] So don’t volunteer so many things in MB issues that you don’t need to do. I mean, I would caution you to allow the regulatory process to drive you into huge conservatisms that make you do all kind of crazy things. It distorts the safety case […] Because the regulatory process will use that uncertainty to take you to ridiculous places that you don’t want to be. […] The regulatory process can drive you to do silly things. It’s not science, but it impacts your safety case dramatically. It might bring you to the worst of worst scenarios, and after a while you start thinking how did we ever get here” (discussion group 3). The obligation to use taxpayers’ money most efficiently was also brought forward in this context.

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Some participants agreed with the previous statements: “I would not want our regulator to be at this meeting. […] I mean there was this statement earlier when [X] said sulphide can destruct bentonite […] we probably would have spent the next few years trying to prove out why that 1 statement is not going to destroy the whole SC and all that we have done and that we do not need to ban bentonite etcetera. So I think having the regulator here would restrict the flow of the conversation. Instead of being able to talk straightforward about the science, you would have to be cushioning everything. I would have to follow my regulator around, clarifying and contextualizing everything” (discussion group 3).

Another participant explained that “as an end-user, we want to see an end to the work. And the end-users get very nervous about microbiology, because it never ends. The techniques are always improving. Next you are going to be at the gene level, then you will get to the enzyme level, it’s just always this expanding field. And when you are trying to close in to get a license, to get a permit, you want the work to come to an end. You don’t want it to open up more questions and have the scientific community sitting at the testimony saying ‘Oh but you didn’t look at this and you didn’t look at that’. I think we are trying to keep it kind of narrow to close in to meet the dates when we want to submit for licenses. And I think that’s part of the fear of the user, that it just opens up more and more questions” (discussion group 1).

Other participants did not agree with such ideas and highlighted the similarity between the interests between researchers, implementer and regulators: “I wouldn’t be that concerned if our regulators would have been at this meeting, because I think the important thing for them is to see that we have a thorough and honest scientific discussion about these issues” (Idem). This participant did, however, point out the importance of the regulator remaining independent, a concern also shared by both the implementer and the regulator according to the speaker. By participating in the same meetings and project, this may be jeopardized, it was suggested.

Still other participants did agree with differing interests among researchers, implementers and regulators, but in an opposite manner. They did not worry about MIND research causing regulators to become more conservative. On the contrary, they hoped that the MIND project could contribute to relaxing the very conservative assumptions that are currently being applied with regard to the impact of MB in the SC. This could for instance happen if it could be identified where MBal activity can be excluded, or by also studying its positive effects, it was explained (plenary session, PAM Lausanne, 2018). As one presenter put it: “today we have very conservative assumptions about microbes, we hope we can be less stringent and more knowledgeable with the help of MIND” (Idem).

Many MIND stakeholders were aware of the ‘socio-political dimension’ of the MIND project and research. Participants for instance referred back to the promise of anonymity multiple times throughout the discussion groups we organised. In light of the recordings, multiple participants ‘joked’ that they should perhaps change their voices, because some of the issues are “politically hot”. During the course of our social science research, we also received an email asking whether we take into account the possible ‘hidden agendas’ of the people participating in interviews and discussion groups. The questioner made this enquiry because he/she wondered whether people may answer questions and conduct themselves in a particular way, because of differing motivations to take part in MIND.

Future European RWM research is currently being discussed in the framework of “European Joint Research Programme in the management and disposal of radioactive waste” (EJP) (https://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/nfrp-2018-6.html). The EJP was prepared within the JOPRAD project https://igdtp.eu/activity/joprad-towards-a-joint-programming-on-radioactive-waste-disposal/). In contrast to the IGD-TP, which is led and driven by implementers, in JOPRAD and EJP implementers, technical support organisations and nationally funded research entities involved in the research and development of RWM are meant to

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join forces. This "blending of stakes" was discussed at a dedicated session at the PAM in Lausanne (2018). One participant explained that "from implementer point of view, it's problematic that research entities have such a big role, because they want to buy what they need" (plenary discussion, PAM Lausanne, 2018). On the other hand, the participant continued that from a researchers point of view, it may be seen as problematic that implementer have such a big role. Because they, and not the research community, then decides what is needed, i.e. what is useful and relevant and what is not (Idem).

Top-down and bottom-up research

By investigating the multiple interests inside and around the MIND project, we discovered what we could coin as a tension between 'opening up' and 'closing down', or between 'what one wants to know' and 'what one needs to know' in disposal research. The MIND Grant Agreement itself clearly states that "The objectives are defined by a prioritized top down approach rather than a bottom up approach driven by scientific curiosity" (MIND Grant Agreement, p. 5). What 'top down' means in this context is also explained (see also section 2.3): "to improve the understanding on the safety-relevant processes, and to integrate microbial processes in the Safety Case conceptualizations" (Ahonen et al., 2016, p.1). In practice, however, a need to find a balance between bottom-up and top-down research was found both pressing and difficult.

Interviewees for instance disclosed their impression that: "The idea seemed to be that a worst case scenario and a no impact scenario would suffice. Microbiologists, however, want to better understand all the microbial processes in between these two extreme scenarios". The interviewees explained that they did not comprehend why for instance, in contrast, it is agreed to study chemical processes in great detail. "Chemists also want to understand the full range of chemical processes and activities that (may) occur during the life span of a geological disposal facility in light of their potential influence on safety; this equally is the case for microbiologists" (interview A).

Another interviewee elaborated upon the tension between bottom-up and top-down research as follows. He/she explained that studies related to requirements for the materials and the density have been conducted in the past, but not systematically: "We have to do this more systematically and look at more than one or two places" (interview C). On the other hand, the interviewee pointed out that the initial hypotheses based on the previous sample survey do seem to be correct, even though for MBists the findings were counterintuitive. "And the reason for that, we don't really know. But the thing is, do we need to know? […] That's one of the things that I'm struggling with. As a scientist I would say, 'oh, I would like to know why'. But is that really important? You could just make the observation that if we have this threshold, if we put the density above that, we would not have any microbial activity. And the reason for that is not really interesting. So that is, what from the industrial part… 'ok it's just a fact. We don't need to do anymore research'. […] So that's the balance that I have to make between... since I am a representative of waste management organisations, so sometimes I have to say stop we don't need to know [...] but as a scientist we need to know" (interview C). A participant in a discussion group also identified this as one of the main personal challenges in this research: "to separate the processes that are really relevant from those that also occur but that are not so relevant" (discussion group 2).

Another discussion group participant elaborated: "the difficulty for those people working in the agencies [implementer] is to stand behind and make sense of all the people running into different directions. And I think that this is a general problem in science, that scientist want to find something new and therefore run in front of the others and those that stand behind sometimes have difficulties organizing this. It is about synthesizing it all in such a way that whatever you try to build, that this information helps you" (discussion group 1, own addition between square brackets).

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The relevance or usefulness of research was thus highlighted. Although MIND has a task dedicated to "Synthesis, evaluation, abstraction and integration of experimental and computational output" (task 3.1), there was discussion about who actually is responsible for this instrumental synthesis. One researcher said: "You just do the research that you want to do and then present it and then it's up to the implementers what to do with it" (plenary discussion, Mont Terri meeting, 2017). Others, however, had differing views. In the context of debating whether there would be a follow up project, a MIND 2, a discussion group participant for instance explained that: "Before, you have to attract more implementers to come and listen and interact and exchange and tell you what are the specific problems they have. [...] We need time, but that does not mean give a green card to whatever type of science and investigations" (Discussion group 2). Another MIND stakeholder pointed out that whether MIND would be a success depends on "making sure that all the results we have are useful for going further into something like performance or safety assessment" (discussion group 1). To this the speaker added: "So not only doing science for the science, which I think we sometimes may want to do with MIND, but really making a difference and making it into future performance assessment" (Idem).

Against this background, halfway through the MIND project, the IRB decided to make a 'gap-list' of high-priority issues (it was agreed at the PAM in Prague in 2017 and discussed at the PAM in Lausanne in 2018). This list was meant to indicate what really are the worries for the implementers. Because, as it was explained, "just because you have MBal activity that doesn't mean you have problems per se". Put differently: existence alone is not relevant, impact is. "Mere existence of microbes is not a concern. Only if they do something, harmful or beneficial, that would not occur anyway". The IRB thus emphasized: "Don't do what you know how to do, focus on the actual worries" and asked the MIND consortium to "quantify uncertainties and correlations, that is what you need in safety assessment" (plenary session, PAM Prague, 2017).

In finding a balance between top down and bottom up research, 'boundary drawing' (between what is relevant and what is not) and 'communication' (in the sense of dialogue, i.e. not one way communication) were thus found key. "It's important to do the right, relevant research for multiple stakeholders, but definitely for waste management organisations [implementers]. You need to educate waste management organisation people. But we also need to understand where they're coming from, from performance assessment. How they might represent processes, which processes they couldn't model and how they use arguments to underpin justifications, that side of the story. We have to communicate" (discussion group 1, own addition between square brackets). Networking with other international research activities (NEA, IAEA) was also mentioned. The IRB members pointed out that they will help spread MIND, highlighting that MB is not simply something that should worry us, but that there are things that can be done about it (plenary session, PAM Prague, 2017). In this context, dealing with uncertainties came to the fore as a very important aspect. "MIND has laid out the whole pallet of what could be relevant, now we need to narrow it down : where is the confidence too low, the uncertainty too high. Where lie the greatest uncertainties?" (plenary session, PAM Lausanne, 2018).

Uncertainties, ambiguities and transferability of research results

The aim of GD is defined as "containment and isolation [of radioactive waste] from humans and the living environment" (Council of the European Union, 2011, art.21), own italics and own addition between square brackets). But are microbes not part of the living environment? Geological disposal indeed is typically presented as a controlled, predictable, passive isolation strategy for long-term radioactive waste management, while a biotic, microbial influenced environment can be considered as dynamic on a range of scales and time spans. The MIND grant agreement underlines that "One of the primary requirements of safe GD systems is general stability and good long-term predictability" (Ahonen et al., 2016, p.3). But at the same time MIND researchers are aware that MB makes RWM

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more complex. As argued throughout the discussion groups, in microbiology, there is no clear answer: “it always depends” (discussion group 1). Because lots of factors are at play. From a scientific point of view, one participant said, there is no doubt that it has to be taken into account when designing repository for example. But by bringing microbiologists into play, you bring in complexity, it was said. This was seen as causing tension, because, it was said, RWM people like models, clear-cut answers, certainty, while microbiology questions things that are stabilized in a lot of people’s minds. Microbiology brings complexity which generates uncertainties which make solutions less clear (discussion group 1).

The fact that microbiology evolves, that it is dynamic, was thus estimated as an important reason for the experienced reluctance of certain actors to support MB in RWM research (interview A) (see also section 2.2). Because the impact of microbiology is difficult to model or to predict over large timeframes (100 000 years). “There is no ‘microbial constant’ for geochemical modelling” (K. Pedersen, Microbiology in nuclear waste disposal – Education and training. Presentation at PAM in Granada, 2016).

