Interdisciplinary perspectives on dose limits in radioactive waste management

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Interdisciplinary perspectives on dose limits in radioactive waste management. A research paper developed within the ENTRIA project

Karena Kalmbach¹ and Klaus-Jürgen Röhlig²

¹ Freie Universität Berlin, Germany

² Clausthal University of Technology, Germany

E-mail: klaus.roehlig@tu-clausthal.de

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Abstract

Within the ENTRIA project, an interdisciplinary group of scientists developed a research paper³ aiming at a synthesis of the technical, sociology of knowledge, legal, societal, and political aspects of dose limits within the field of radioactive waste management. In this paper, the ENTRIA project is briefly introduced and the work on dose limits is put into the perspective of this much larger project. Selected aspects of the ENTRIA work on dose limits related to the different roles such limits play for different actors as well as to the specific case of nuclear waste disposal are presented. The work recognizes that such limits are indispensable for technological developments and legal security but, at the same time, depend on country and project specific circumstances. This may result in serious conflicts and concerns in public debates as well as in the political realm. In order to better understand the interaction and interdependencies of these various contexts in which debates about dose limits play out, future interdisciplinary research is needed. This research should contribute to an open discourse on dose limits which reflects underlying values, objectives, actors and procedures that have defined present dose limit regimes. Additionally, this research should indicate paths for potential alternatives and complements to these established regimes.

³ The authors involved in the development of this research paper are (in alphabetical order): Achim Brunnengräber, Peter Hocke, Karena Kalmbach, Claudia König, Sophie Kuppler, Klaus-Jürgen Röhlig, Ulrich Smeddinck, Clemens Walther.

Keywords: radioactive waste management, governance, geological disposal, dose limits, interdisciplinary research

(Some figures may appear in colour only in the online journal)

Introduction

Recognising that radioactive waste management (RWM) concerns society as a whole and therefore needs more than technological and natural science research, BMBF (Bundesministerium für Bildung und Forschung, The German Federal Ministry of Education and Research) is funding, inter alia, the joint research project ENTRIA (reference no. 02S9082A-E). The acronym ENTRIA stands in German for ‘Disposal Options for Radioactive Residues: Interdisciplinary Analyses and Development of Evaluation Principles’ (www.entria.de). ENTRIA is a five year project (2013–2017). It is carried out by 12 departments and institutes from German universities and major research institutions and one partner from Switzerland. The disciplines represented within the ENTRIA team, which consists of more than 60 researchers, are natural sciences, civil engineering, philosophy, law, political sciences, and technology assessment.⁴

The ENTRIA team supports the development of interdisciplinary research approaches as well as professional (academic) education and knowledge management. By carrying out interdisciplinary research and by educating PhD students and postdoctoral researchers beyond the limits of their respective academic disciplines, ENTRIA contributes to the establishment of a durable culture of interdisciplinary collaboration in the field of radioactive waste research in Germany.

The work of ENTRIA consists of research (both within single academic disciplines and cross-disciplinary) into the three waste management options:

- Deep disposal without retrievability provisions
- Emplacement in deep formations with monitoring and retrievability
- Prolonged surface (or near-surface) storage

These options were chosen because they are today’s most thoroughly researched long-term management options for nuclear waste. Therefore, from a strategic point of view, they are the ones with the highest potential for implementation in the foreseeable future. Moreover, a focus on different options would require research for at least several decades, during which prolonged surface storage or retrievable emplacement in deep formations would still be necessary.

In addition to conducting topic-specific research on these options within single academic disciplines,⁵ ENTRIA engages in interdisciplinary research focused on the development of evaluation principles and knowledge about the interconnection of the various context structures in which decisions about the implementation of a specific RWM option are embedded.

⁴ The institutions involved in ENTRIA are: **Clausthal University of Technology**: Institute of Disposal Research, Institute of Mineral and Waste Processing, Waste Disposal and Geomechanics, Sub-contractors, e.g. **risicare GmbH** (Switzerland); **Technische Universität Braunschweig**: Institute of Law, Institute of Foundation Engineering and Soil Mechanics, Institute for Building Materials, Concrete Construction and Fire Protection; **Leibniz Universität Hannover**: Institute for Radioecology and Radiation Protection, Institute of Materials Science; **Karlsruhe Institute of Technology (KIT)**: Institute for Technology Assessment and Systems Analysis, Institute for Nuclear Waste Disposal; **Freie Universität Berlin**: Environmental Policy Research Centre; **Christian-Albrechts-Universität zu Kiel**: Chair for Environmental Philosophy and Ethics.