As one MIND researchers wrote it to us in an email: “People tend to have more faith in predicting abiotic systems as compared to biotic ones – to which I can agree to a certain level” (email of 22/02/2014). Or as another MIND stakeholder explained: “When talking about MB, people think about epidemics, viruses, … : ungraspable, invisible and uncontrollable things. While geology, on the other hand, implies stability” (dinner discussion, Mont Terri Meeting, 2017).

This topic of microbiologically induced uncertainty, complexity and unpredictability was taken further during the discussion groups. It was explained that “microbes may cause multiple bifurcations in evolution scenarios” (group discussion 2). “If microbes do this, then you get, that but also that, which suddenly gives you another problem. So in a way, you just can’t stop. You cannot stop with one process of MB, you really have to understand the whole chain” (discussion group 2). During another discussion the difference between models and experiments was also brought forward in this context. “In my nuclear agency, most people are engineers. They don’t like microbiologists so much! Because whenever they ask me a question, my answer is always: it depends. And they like to put everything into this nice, clean box. But the problems that need to be addressed, are not boxed very easily. [...] In my agency they also really like models. Because it gives this pretty picture that they can see and visualize and understand. And it’s much harder for them to understand experiments. And a lot of the experiments people are doing are going on for years, and they like to have results, but the results do not come fast enough from the empirical field” (discussion group 1).

In the context of discussing context dependency and the difference between abiotic and biotic systems, it was also explained that, in the context of GD, one cannot treat the underground as a ‘natural system’ anymore. Constructing a GD facility in the underground turns it into an anthropogenic environment, which brings in additional complexity. “Despite the ambiguity related to the possible presence of an indigenous microbial population in the host rock, microorganisms will be ubiquitously present in the repository as it will not be possible to build a repository in a sterile manner” (Ahonen et al., 2016, p.26). It was for instance explained that, in natural circumstances, microbes may not be able to live in e.g. Boom clay, due to its density. But this is different in an excavation environment. “It has been shown that just providing space – what will occur during construction of the repository – is a sufficient condition for bacterial activity what is shown during almost all borehole experiments. [...] Next to space, a microbial community needs to obtain energy to fuel their metabolic processes [...] which can be provided by the organics present in the radioactive waste” (Ahonen et al., 2016, p.26). The MIND research therefore had to focus on naturally available MB, while at the same time the importance of excavation, entering anthropogenic actants, creating a chemically damaged zone, is underlined.

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Transferability of research results across disposal sites, concepts and wastes

In line with the statement that, with MB, "it always depends', it was explicated that many uncertainties are related to particular, site and design dependent disposal system complexity and heterogeneity.

At the PAM in Prague, it was for instance explained that different clays have different capacities to block microbial activity. Even within clays with a similar density, microbes may behave differently (one also has to look at site specific water content, pH, pore space, pore water composition, …). And with regard to studying e.g. the influence microbes may have on gas pressure: this may be an issue for e.g. France, but not for e.g. Sweden, because they have cracks in the host rock, it was said (plenary discussion, PAM Prague, 2017). This context specificity for natural barriers was also found valid for artificial barriers, e.g. for the influence of microbial activity on backfill and plugs and on the waste canister materials. It was for instance pointed out that "the design of the repository needs to take into account the presence of microbes, especially for metallic corrosion, the corrosion of copper, for the waste disposal in granite, the corrosion of (stainless) steel" (group discussion 2, own italics). In this regard it was explained that disposal designs relying more on artificial, engineered barriers have a higher interest in MB than those depending on natural, geological barriers. And it was added that this could explain why the Nordic countries with their own histories and political culture may be more interested in studying MB. Countries relying more on the natural barriers, would have an interest in microbiologically induced corrosion effect notably the context of reversibility and retrievability (interview B).

It was thus concluded that e.g. French, Swiss, Belgian and Scandinavian concepts differ – what is relevant for one may not be relevant for another. And this complicates things, it was said, "you always have to specify which concept you are talking about" (plenary discussion, PAM Prague, 2017). As a discussant explained: "There's contrasting things that I find interesting. There's a lot of people trying to prove methanogenesis but we think that's a good thing, so we'd love it if you could prove it, but I don't think you can. Sulphide in our system is bad, not because it causes corrosion, but because it stops corrosion. In our case, sulphide is a passivation agent for steel [...] while we don't want passivation we want activity. So this is what confuses people. It's funny… One guy is saying it's really bad because it causes corrosion, another because it stops corrosion" (discussion group 3).

The MIND researchers tried to deal with context-dependency and -variability by addressing different aspects in different work packages. Related to this, one participant in a discussion group stated: "This comparing… maybe that's the complexity of this project. You're bringing in the low and intermediate level waste as one work package and the high level waste as another, but a process that is good in one is not necessarily good in another. So in one work package you're working hard to show sulphate reduction is happening, and in another work package to show it's not. That causes a conflict" (discussion group 3). Another participant added: "Yes that's part of the conflict, and when there's site specific issues that will be contradictory as well, even within one type of waste" (Idem).

One group participant thus concluded: "If we can find issues that are independent of waste, disposal concept and host rock, that would be great – this we can jointly discuss". But it was also said that international standards on biology are not possible, not comparable to e.g. steel. Because it is too context dependent (chemistry of soil, temperature, season, …) (Idem).

Here too the fact that geology changes from a natural to an anthropogenic environment in the context of GD was pointed out. Radioactive waste repositories will not be sterile and microbial processes will occur, the influence of which on the disposal system thus needs to be studied. But this too is both context and also time dependent. Therefore one needs to study microbial activity not only in different disposal concepts and different locations, but also for the different phases of GD (both the implementation and the post-closure phase, when e.g. clay density goes up again).

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In the context of transferability of research results, sectoral differences were also mentioned, e.g. between the oil and gas sector and the RWM sector. “The industry, the engineers that prepare the bore heads for drilling for oil and gas, they have known for a long time that when you have organic matter and sulphate, you do have an increase in your sulphate concentration, and this increases corrosion. So this is known. But perhaps they never discussed this matter with the nuclear engineers” (discussion group 1).

Are microbes a good thing or a bad thing for RWM?

As already touched upon during the previous section, uncertainties also sprung from a diverging appreciation of microbes’ impact on the safety of GD. Do they have more of a negative or more of a positive effect? While the dominant discourse seemed to highlight their potential detrimental impact (see also section 2.2), a participant to a discussion group felt compelled to intervene: “[...] maybe you go away now thinking oh microbes that’s really something the agencies worry about so much and they hide it and they don’t want anybody to open Pandora’s box. And that’s not really the case. [...] In reality, at [X] at the time, they even wrote down that we should invite microbes”. After explaining various MB processes, the discussant concluded: “So I have always been saying, not that we should invite them because they will come anyhow, but it’s nothing that we should worry about more than about e.g. sociology in RWM” (discussion group 1). During an interview, a similar positive plea for microbes was made. Focusing upon a specific disposal concept, the interviewee said: “Up to now, there is not a single case where somebody could really show that if you have microbes, it will be a lot worse. There are some cases that, if there would be microbes and if they can do what they have done in the laboratory, that it will be significantly better” (interview B).

When discussing this experienced focus on the potential negative impacts of microbes on GD, one participant pointed out that “there is still a very high proportion of projects that try to show that something is bad”. When asked whether the participant thought that “that is what is happening here too, that that is what MIND tries to do?” the answer was: “Yes. And I think it’s partly our fault. Because we’re telling them if they have something good we’re not going to fund it, but if they have something bad then we’ll give you some money because we need to study that. [...] There is a natural tendency to overemphasize the bad things. When you holistically look at MBal effects, I see them as a relatively good thing for repository performance” (discussion group 3).

Against this background, the potential to positively put microbes to work was also discussed. Can their positive capacities be engineered into the repository? “There are microbes with certain characteristics that for instance live in plants and have great characteristics: can we bring them to underground?” it was asked (plenary discussion, Mont Terri meeting, 2017). There seems to be potential for this, it was answered, since bacteria are specialized in finding energy sources, they just switch on other genes depending on their environment. When asked whether we can really deploy and rely on microbes to contribute positively to the SC, an interviewee nevertheless answered: “Nobody is able to say that, especially on the long term”. During a discussion group it was further explained that the potentially positive impacts are not included in the SC. Because you cannot rely on a potential process that is difficult to predict and very context dependent. Therefore, while positive impacts could be a nice aid, the SC is based on conservative scenarios that only take into account the potential negative impact of microbes. It was for instance explained how hydrogen gas production has already been observed at radioactive waste storage facilities, but also that oxidation occurs rather quickly. “So we install the ventilation systems based on conservative assessments, knowing that in reality we can probably worry a little less about the accumulation of hydrogen gas. And we know that it’s probably microbes that do this, because nobody else can, but we don’t have to go in and look who does it” (group discussion 2).

Assessing the actual impact of microbes

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In line with the discussion on whether microbes are a good or a bad thing for RWM, or both, we wondered how much we can actually say about their concrete impact on radioactive waste disposal. The MIND grant agreement clearly states that "the emphasis will be on quantifying specific measureable impacts of microbial activity on safety cases under repository-relevant conditions, thus altering the current view of microbes in repositories and leading to significant refinements of safety case models currently being implemented to evaluate the long-term evolution of radioactive waste repositories" (MIND Grant Agreement, p. 5, own italics). But other, later reports and accounts take a softer tone. The first yearly evaluation report, for instance, still clearly describes the potential impacts of microbes on a GD system, but it focuses not on "quantifying specific impacts" but on "understanding processes": "Microbial activity can have an impact on the long-term integrity of the engineered barrier systems and consequently, it is important to demonstrate the limits of viability of microbes both in buffer material and in the near field of the canister. Microbial activity can influence the mobilisation of radionuclides either by immobilising them or by enhancing their mobilisation, it can contribute to the gas build-up of the gas phase by the production of gas or they can reduce the gas pressure build-up resulting from the anoxic corrosion of the waste containers or microbial activity by SRB may influence the corrosion of the metal canisters. Understanding all these processes is of paramount importance for the geological disposal of radioactive waste" (Ahonen et al., 2016, pp.25-26, own italics).

Clearly the IRB members had hoped for tangible and targeted results that can be translated into straightforward recommendations and, if need be, concreate actions. But, halfway through the MIND project, a member stated the following: "When will the MIND project be a success? When they start addressing or giving answers that will impact directly on the SC. And I'm not sure all processes are understood enough. There will always remain questions to be answered in science. I wouldn't be surprised if there will come a MIND 2 after MIND 1" (discussion group 3).

So how concrete will MIND's recommendations towards the development of the SC be? Will actual changes be proposed for the repository design for instance (the choice of canister materials, the choice of extra protection for the canisters (e.g. biofilms), the choice of buffer materials (seals, plugs, backfill)? Some MIND researchers have ideas about this. Someone for instance thought about a Teflon layer on the copper canisters, because microbes cannot grow on it (interview C). Others, however, keep to "studying processes" and say that "they never had the intention to really intervene with the safety case" (participatory workshop, Mol, 23/10/2018, see also chapter 2 section X).

Dealing with uncertainty

As illustrated throughout the previous sections, MIND researchers and stakeholders are aware of context dependency, the fact that 'everything is linked to everything' in MB, which implies levels of complexity, uncertainty and unpredictability. But how to deal with this, and how to communicate about it? Different positions could be discerned among MIND stakeholders.

One participant in a discussion group for instance disclosed the following: "Microbial effects are always associated with very high uncertainty, because of the way we talk about them. This meeting was also reaffirming that. So my motivation for coming, I'm here to do damage control on our project. Because I'm worried that this stuff is going to come out, people are going to hear it and it's going to cause problems" (Discussion group 3). On the one hand we could thus discern a trend towards thinking about uncertainty as something that causes stress, and, subsequently, as something we can and should tackle and incrementally solve. Some MIND researchers for instance highlighted that the more you know about microbes, the better you understand them and the more you will know what they will do and what will happen. Here, the uncertainty and unpredictability surrounding MB was explained as "more a social thing, how people understand it". And the way to tackle this was formulated as: "We need to provide more information" (plenary discussion, PAM Prague, 2017).

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On the other hand, other MIND stakeholders seemed to accept that a certain level of uncertainty and unpredictability is unavoidable, especially taking into account the extended timeframes implied by RWM, and thus something we should come to terms with in one way or another. When for instance one PAM participant commented: “Your research reflects the complexity that is out there in reality, it’s like Pandora’s box”, a MIND researcher answered: “Yes in a way we do open Pandora’s box, but it does not have to be a doom scenario, we don’t understand it fully, but the black box does take you in a certain direction which does not have to be a frightening one” (plenary discussion, PAM Lausanne, 2018). In a discussion group, a participant put it as follows: “From the point of view of a MBist, the success would be when we are able to talk with people about what we cannot foresee, and about what we can and don’t understand. Having an agreement on the level of knowledge that we have, and stop talking about “demonstrating safety” [while] nevertheless we can agree that it would be the least bad solution” (discussion group 2, own addition between square brackets). Another participant agreed and formulated it like this: “We need to understand the processes and in a good level of detail. So that, later, we can argue, when doing the safety assessments, why or why not proposing some hypothesis on thickness or metals will be able to withstand the most worst conditions also due to the effect of bacteria. It will never be possible to make predictions for which everybody will say: this is very likely that it will be this way. So one day, you will have to assume, based on all the insights, not only from MB but also from chemistry, physics, which are the processes, the phenomenology, that you will most likely have” (discussion group 2).

Multidisciplinarity

GD and SC research involve multiple disciplines, ranging, among others, from geology, engineering, hydrology and chemistry to MB. “SCs are very holistic process arenas, there’s lots of different elements to it” (discussion group 3). In this regard, all stakeholders in the MIND project seemed to agree with the following statement: “You can’t have a hive mentality. The way out of that is dissemination and training and education, get the message out there, talk to all the different disciplines. That’s a necessity really, a lot of cross over with other areas”.

This necessity was backed up by both practical experiences and theoretical insights throughout the MIND project. One MBist for instance recalled “one time when we opened an experiment, one of the corrosion specialists there actually exclaimed ‘oh my god what is this!’ And we said ‘well, didn’t you expect this? I did!’” (discussion group 1). A similar experience occurred in the Mont Terri underground research laboratory (URL). Researchers explained that an experiment to measure hydrogen diffusion coefficient took place there. But the experiment failed, because the hydrogen was gone really quick. The experiment was repeated, but with same result. This was a mystery to the chemists, but no surprise at all for MBists, it was explained (discussions during the Mont Terri URL visit, 2017).

One participant made a direct link between such experiences and why MB seems to be coming to the foreground today. In explaining why MB is gaining ground in disposal research today, this participant said: “It has to do with the education of engineers” (discussion group 1). Another participant added: “We need to educate waste management organisation people. But we also need to understand where they’re coming from, from performance assessment. How they might represent processes, which processes they couldn’t model and how they use argument to underpin justifications, that side of the story. We have to communicate” (discussion group 1).

On the one hand, it was thus highlighted that different disciplines need to collaborate and merge their insights. During the dinner at the Mont Terri meeting, one participant stated: “In fact we would need to redo the same experiments with and without bacteria. The problem really is the divide between geology and MB. Most projects still run them separately. But you cannot do A and B separately and then just add them up” (dinner discussion, Mont Terri meeting, 2017). This stakeholder thus promoted not only multidisciplinary (people from different disciplines working together, each drawing on their

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disciplinary knowledge), but also interdisciplinary research (integrating knowledge and methods from different disciplines, using a synthesis of approaches and insights).

The need for multi- and interdisciplinary research including MB in the context of the SC was emphasized by some MIND stakeholders, because, they said, intra-disciplinary research results can simply be wrong. “If in your experiment, in the lab or in situ, you don’t care about microbes, you can have important perturbations in your measurement, and then it’s not correct to present the real situation [...] there is no question that it can be left out if we really want to develop system understanding” (group discussion 2). The varying relevance or prominence of different disciplines in different time phases (e.g. the shorter versus the longer terms) and disposal system areas (e.g. the deep underground (far field) versus nearer the surface (the near field)) was also brought to the fore in this regard. “Especially in the more initial phase the role of MB is important. The implementation phase, when things are open and a lot of equipment and foreign materials are involved. But this also influences the evolution scenarios and thus requires us to also review the studies on the long term and the far field. Microbes may cause multiple bifurcations in evolution scenarios” (discussion group 2).

It was also explained that the boundaries between disciplines are not black-and-white. “Where does mineralogy, geochemistry, … end and MB start?” it was for instanced asked (plenary discussion, Mont Terri meeting, 2017). One researcher explained how he/she was originally trained as a geologist, but then became a chemist, a ‘geochemist’. He/she started looking at nitrate in the waste disposal system, and thereby became interested in MB. He/she studied books and literature for about ten years and now feels rather comfortable in this field too. So he/she dares to refer to him/herself as a ‘bio-geo-chemist’. Nevertheless, he/she compared it to being a duck: it can swim and dive, and walk and fly – but no matter what it does, it will never be comparable to the expert, be it a dolphin or an eagle (Interview B).

Multi- and interdisciplinarity were thus esteemed valuable and necessary. It was also promoted in the first MIND annual report: “Overall, the project is multidisciplinary, covering essential fields of microbiology, geochemistry and numerical modelling. The final aim of the project is to combine the information from these different starting points to understand in detail all biogeochemical processes relevant for nuclear waste management” (Ahonen et al., 2016, p.26). Nevertheless, multiple challenges also became apparent throughout the project in this regard. We understand these challenge in that knowledge conflicts may arise due to the cutting across of traditional disciplinary boundaries: actors are forced to operate in a context of strategies and networks that are new to them and in which their standard knowledges, methods and conceptions are challenged. This may cause a sense of frustration and even dislike. To cite one participant in a discussion group: “In my nuclear agency most people are engineers. They don’t like microbiologists so much!” (discussion group 1). Another stakeholder explained: “When, as a MBist, you try to explain something, you realize that the people you talk to aren’t trained enough to understand you, even with regard to simple processes like how life processes work. That life generally increases order inside, and decreases order outside. Now when you talk to geochemists or modellers, they think that everything will always be smoothened out and even, and everything goes to equilibrium. While exactly the opposite thing happens when life processes happen. The driving force behind life processes and chemical processes is very, very different. And it is these differences that need to be understood in order to be able to explain why MB is important. The multidisciplinary aspect of RWM, really taking everything, from life to engineering and society, is a huge challenge in itself, to have the same language and communication” (discussion group 2).

Reaching a “common language, common understanding” was thus pointed out as the most significant challenges. “One of the biggest challenges for MBist is to communicate and discuss with other disciplines. And really develop a common language. The challenge is to sort of apply the common knowledge in MB, which is huge, we know a lot. But to apply that knowledge, that is a challenge, and to see can we communicate and create a common language, from both sides. Can I explain something

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to you and can you explain something to me. I think these multidisciplinary aspects are the biggest challenge, there really is nothing of the kind done ever before. From MB, we can understand the history quite well, but to extrapolate all that to the future and mix it with chemistry, geology and all that, radionuclides with life processes, I think that's the biggest challenge" (discussion group 2). The meeting at Mont Terri, where researchers of four different projects met to exchange their finding and to jointly visit the Mont Terri underground research laboratory to see each other's experiments, was found very positive in this regard. At the same time, multiple participants to this meeting expressed that they could not always follow all the different presentations and found some of them very specific and detailed. There thus exists a great opportunity for learning in this regard.

Internal diversity within MB, within MIND, among microbes and among MBists

The different research tracks within the MIND project also revealed MB in itself as a very diverse discipline, and the MIND consortium as a very heterogeneous network. This was found to make it "tricky, because you have to digest all this knowledge and then, from such multidimensional matrixes, come up with a smart recommendation. It's very difficult to put all the pieces of the puzzle together!" (plenary discussion, PAM Lausanne, 2018). During the lunch at the Mont Terri meeting, a participant disclosed the sense that "sometimes a synthesis is lacking: [...] There is such a variety of things being done that one does not know what to look at anymore". Another MIND stakeholder also expressed the feeling that it is difficult to define a way forward or to draw conclusions. MB and MIND are very heterogeneous, and thus it is a challenge to speak as one, to communicate with one another and to the outside world (plenary discussion, PAM Prague, 2017).

The MIND MBists also experienced this diversity themselves, in MB as such and within MIND. An interviewee for instance explained that "MB departments at universities commonly do 'white MB', dealing e.g. with yeasts, aging etc., i.e. more clinical MB. This is considered more 'sexy' than microbiology on or in the ground" (Interview C). A discussion group participant explained that, in this field, "MIND is the first time that Europe has come together and is trying to work together. That didn't happen the first 30 years" (discussion group 2). This was acknowledge as a challenge, but also an advance. MIND was explained as a unique, first of its kind project where MBists are "trying to fill in all these gaps in knowledge and [thus] had to involve so many different groups internationally" (discussion group 1).

This challenge of internal diversity in MB was explained as springing not only from emphasizing different techno-scientific aspects, but also from more social dimensions. "When we were pushing for this program, I was approached by some other people who explained to me that of course MB should have a network, but I should not apply for a program, definitely not. So I was like 'what is this?!'. So we applied for a program and we got it. There were 6 applications, MIND was number 2, and number 3 that got money was run among others by the people that recommended me not to apply for the project! So you can understand what happened there, they didn't want the competition. That was on the European level. But then I am quite sure it will also be on country, organization level. You find this fight on all levels, even within organizations maybe even within your own laboratory" (discussion group 1).

3.2.2 b) Non-expert conceptualizations

Building on the findings above, we initiated a participatory workshop in Mol (Belgium) on 23 October 2018 with the aims of: (a) identifying how non-experts (e.g., members of informed civil society) perceive of, and communicate, the role of microbes and microbiology in a geological nuclear waste disposal; and (b) suggesting ways to fruitfully integrate public values, considerations, and communication strategies into ongoing research and development (R&D) processes and

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communication strategies related to nuclear waste disposal. More broadly, the workshop aimed at stimulating reflexive learning among participants. Workshop participants included:

- 14 members of Mols Overleg Nucleair Afval (MONA), a nonprofit organization consisting of local Mol residents, representing local communities and their stakes in nuclear matters;
- 4 SCK•CEN life scientists (3 microbiologists and 1 specialist in geological disposal and safety), directly involved in the MIND project;
- 1 member of NIRAS/ONDRAF, Belgium's nuclear waste management organization.

These participants had accepted an invitation (in Dutch), circulated by MONA in August-September 2018. Along with practical information, the invitation contained questions to trigger their interest in the topic:

> *Which microbes impact radioactive waste, and how? Do they eat the waste? Or do they only eat the protective packaging? Why have we not heard of them before? You are invited to discuss these and related matters (long-term safety, dealing with uncertainties, the role of various disciplines in radioactive waste management) with other stakeholders in a participatory workshop.*

These questions served as a starting point for reflection and discussion, in line with the workshop's aim of eliciting reflexive learning among participants.[2] They were geared towards:

- Raising awareness among scientists and lay persons about the opportunities and challenges of integrating microbiology into nuclear waste management;
- Inciting joint discussion about the scientific and social value of this type of research, with due attention for potential risks, safety issues, and uncertainties inherent in designing and implementing nuclear waste management strategies and technologies for the future.

The workshop was structured in four stages, of which three plenary (stages 1, 2, 4) and one sub-plenary (stage 3). The latter consisted of parallel sessions with three subgroups, each composed of 6-8 participants. A concise overview of these stages is provided below.

1. Introduction stage (plenary): Workshop moderators (social scientists) introduce the aim and method of the workshop and provide participants with information about MIND and the role of microbiology in nuclear waste disposal;

2. Presentation stage (plenary): microbiology experts involved in MIND present their research work to workshop participants;

3. Discussion stage (subgroups of 6-8 participants, comprising a mix of stakeholders and moderated by a social scientist): Workshop participants jointly consider and debate the following questions:

    a. What is your view of this research?

    b. What do you consider to be the most important aspect of this research?

    c. Does this change your view of geological disposal? If so, how? If not, why not?

    d. How should research of this kind be communicated to society?

[2] Following Lave (1993), social or collective learning is stimulated when experts engage with perspectives voiced outside their professional environment (e.g. laboratories, working environment, research networks).

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    e. What else should we be debating or considering?

4. Reporting stage (plenary): Subgroup moderators and/or rapporteurs summarise main threads of discussions.

Stage 2 included screening a short video on the roles of microbes in radioactive waste management, which was created by MIND research partners: https://www.youtube.com/watch?v=RGZsWeIF5is
In stage 3, one social scientist in each group moderated the interactions between participants; while another observed and took notes, with due consideration for issues tacitly embedded in conversation, such as: Which issues and considerations do participants subject to discussion? Which issues and considerations do they take as essential (non-negotiable)? Which new issues do they raise?

All data of the conversations were collected using digital audio recorders. Using our personal notes from participatory observation as a guide (e.g., notes on nonverbal cues), they were transcribed in Dutch and compared to written material presented by participants during the workshop.

Below, we present findings from these discussion and reporting stages (3-4), where conversation ensued between the different stakeholders in response to questions a-e. Findings are clustered by theme rather than presented chronologically.

Workshop findings

The first observation is that despite their ongoing involvement in radioactive waste management, non-expert participants (i.e., MONA members) had never, or only tangentially, heard of scientific research on radiation-eating microbes. Both in the plenary and sub-plenary sessions, participants expressed **unawareness about the MIND research project** and **unfamiliarity with related research on the role of microbes and microbiology in radioactive waste and its management;** as the following statements (translated from Dutch) illustrate.

- "This research is entirely new to me."
- I had never heard of this before."
- "I had no clue… [This adds] a new dimension to conventional stories [about radioactive waste management] involving concrete and gasses."

These utterances unfolded with several **demands for clarification addressed to scientists,** with various participants raising questions throughout the workshop about a range of scientific and technical concepts and representations, such as corrosion, sulphate reducing chemical reactions, and calculations, among others. Building on these statements, various workshop participants emphasized **the need for more research of this kind,** for a variety of reasons:

- "To get a more complete picture of research and its implications for radioactive waste management."
- "…this research sheds light on the positive and negative aspects of present and possible radioactive waste strategies."
- "Because many uncertainties still exist, we need to get a better understanding of the microbes and their activity."

The **issue of uncertainty** triggered further debate, with some participants arguing that uncertainties – both scientific and social – should be understood as an invitation to conduct more research on the topic. This may in turn, generate trust in radioactive waste governance. As one rapporteur argued on behalf of his subgroup:

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- "More research is better… Even if this [research] brings uncertainties, including technical challenges and the need of finding a common denominator among different disciplines."
- "Sharing uncertain knowledge among scientists and with the public is difficult… But raising difficult questions is in itself reassuring…," and "…the fact that you look from all points of view gives more certainty, not less."

In these interactions, participants pointed to a significant challenge for MIND researchers and other scientists who research complex topics that have potentially far-reaching public impact: To clearly communicate research and research findings to broader audiences by "significantly simplifying their language," but without denying or reducing scientific complexity. As one group spokesperson pointed out, the aim should be to achieve **"the right balance" between clear communication on the one hand and doing justice to science on the other.**

Several participants argued that in the process of communicating science, establishing the **trustworthiness of communication** is an overriding concern. They argued that trust is generated in the following interrelated ways:

- By "being open about uncertainty";
- By understanding that "admission of uncertainty generates [public] trust";
- By having people "get closer to the science."

One workshop participant, however, questioned such views, arguing that it is not opportune to communicate research when results are "still unclear or ambiguous," as doing so could erode, rather than generate, public trust. He suggested that **scientists must learn to communicate their research "when they know enough,"** adding that they must **learn to identify the scientific results that a particular audience needs to know,** from among "all of the scientific results that are out there."

Talk of uncertainty also prompted responses from scientists, with one scientist stressing on two occasions that **science *is* able to control uncertainty:**

- "We *can* control uncertainty."
- "We shouldn't exaggerate the uncertainties either. We can point out the limits of microbiology."

She added that much uncertainty resides in **how science is communicated rather than perceived;** and acknowledged the value of the workshop as a means of promoting scientific communication and the importance of being seen to communicate to society:

- "We are here to broadly communicate our research…"
- "Communication is gaining importance for the public and for us."

Participants also raised **new questions** and addressed **underrepresented issues,** including a question about the role of microbes in low and intermediate level waste (LILW), and another about how research on the impact of microbes on the safety of repositories:

- "Why not also study microbes in LILW? It is acuter and maybe also interesting."
- "What is needed in this workshop is a stronger focus on how this research links to safety."

These statements were met with pleas for openness and a request for more research, with one participant exclaiming that considerable **progress has been made in how debates between all parties are held:**

- "Now it is evident to have these debates… thirty years ago this was not the case."

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The same statements incited **debate about national and international radioactive waste management policies.** Referring back to the presentations provided by scientists (stage 2), one group spokesperson raised the following question:

- “What can we learn from other countries, such as Finland, where research of this kind appears to be more accepted?”

Another participant drew a “contrast with the Belgian approach,” and raised the question:

- “…whether demonstrating that bacteria or microbes do not significantly impact clay should inform the research?”

These issues triggered a brief discussion about what types of research on radioactive waste receive funding, and why, acknowledging **differences between governmental and scientific commitments to research.** With these considerations, some participants stressed that difficult choices and trade-offs have to be made, including giving consideration to **economic cost and feasibility:**

- “Will nuclear energy still be affordable?”
- “Will we ever deal with the nuclear waste?”

These questions, they argued, should also be in focus, along with the wider policy and economic context which impacts science.

3.3 Concluding remarks

The examples provided in this section are indicative of the considerations and topics raised by experts and non-experts (workshop participants). Several of the issues presented and discussed in the workshop (e.g., interdisciplinary collaboration, public communication, uncertainty management) resonate with concerns and considerations voiced within the MIND project. They are recurrently debated among scientists, for instance at MIND meetings and conferences. Workshop participants reproduced and reiterated these issues, while also shedding new light on them, for instance when stressing the importance of trust in the communication of uncertainty and by probing the relationship between MIND research and public safety. These observations are a first step towards sensitizing MIND stakeholders to their own research concepts and practices, including the value all stakeholders, without exception, ascribe to public communication – particularly as research on the role of microbes in radioactive waste is characterized by a considerable degree of exoticness, uncertainty, and ambiguity.

3.4 References (Part A)

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3.5 Empirical material (Part A)

Participant observation

- MIND First Project Annual Meeting, Granada, 2 – 4 May 2016
- Joint BN, GD, HT, MA Meeting, Mont Terri, 6 – 7 February 2017
- MIND Second Project Annual Meeting, Prague, 3 – 5 May 2017
- MIND Third Project Annual Meeting, Lausanne, 7 – 9 May 2018

Discussion groups

- Discussion group 1: MIND Project First Annual Meeting, Granada, 3 May 2016
- Discussion group 2: Joint BN, GD, HT, MA Meeting, Mont Terri, 7 February 2017
- Discussion group 3: MIND Project Second Annual Meeting, Prague, 6 May 2017

Interviews

- Interview A: 26 October 2016
- Interview B: 6 February 2017
- Interview C: 22 February 2017

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4 Public perception and how to communicate about microbiology in the context of geological disposal projects (Part B)

In this section, we shed light on the public perception of microbes in a geological disposal, and provide communication guidelines for experts on how to communicate among themselves and with wider audiences about microbiology in the context of geological disposal projects.

For this, we applied the following methodological approaches:
i.) An exploratory literature review of risk communication and risk perception has been conducted;
ii.) We investigated how different communication stimuli affect the perception of the role of microbes in RWM among different target groups by using an embedded experiment in an on-line survey;
iii.) In order to improve scientific outreach and communication about microbes in RWM, the MIND experts have been challenged with a role-play, discussion and brainstorming on the workshop "Speaking for, with and about microbes"
iv.) An exploratory media research on reporting about microbes in geological disposal has been conducted.

4.1 Background

4.1.1 Risk perception

Human behavior is primarily driven by perception and not by facts (Renn 2008). The main communication challenge is that the experts and the public frequently disagree when it comes to risk assessment. The most prominent theories related to risk perception are the psychometric paradigm and the cultural theory. These two theories argue that people use cognitive heuristics in sorting and simplifying information, leading to biases in the comprehension of risk. The psychometric paradigm was created by Fischoff, Slovic and Lichtenstein (1978) and later became a leading model in the field of risk perception. The psyhometric paradigm scholars, e.g. Slovic (1987), Renn (2003), Havenaar and colleagues (2003), Knight and Warland (2005) and Sjöberg (2000b) identified numerous factors responsible for influencing the individual perceptions of risk, including dread, newness, stigma and other factors. In this approach, the patterns of risk perception are measured by using a numerical scaling technique. The measurement expands the factors that influence risk perception beyond the classic components of harm and probabilities of their occurrence and hence it expands the realm of subjective judgment about the nature and magnitude of risk. Jaeger (2008, p. 106) listed the four characteristics of the psychometric paradigm:

1. *Establish risk as a subjective concept, not an objective entity;*
2. *Include technical, physical and social, psychological aspects in assessing risks;*
3. *Accept opinions of "the public" as a matter of academic and practical interest; and*
4. *Analyze the cognitive structure of risk judgment, usually employing multivariate statistical procedures such as factor analysis, multidimensional scaling or multiple regression.*

Since the psychometric paradigm appears to be an effective tool for the prediction of risk perception, it has been widely tested empirically and it is still being developed in order to identify the risk attributes or dimensions supposedly underlying people's preferences. This model has been used as a basis for extensive work on risk communication by many scholars (for instance Fischhoff et al., 1978; Renn, 2008; Sjöberg, 2000b; Slovic, 1987). The model is based on a number of explanatory scales corresponding to various risk characteristics, which are an empirically driven explanation of contextual characteristics that individual decision-makers use when assessing and evaluating risks. Some of these scales involve whether the hazard was involuntary or not, whether it was catastrophic, delayed or

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immediate, whether it was already known to science, and other factors. The psychometric model was shown to explain up to 60% of the variance of perceived risk - very high correlations between the basic scales and risk perception or risk acceptance were reported in different papers.

Some qualitative characteristics	Explanation of influence and some authors	Explanatory scale	Some comparable risks	Possible communication approach
Personal control	Increases risk tolerance	controllable – not controllable	Driving car vs. flying in the airplane	Practical and emotional involvement in risk governance.
Institutional control	Depends upon confidence in institutional performance	trust, confidence in institution	Accident in high trusted company vs. accident in low trust company	Building social and institutional trust in risk management.
Number of exposed	Decreases risk tolerance	catastrophic – chronic	Plane accident – car accident	Preventive actions e.g. exercises and transparent risk management.
Voluntariness	Increases risk tolerance	voluntary – involuntary	Smoking vs. food poisoning	Stakeholder process
Mortality	Decreases risk tolerance	fatal – not fatal	Aids vs. angina	
Knowledge	Increases risk tolerance	new technology – established technology	Genetically modified food vs. using pesticides	Communication program for increasing knowledge and experiences.
Familiarity	Increases risk tolerance	familiar – not familiar	Medical X rays vs. nuclear waste disposal	Communication campaign makes it familiar
Dread / fear	Decreases risk tolerance	fear – no fear	Nuclear accident vs. Radiation of mobile phone	Since feeling of helplessness triggers fear give the instruction what to do …
Artificiality of risk source	Amplifies attention to risk Often decreases risk tolerance	human – natural	Radon vs. nuclear installation	Clarify the meaning of "natural" e.g. using preservatives in food, or explain natural radiation.
Blame	Increases quest for social and political responses	Degree of legal or social responsibility	Deliberate release vs. accidental release from nuclear installation	Since more that risk is seen as unfair the more is judged as severe and unacceptable the sharing the responsibility and stakeholder process are good comm. approach.
Benefit	Increase risk tolerance	Benefit to self-vs. unclear or inequitable	Worker exposure vs. public exposure	Dialog with the local community
Effect on children	Decrease risk tolerance	Children specifically at risk	Higher cancer risk	Recognition of differences in the risk incurred, and modification of policy accordingly

Table 2: Some psychometric risk characteristics and possible communication approaches. In (Perko, 2012) : Adapted and upgraded by Perko T. (2012) from literature (Covello, 1983), (Slovic, 1987), (Renn, 2003), (Havenaar et al., 2003), (Knight & Warland, 2005), (Renn, 2003) and (Sjöberg, 2000b)

As a challenge to the psychometric paradigm, "Cultural theory" arose. The theory was developed by Douglas and Wildavsky (1982) and was later on integrated into quantitative studies (Dake, 1992; Wildavsky & Dake, 1990). In this theory, the individual approach to risk evaluation is replaced by a societal approach. The emphasis lies on the structure and functioning of groups in societies, and risk evaluation is placed on the meaningful relationships of either individuals or populations with understanding of the contextual and cultural structures of individuals within social groups. Cultural theory explains why people come to accept or reject environmentalism and why they choose which

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potential hazards to fear and which to ignore. It proposes that differences in risk perception between groups within society, such as experts and lay people, arise from different social characteristics and patterns of social relations, rather than because one group is inherently more logical or rational than the other. The theory is based on anthropological research and holds that patterns of social relationships are dependent on an individual's worldview. It refers to the extent to which individuals are bound by feelings of belonging or solidarity. The tighter the bonds, the less individual choice can personally be controlled.

The main criticism against cultural theory is that the model has not been able to explain more than 5% - 10% of the variance of perceived risk (Sjöberg, 1999, 2000a). However, in a study by Buss and Craik (1983), cultural theory explained 16% of variances in risk perception of nuclear power. In addition, the explained variance of the perceived risk can increase if the elements of cultural theory are integrated into more extensive models.

In contrast with to mono-disciplinary approaches to risk research, a group of scholars from a wide range of disciplines combined findings from psychology, sociology, anthropology and communications theory to develop the *"Social Amplification of Risk Framework*" (SARF) (Kasperson et al., 1988). This framework aimed at explaining how communications of risk events pass from the sender through intermediate stations to a receiver, and if the process serves to amplify or attenuate perceptions of risk. All links in the communication chain - individuals, groups, the media, etc. - contain filters through which information is sorted and understood. The main thesis of SARF states that risk events interact with individual psychological, social and other cultural factors in ways that either increase or decrease public perceptions of risk. Behaviours of individuals and groups then generate secondary social or economic impacts, while also increasing or decreasing the physical risk itself. The theory attempts to explain the process by which risks are amplified, receiving public attention, or attuned, receiving less public attention. Risk is recognized as a complex phenomenon that involves both biophysical attributes and social dimensions. The concept of the social amplification and attenuation of risk provides an approach that makes it possible to study how the way that social institutions process a risk will shape both its effects upon society and the responses of management institutions and people. The theory may be used to compare responses from different groups in a single event, or analyze the same risk issue in multiple events. In addition, it was comprehended that in a single risk event, some groups may amplify their perception of risks, while other groups may adjust or decrease it (Kasperson et al., 1988). Scientists have started to argue that risk is socially constructed. The interpretation of physical threats is not just a subjective process engaged in by individuals, but it is also strongly affected by the way of life, world view, society, norms, values, institutions and other influences that the members of social groups have in common. The physical risk is therefore prioritized in order to facilitate collective action.

4.1.2 The meaning of trust

The meaning of trust in the field of risk perception and communication was examined in many studies, for instance in a study by Frewer et al. (1996) on food-related risks, in Flynn et al. (1992) regarding opposition to a high-level radioactive-waste repository, in Lofsted (1996) and in Costa-Font et al. (2008) in relation to nuclear power plants, and in Greenberg and Truelove (2011) in the context of nuclear accidents. These studies found that the perception of trust and credibility of a communicator is dependent on the perceptions of his/her knowledge and expertise, honesty and care (Peters et al., 1997). It was proven that effective communication requires respected and trustworthy sources (Fischhoff, 1991; Morgan et al., 1992). Conversely, not knowing whom or what to believe can make risk decisions intractable, and a lack of credibility and trust can erode relations between experts (the communicator) and the public. In general, people will be more accepting of risks that are perceived to be generated by a trusted source, compared to a questionable one (Fischhoff, 1991). However, trust is not created by knowledge in itself. Rather, trusted sources are seemingly characterized by multiple positive attributes, since sources with moderate accountability are seen as the most trusted ones

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(Frewer et al., 1996). In the late 1990s, concerns were expressed about the quality of risk-related public discourse and communication that took place with regard to complex and controversial technologies. The question was raised whether society or individuals might be harmed by contentious, overly adversarial public debate about new technologies, including nuclear technologies. Some scholars, for instance Fischoff (1995), discussed the obligations of citizens and societal institutions to facilitate a well-reasoned discourse that is respectful of the opinions of others. It was noted that, with the increasing complexity of technological innovations, people find themselves in a position of not knowing much about highly complex and potentially dangerous technologies and novelties. They therefore must rely upon their judgments about whom to trust (Gaskell et al., 2004).

4.1.3 Risk communication and engagement

Risk communication was in the previous century seen as a form of technical communication and education whereby the public should be informed about risk estimates. Later on, risk communication was seen as a marketing practice with the aim to persuade people to adopt a certain message. In current societies, risk communication is considered as a socio-centric communication based on public participation with which the gaps between stakeholders can be bridged (Leiss & Powell, 2004). The participation of a wide range of stakeholders is the key to avoid possible exclusion of persons or groups who are key participants in the process, and the empowerment of stakeholders to understand the situation and to have autonomy in the implementation of their personal actions to improve it. It is stressed that risk communication should not only be effective, but also ethical, which requires taking values into consideration. There are values at stake, which means that decisions have to be made in a democratic way, after serious debate about values and not merely about numbers. The procedure should be legitimate (requires legitimate procedure for discussing the values and emotions associated with risks), it should be ethically justified (ethical deliberation about the values and emotions involved in different messages) and the effects should be adequately addressed.

Stakeholder involvement is of paramount importance to develop effective environmental and health related policies, their implementations, and to reach a shared problem understanding with affected communities in a sustainable and cost-effective manner. Involvement may take the form of sharing information, consulting, conducting dialogues or deliberating on decisions. Through stakeholder involvement, public concerns can be addressed in an open and transparent manner and trust can be built between the different parties. Furthermore, stakeholders may end up developing a kind of ownership of the solutions to be implemented. It is effective if communication and stakeholder involvement are planned at an early stage of the program.

Conflict between stakeholders is common when considering options for nuclear waste management. Such conflicts are often driven by differences in how the activities' benefits and risks are distributed, valued and perceived. This may reflect differences between individuals, groups and authorities in their motivation, values, goals, level of knowledge, interests, their perceptions, beliefs about the objectivity and efficacy. In addition, arguments over the objectivity, validity, credibility and relevance of scientific findings are common in debates related to health effects. The participative process should lead to effective, democratic, ethical and transparent decisions.

4.2 Results

4.2.1 Perception of microbes in a geological disposal

In order to investigate perceptions of microbes in a geological disposal, an exploratory on-line questionnaire has been applied. The questionnaire was distributed to both experts and non-experts in micro-biology. An invitation to complete the survey was sent to students of Social Sciences and Humanities from the following universities: University of Antwerp and University of Liege in Belgium and Universitat Pompeu Fabra from Barcelona, Spain. The students have been asked to further

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distribute the questionnaire. Also the MIND project partners and consortium members have been asked to respond. The questionnaire has been open from March to April 2019.

The exploratory questionnaire addressed the following topics:

- How interested are you about bacteria and microbes in general?
- How do you perceive the potential risk to your health from bacteria and microbes?
- How interested are you about radioactive waste?
- In your opinion, what is the potential health risk to people living near a radioactive waste disposal?
- Do you think that it is worth to invest in this kind of [microbiological] research?

The questionnaire contained an embedded communication stimulus -a video- explaining microbes in a geo-disposal of high level radioactive waste. The video has been developed by Ecole polytechnique federal de Lusanne (EPFL), and can be found through this link: https://www.youtube.com/watch?v=RGZsWeIF5is

A total of eighty-five people responded to the questionnaire (N= 85). Of these 85 respondents, 62.2% were male, 37.6% female and 1.2% other. More than 40% of respondents received an invitation to fill in the questionnaire through a friend or colleague, while 34% received the link through the MIND project, 20% was invited through their university and a minority received the link through their local community, or directly from their professor. Given the population from which respondents were selected, a very large majority of respondents (95,3 %) have obtained a university diploma as their highest educational level. Figure 1 provides an overview of the age of the respondents, according to birth year.

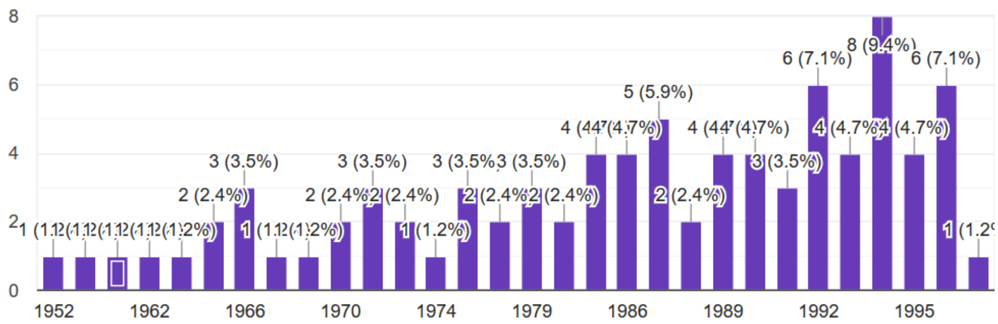

Figure 1: Respondents by birth year

The questionnaire was designed in such a way that it focused first on respondents' general perceptions of bacteria and microbes, before turning to the issue of radio-active waste. Next, a short communication stimulus in the form of a video was provided, and after watching this, respondents were asked again to answer the questions on perceptions of radioactive waste.

Respondents have been asked to indicate their general interest in bacteria and microbes in general and their risk perception of microbes for their health more specifically. Results show, that in terms of general interest, about 45% of respondents indicated to have a high level of interest in microbes and bacteria ('very much' or 'a lot'), while about 26% showed little to no interest ('not much' or 'not at all'). The detailed results can be consulted in figure 2. Focusing then on risk perceptions regarding bacteria and microbes, the largest group of respondents (40%) stated to perceive the risk of bacteria and microbes for their health as 'moderate', while about 36 % perceived this risk as 'high' or 'very high'. Detailed findings can be found in figure 3.

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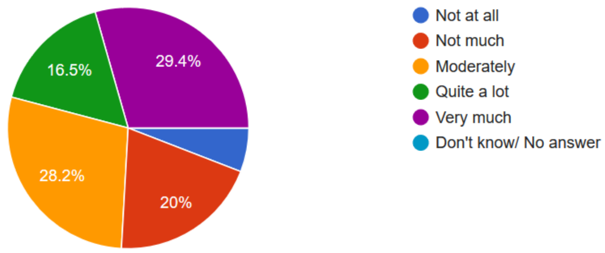

Figure 2: Interest in bacteria and microbes in general

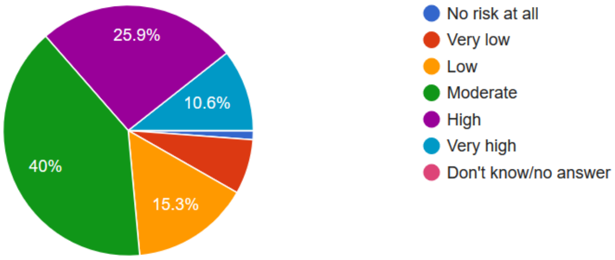

Figure 3: Perceived health risks from bacteria and microbes

The next set of questions investigated interest in radioactive waste and risk perception of radioactive waste disposal. Results show that a majority of respondents (67%) show a clear interest in the topic ('very much' and 'quite a lot' interested), while only a very small minority states to have no interest at all in radioactive waste (see figure 4). In terms of health risks connected to living in the close proximity of a radioactive waste disposal, respondents seem to perceive relatively little risk (see figure 5). The majority of respondents indicated to perceive this risk as low (22,4%), very low (26,5%) or inexistent (5,9%), while only a minority of respondents perceive this risk as high (9,4%) or very high (5,9%). This latter finding is to a certain extent surprising, given that in the 2017-2018 SCK•CEN Barometer almost half of respondents indicated to perceive a high (28%) or very high (20%) risk of radioactive waste to their health(not related to living in the proximity of a disposal site) {Turcanu, 2018 #888}. In a next question, respondents were probed regarding their trust in waste disposal technology. Here, a majority of respondents (68,2%) stated to 'agree' (38,8%) or 'strongly agree' (29,4%) with the statement that 'waste disposal technology will do what it needs to do' (see figure 6). This high level of trust corresponds to the low perceptions of risks reported.

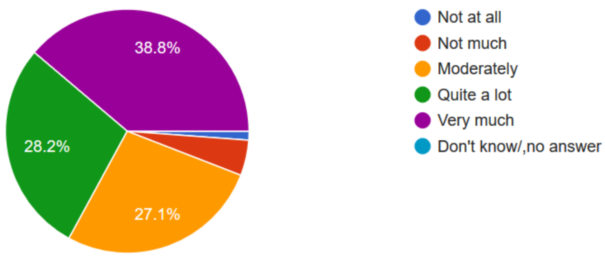

Figure 4: Interest in radioactive waste

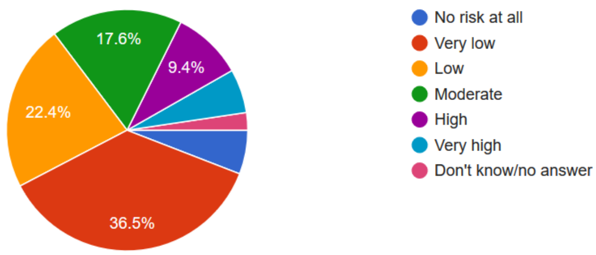

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Figure 5: Perceived health risks of living in close proximity of a radioactive waste disposal

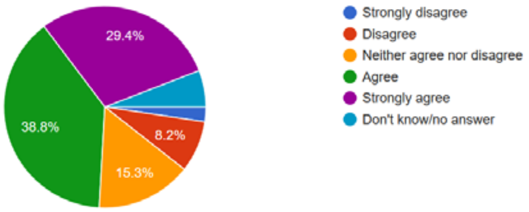

Figure 6: Level of agreement with 'waste technology will do what it needs to do'

Once these questions were answered, the respondents were asked to watch a short online video (2min54) on microbes and the relevance of microbiology in the field of radioactive waste disposal. The video was developed by Ecole polytechnique federal de Lusanne (EPFL), and provides a highly accessible introduction to the disposal of radioactive waste, the technology involved, and the potential role of microbes in this disposal. It highlights especially potential benefits of microbes in long-term disposal, and argues for the relevance of further research in this area. Figure 7 provides a screenshot and a link to the video.

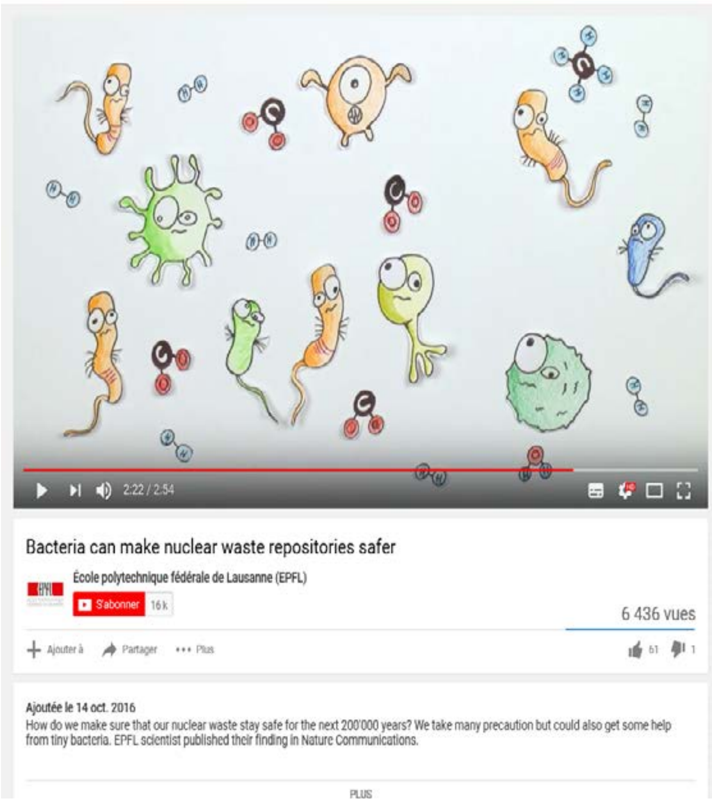

Figure 7: Video screenshot. Source: https://www.youtube.com/watch?v=RGZsWeIF5is

Having watched the video, respondents were first asked to evaluate whether or not they found the film 1) informative, 2) trustworthy, and 3) biased. Overall, on a scale of 1 to 7 (1= informative, 7 = not informative) a majority of respondents (1-2 = 62%) found it informative, while none of the respondents found it absolutely not informative (7 = 0%). Similarly, a majority found the video trustworthy (1-2 = 61,7%), while no respondent found it absolutely not trustworthy (7 = 0%). While the video thus seemed to be perceived as trustworthy and informative, responses were less clear in terms of whether it was biased or not. While only one respondent indicated that the video was clearly biased on a scale of 1 to 7 (1 = biased, 7 = non-biased), most respondents seem to position themselves in the middle (3, 4, 5 = 58,8%), thus perceiving the film neither as clearly biased, nor as clearly un-biased. Regarding this latter

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finding, it can be noted that the video was also discussed at a MIND-workshop, where participants indicated to find it rather biased. This was mainly attributed to the fact that while the film mentioned both benefits and disadvantages of microbes in the long-term disposal of radioactive waste, it mainly focused on the benefits.

Subsequently, respondents were asked again to answer the questions regarding perceived health risks of living in close proximity of radioactive waste disposal sites, and their trust in disposal technology.

Focusing first on risk perceptions, a differentiation was made between respondents who can be thought to be experts (n=28) and non-experts (n=54) in microbiology, investigating the different potential impacts of this video as a communication stimulus. The answers of the non-experts after watching the video largely correspond to the answers they provided before watching the video. As demonstrated in figure 8, both before and after watching, a large part (before = 56%, after = 53%) of respondents perceive potential health risks of living in the proximity of a radioactive waste disposal as either low (before = 19%, after = 18%), very low (before = 31%, after = 30%) or non-existent (before = 6%, after = 5%). For the experts, we equally see a correspondence in the answers provided before and after watching the communication stimulus (figure 9). Also here, a majority of respondents (before = 81%, after = 75%) perceives health risks related to living in the proximity of a radioactive waste disposal as either non-existent (before = 7%, after = 4%), very low (before = 46%, after = 39%) or low (before = 28%, after = 32%). There are thus some minor differences in the percentages before and after watching the video, but given the small number of experts (n=28), minor changes in number of respondents per category, result in rather high differences in percentage points. These exploratory results also indicate that experts in microbiology seem to perceive less health risk related to living in close proximity than non-experts, although the number of participants in each category is too small to test the statistical significance of this statement.

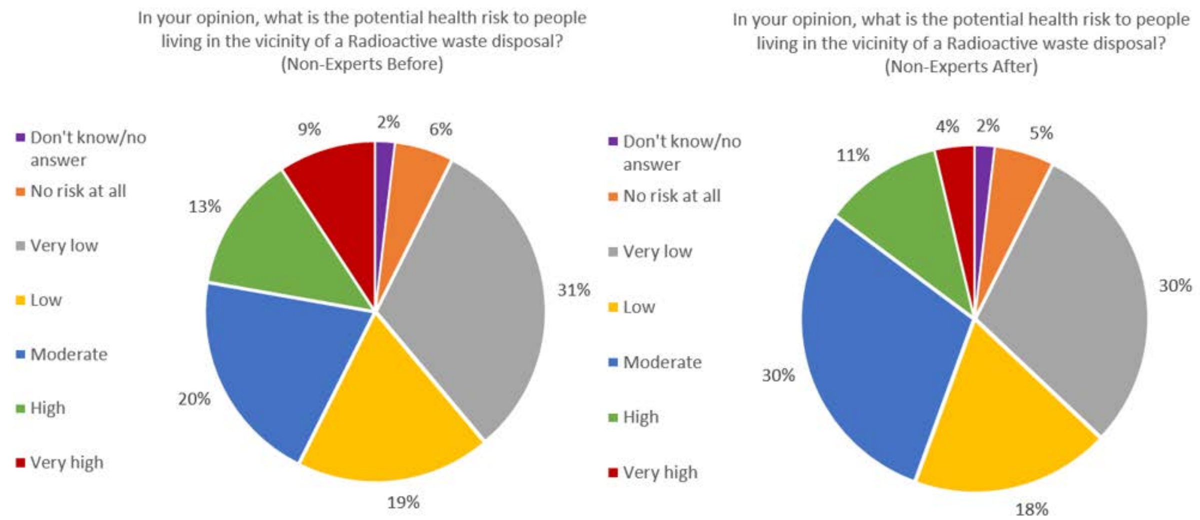

Figure 8: non-expert risk perceptions of radioactive waste deposit, before and after communication stimulus

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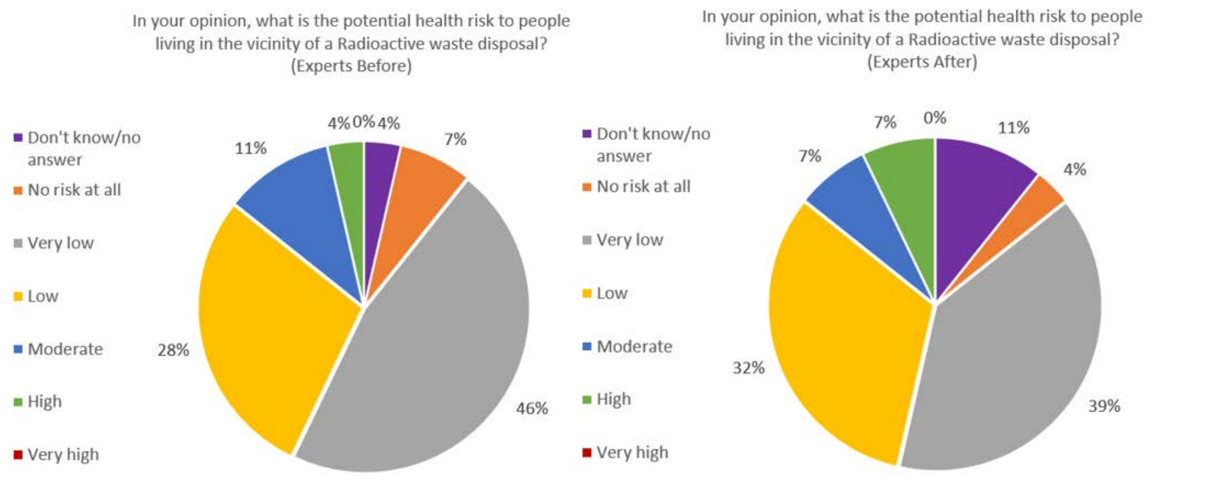

Figure 9: expert risk perceptions of radioactive waste disposal, before and after communication stimulus

In terms of trust in disposal technology, both before and after the communication stimulus, a majority of respondents (before = 68,2%, after = 70,6%) show clear trust in this technology. As figure 10 demonstrates, some small changes in the proportions of each answering category are discernible, thus possibly hinting at a small effect of the video, but this again could not be tested for statistical significance with this small sample.

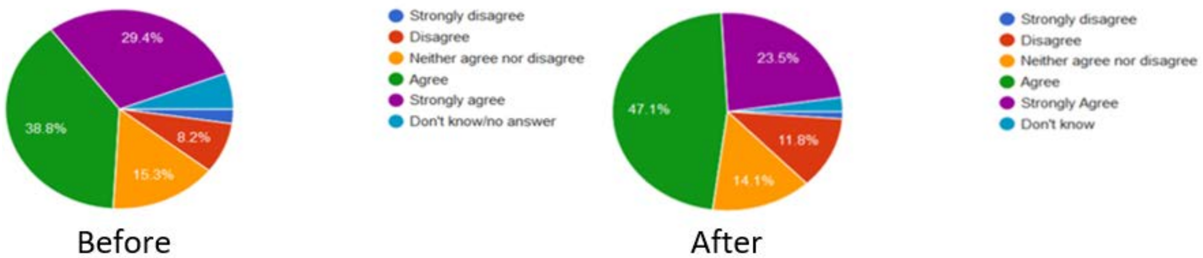

Figure 10: trust in disposal technology, before and after communication stimulus

As a final question to the questionnaire, respondents were asked whether they perceived microbiological research in geological disposal (as presented in the video stimulus) as worthy to invest in. The large majority of respondents (91,7%) agreed with this statement, thus demonstrating the perceived relevance of microbiology in radioactive waste disposal.

4.2.2 Communication

Based on the document analysis, media analysis and a dedicated workshop "Open up your MIND", we noticed that microbiologists (MB) have multiple motivations to communicate. The following communication **objectives** have been identified:

- To share the findings related to MB in RWM and excitement of science.
- To increase appreciation for MB as a useful way of understanding and navigating the RWM.
- To increase knowledge and understanding of the MB related to a RWM.
- To influence people's opinions, behavior, and policy preferences.
- To engage with diverse groups so that their perspectives about MB to RWM can be considered in seeking solutions to a societal problem that affect everyone.

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In a communication process, microbiologists are faced with many challenges. We identified challenges specific to communication with non-experts and challenges specific to experts from other disciplines than microbiology.

There are many **challenges**, **that MB are faced with in communicating with non-experts**.

- There is no single audience for scientific information;
- The complexity of scientific methods & information, and the ways in which science progresses;
- The ways in which people process such information;
- In the RWM the societal implications of science are controversial;
- There is substantial disagreement about the findings within the scientific community;
- The complex, dynamic and competitive communication media environment.
- The results of research can be insufficient, ambiguous, or uncertain, and scientific conclusions can change over time as new findings emerge.

These challenges can be found in all collected documentation. The following quotes are indicative examples of some of these challenges: *"after 3 years of intense discussions between MBists and the IGD-TP, MB was included in the 'key topics' of the SRA of the IGD-TP"* . (interview A);
"… you can see research as linear and incremental, but often it is also about individual interests and what is popular at a certain moment in time." (discussion group 2)
"*we have to agree how to separate the processes that are really relevant from those that also occur but that are not so relevant*" (discussion group 2).
"*I'm worried that this stuff is going to come out, people are going to hear it and it's going to cause problems*" (Discussion group 3).

In addition, MB are faced with specific challenges in communication with non-experts related to microbiology in radioactive waste management:

- Attitudes and motivations of stakeholders; e.g. waste agencies
- Financial and time constraints: finding a balance between science for the purpose of gaining knowledge ("It is interesting…") and science for the purpose of RWM ("What is sufficient…")
- Regulatory process is not flexible (balance between scientific interest and regulation- safety case)
- Complexity, uncertainty and unpredictability
- No common language and low understanding
- Low trust and understanding between stakeholders …

The following quote, for instance, describes low trust and understanding between stakeholders:
e.g.: *I would not want our regulator to be at this meeting. […] I mean there was this statement earlier … "I wouldn't be that concerned if our regulators would have been at this meeting, because I think the important thing for them is to see that we have a thorough and honest scientific discussion about these issues".*

The MBs should make choices about what scientific evidence to communicate, when, how, and to whom. The decision is a reflection of the communicator's values and ethics.

In addition, this research identified wrong thoughts in communicating microbes with non-scientists. The most appearing wrong thought relates to the "Deficit Model". This is a common assumption that a lack of information or understanding of science explains why more people do not appear to accept results from MB or support policies that are consistent with scientific evidence. The research on MIND communication, shows that audiences may already understand what scientists know, but for diverse reasons, do not agree or act consistently with that science. In addition, people rarely make decisions based only on scientific information; they typically also take into account their own goals & needs, knowledge & skills, and values & beliefs.

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Challenges in communicating microbes to experts from other scientific disciplines than microbiology.

The difficulties in cross-disciplinary communication result in many issues that are largely different from those associated with the detachment of non-scientists from science. Effective cross-disciplinary communication is a precondition for successful interdisciplinary work. We identified different issues of cross-disciplinary communication and interdisciplinary research in RWM. For instance, radioactive waste management illustrates the complexity of interdisciplinarity and the problems of political control; it is fragmented into numerous disciplines, sub-disciplines, and research fields, which makes communication processes even more complex. The more distant the research fields are, the bigger the obstacles of understanding and communication are.

Two different approaches to improve communication between different disciplines can be used: cognitive and social. These two strategies can of course be interactive.

"*Cognitive strategies seek to level out the differences in disciplinary knowledge, or at least to enable successful communication despite the differences. Ideally, cross-disciplinary communication requires that scientists from different disciplines share the same knowledge basis— knowledge of the world, knowledge of methods, and knowledge of values. However, as long as there are different disciplines in the proper sense, any common basis of overlap is modest in scale, because disciplines greatly differ in how they describe the world, in their methods for validating knowledge and solving problems and in assessing the quality and importance of pieces of knowledge*." (Schummer, 2008, p. 5.)

The following approaches can be applied to bridge the communication gap between different disciplines (Schummer, 2008):

- **Reductionism**: restructure disciplinary knowledge – to fundamental knowledge. (specific concepts, theories and models,… should be translatable into language or theories of other discipline)
- **Simplification**: seeks a common basis in everyday knowledge (metaphors, images, common-sense understanding of what matters and is useful).
- **Modularisation:** divides up an interdisciplinary project into mono-disciplinary module e.g. sub-projects (well-designed organisation, regular exchange and flexible arrangements are precondition)
- **Facilitation or mediation**: mediator translate not only between disciplines but also between opinions

"Social strategies alone cannot directly enable cross-disciplinary communication because they cannot overcome the cognitive gaps between disciplines. However, they can establish social conditions under which mutual learning and understanding are improved and they can weaken the social commitments of scientists to their specific discipline to increase mutual openness."(Schummer, 2008, p. 6.)

An example of social strategy applied to improve communication between different disciplines is multidisciplinary teaching rather than the monodisciplinary education (no disciplinary focus, journals with what is going on beyond one's own research, weaken the bureaucratic boundaries established between disciplinary departments, funding for interdisciplinary projects …).

"*One MIND researcher explained how he/she was originally trained as a geologist, but then became a chemist, a 'geochemist'. He/she started looking at nitrate in the waste disposal system, and thereby became interested in MB. He/she studied books and*

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literature for about ten years and now feels rather comfortable in this field too. So he/she dares to refer to him/herself as a 'bio-geo-chemist'. Nevertheless, he/she compared it to being a duck: it can swim and dive, and walk and fly – but no matter what it does, it will never be comparable to the expert, be it a dolphin or an eagle".

(Source: MIND Interview B)

4.2.3 Guidance for effective communication about microbes in radioactive waste management

The MIND project recognised that only few scientists in MIND have had formal training in science communication or in media communication, although a variety of programs for such training exist. Moreover, only few institutes have efficient, pro-active and accessible science outreach officers. MB must compete for attention in a complex and fast-changing media environment that can be difficult to penetrate. However, MB may contribute to public communication about RWM as stated during a MIND event: "*Of many articles in newspapers about RWM, the only positive one was about microbes*" (PAM Prague).
New trends have entered the field of science, technology & society that are an opportunity for MB to improve communication. These trends are social media, citizens journalism, citizens science, open source information, science diplomacy, new regulations on public rights for information and stakeholder engagement…

Objectives

This chapter sets out the guidance for efficient communication about MB in RWM. The guidance informs MB on why they have to communicate and engage and how they can do this. The best communication and stakeholder engagement practices and the tools developed and used by MB are collected and shared in order to:

- To increase the recognition of an MB as a stakeholder in decision-making related to RWM;
- To identify the key stakeholders of MB and map possible interactions;
- To support MB in their development of communication and stakeholder engagement strategies;
- To share good practice, ideas and resource material for communication related to MB in RWM.

Stakeholder mapping for MB in RWM

Clear identification of a stakeholder (with whom do we wish to communicate and engage) is of extreme importance for sound communication. The following questions can guide MB to map stakeholders:

- Who is directly affected?
- Who is indirectly affected?
- Who makes decisions?
- Who will communicate on the same issue?
- Which other agencies, actors, institutions, experts, NGO's are involved in RWM topic?
- Who will be interested in the MB?
- Who is influential in the field of MB and RWM?
- Who can disseminate important MB findings?

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An attempt for stakeholder identification has been done. It must be acknowledged that the majority of these stakeholders will not be experts in MB.

- Expert groups: all disciplines involved in RWM
- Non-expert groups: general public, local communities
- Stakeholders with an interest and/or duty of care in the system of radiation protection of humans and the environment and its improvement in RWM. These include authorities, national and international organisations, industrial stakeholders, operational protection specialists and implementers
- Stakeholders with responsibilities for ensuring adequate radiation protection of those exposed. These will include for example policy makers, those involved in international standards development, and national authorities
- Stakeholders in the wider scientific and academic communities. This group will include those actively involved in research on issues relating to RWM, and those who have skills applicable to the relevant questions and issues
- Stakeholders with interest in RWM; this group will include mass media, schools, non-governmental organisations, etc.

Methods and tools for public communication

The following methods and tools can be used for public communication:

- Make lay summaries of your research especially research articles and publish them on all possible communication channels for instance internet pages of institutes and universities.
- Drive attention to the published article with compliments on the publication published on-line, e.g; "*Congratulations to Perko for her paper in Nature Communications*! The research …".
- Put it in a context, link it to a recipient and respond to the question "*What is here for me?*". For instance: *» How do we make sure that our nuclear waste stay safe for the next 200'000 years? We take many precaution but could also get some help from tiny bacteria. EPFL scientist published their finding in Nature Communications.«*
- Use Multimedia & Visuals. For instance: https://www.youtube.com/watch?v=RGZsWeIF5is
- You can opt to include a video abstract with your article
- Include ORCiDs and social media handles (Facebook, Twitter or LinkedIn) in your communication about the research and published article.
- Try to keep it on the public agenda with Share it, like it, comment it, discuss it … in a commentary sections on internet.
- Use Story telling & messaging techniques when reporting MB research to lay public. The following example is taken from https://www.asianscientist.com/2015/06/print/eat-waste-microbes-helping-clean-fukushima/ (accessed in October 2018)

  Firstly, drive an attention to the topic in first lines, e.g. "*Five-hundred meters below, in a dark, sprawling warren of underground labs, scientists are at work on one of the nation's most pressing problems: what to do with its nuclear waste"*

  Secondly, *s*tate the problem, *e.g. "All nuclear countries now are moving towards geological disposal, where nuclear waste is converted into a form that's ready for long-term storage and then buried underground in a suitable geological formation"*

  Thirdly, provide a soulution. *E.g. "If you choose the right geological material, then hopefully those things won't migrate. But it's great to know that there's biology down there that will give you an extra barrier".*

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Be concrete and not abstract as much as possible. *E.g. "The UK has accumulated around 4.5 million cubic metres of nuclear waste, enough to fill London's Wimbley stadium four times"*

Lastly, address risk perception factors, for instance controllability. E.g. *"…the way bacteria process waste products means hazardous material is less likely to seep into the environment".*

- Make news out of your research. Respond on the basic 5Ws: Who, What, When, Where and Why. A story is only news if the readers find it interesting and novel. To be newsworthy, the story needs to have one or more following characteristics: Extraordinary event, New unusual information, Conflict, Drama, Tragedy, Presence of elite of celebrities, The situation (event) can be personalized and The event evokes emotional response. The following examples have been found in media: *"Battling Corrosion in Nuclear Waste Storage Facilities"; "Scientists discover bacteria that help with nuclear waste cean-ups.", "Awards for 2018…"; "Mop up our Cold War-era waste"; "Solution to toxic waste clean-up"; "More effective…natural process…"*
- Try to reach out & engage with events, for instance with Annual meeting of the Microbiology Society or a workshop. Carefully frame the event in an interesting story. For instance, "Let them eat waste… immobilize to make it safer. … give us more confidence." (https://www.google.be/amp/s/www.newscientist.com/article/mg23431211-300-radiationeating-bacteria-could-make-nuclear-waste-safer/amp/, accessed in October 2018)
- Engage with specialized media reporting, for instance World Nuclear News. For this you initiate a contact, discuss with a journalist, point out the most important messages and verify the draft… An example at http://www.world-nuclear-news.org/Articles/Chemistry,-minerals-and-microbes-in-nuclear-waste
- Think global – act local! Publish it in a local or regional media first. Local media are a gateway. When published in local media, national media may pick it up. E.g. https://www.manchester.ac.uk/discover/news/scientists-discover-hazardous-waste-eating-bacteria/
- Help journalists to make the story scientifically correct. The Science Media Centre from UK made the following guidelines, drawn up in consultation with scientists, science reporters, editors and sub editors, to ensure that the reporting of science and health stories is balanced and accurate. (https://www.sciencemediacentre.org/wp-content/uploads/2012/09/10-best-practice-guidelines-for-science-and-health-reporting.pdf; accessed on 2nd of May 2019). For this guide, the guidelines are adopted to be useful for MB in RWM.

When you report your scientific results to the journalist:

- State where the research has been published or presented or reported e.g. conference, journal article, a survey, etc. Ideally include enough information for readers to look it up or a web-link.
- Specify the size and nature of the study – e.g. who/what were the subjects, how long did it last, what was tested or was it an observation? If there is space, mention the major limitations.
- When reporting a link between two things, indicate whether or not there is evidence that one causes the other.
- Give a sense of the stage of the research e.g. new dosimeter, clean-up stage, cells in a laboratory or trials in humans, and a realistic time-frame for any new technology.
- On health risks, include the absolute risk whenever it is available in the press release or the research paper i.e. if 'low dose exposure increases the cancer risk' state the outright risk of that cancer, with and without particular exposure.

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- Especially on a story with public health implications, try to frame a new finding in the context of other evidence e.g. does it reinforce or conflict with previous studies? If it attracts serious scientific concerns, they should not be ignored.
- If there is space, quote both the researchers themselves and external sources with appropriate expertise. Be wary of scientists and press releases over-claiming for studies.
- Distinguish between findings and interpretation or extrapolation; don't suggest health advice if none has been offered.
- Headlines should not mislead the reader about a story's contents and quotation marks should not be used to dress up overstatement. For a complete and original guide look at https://www.sciencemediacentre.org/wp-content/uploads/2012/09/10-best-practice-guidelines-for-science-and-health-reporting.pdf

- Create and use videos. Share a lecture or presentation with a wider audience, explain the background to your research (compile visual tours of research facilities, blog posts about research, footage of the lab, and frequently-asked-questions into a video); record and review (Compile recordings from a public talk, appearing at a science café, going to a conference, or traveling into the field to tell a visual story about your research to give audiences a special behind-the-scenes look); Supplement presentations with videos (Videos can add depth, showing context – especially for field research – and bringing in additional voices, such as colleagues and partners.); Enhance blogs or websites (Introduce people, research, books, projects ... Tell personal stories.); Post videos to social media sites ; Shoot video footage that shows science in action (Journalists appreciate it!)
- Use Multimedia & Visuals. For instance: *"Imagine bacteria cleaning up nuclear waste"* at https://www.youtube.com/watch?v=LxaAWbN2koo accessed in October, 2018.
- Write a blog on your research, process, (non)findings, results… For example: http://blogs.discovermagazine.com/d-brief/2018/08/13/oklo-natural-nuclear-reactor-waste/#.W7YDv3kUkkE, accessed on October 2018.
- Post your videos.
- Set up a training for science press officers at research institutions
- Roll out introductions to the media seminars for scientists
- Make lay summaries of research proposals & findings
- Secure more access for journalists to peer reviewed literature
- Recognise and reward excellent science by getting science prizes included in major national awards ceremonies
- Create a new "Before the Headlines" expert group for journalists
- Make an expert group "Behind the Headlines" for the public
- Set up a short (weekly) fellowships to allow science reporters time to pursue original and investigative stories.

4.3 Concluding remarks

The previous sections have provided insight in how effective communication can help microbiologists to gain recognition both among the wider general public, and in the scientific community focused on geological disposal of radioactive waste. As such, it proves relevant for a scientific discipline

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(microbiology) which is confronted with feelings of uncertainty regarding its entering position in a scientific network which has a long history of establishing itself (geological disposal). Moreover, the communication tools provided in this second part of the report, also can prove highly useful to any researcher or scientist who aims for a wide recognition of her/his work.

4.4 References (Part B)

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