⁵ For instance, with regard to nature science and engineering, these projects include research into geomechanical and mining issues and the transport mechanisms of radionuclides in specific soils or into construction material for surface storage building.

However, ENTRIA's purpose goes beyond purely scientific research and education: the project is also dedicated to engaging a broader interested public through workshops, seminars and public lectures.

It goes without saying that inter- and transdisciplinary research in RWM dates back long before the start of the ENTRIA project. But while there is already a wide range of general literature, theoretical reflections and case studies available, interdisciplinary research in RWM has not yet become the norm. There have been changes in the field, but there is still significant room for improvement. The following short account of recent developments in radioactive waste research and management sheds light on some crucial aspects of the current state of the field:

- For decades, political sciences, social sciences and technology assessment have addressed RWM issues. In the 1970s and early 1980s, research from these disciplines was largely a kind of inventory-taking of the critical debates and concrete opposition movements that mushroomed in Europe and North America in response to disposal projects. This research was embedded in a broad disciplinary interest in the so-called 'new social movements' and aimed at explaining, contextualizing and theorizing this widespread (pro)active public engagement. In the 1980s and 1990s, however, many social scientists focused on the question of how this opposition towards state nuclear waste policies could be overcome. It is the background of this research that made the anti-nuclear movement take a critical stance towards social scientists, as many activists considered the role of these researchers to be 'acceptance brokers' working for the nuclear industry. From the mid-1990s onwards and against the backdrop of many failed disposal projects worldwide, social scientists have broadened their perspectives and have taken into consideration ethical questions (for instance intergenerational justice) and alternative disposal options (like multi-national repositories) (Salomon *et al* 2010). Interconnections between research axes and political interests have also become a topic of social scientists' work (for instance: Macfarlane 2003). Among the most recent endeavors to bring together social scientists from various disciplines working on nuclear waste is the INSOTEC project (www.insotec.eu). The humanities' perspectives are, however, still often underrepresented or even left out of these interdisciplinary collaborations.
- Based on the increasing recognition that interaction between technical and non-technical disciplines is needed, administrators and policy makers concerned with 'technical' RWM projects increasingly aim to integrate the social sciences in their discussions. This is particularly visible at conferences and symposia such as the OECD/NEA 2010 Reversibility and Retrieval Conference (www.r-r-reims2010.com), the EU 2013 EURADWASTE conference (http://cordis.europa.eu/fp7/euratom-fission/euradwaste-2013_en.html), and the OECD/NEA 2013 Safety Cases Symposium (www.oecd-neo.org/rwm/docs/2013/rwm-r2013-9.pdf). The EU FP7 project MoDeRn ('Monitoring Developments for Safe Repository Operation and Staged Closure', www.modern-fp7.eu) is an example of including non-technical issues into technical project work. While clearly focusing on technical aspects such as monitoring technologies, the project also undertook research on stakeholder involvement in order to derive reasons and objectives for monitoring, on which guidance on the development and implementation of monitoring programmes could be based (White 2014). The ongoing follow-up MoDeRn2020 (www.modern2020.eu) has a dedicated Work Package on 'Societal Concerns and Stakeholder Involvement', the outcomes of which will be accounted for when developing monitoring strategies.
- In a number of synoptical studies, attempts to assess RWM options with consideration of technical and non-technical aspects were undertaken (e.g. EKRA 2000, AkEnd 2002,

Figure 1. The structure of the ENTRIA research project (Graphic by ENTRIA).

NWMO 2005, CoWRM 2006, Streffer *et al* 2011). However, these studies focus on policy and governance (or advice thereof) addressing issues such as the choice of RWM options or site selection procedures, rather than on interdisciplinary research. Most of these studies were explicit parts of RWM programmes, mandated by policy makers or RWM organisations, and carried out by temporary or permanent advisory bodies.

Despite these recent endeavors within academia, various administrations and expert groups concerned with RWM to combine perspectives from different academic disciplines on the nuclear waste issue, we find that in the broader public debate on RWM, these various perspectives remain very much unconnected. Therefore, one of ENTRIA's overall aims is to contribute to a more systematic description of the three key RWM options, their scientific comparison, and communicate basic features, advantages and drawbacks of these options to academic and non-academic audiences. In order to fulfil this overall aim, ENTRIA's different work packages identify and assess key features, advantages and drawbacks of these three options from their discipline-specific viewpoint. Results are then brought together and synthesised in so-called 'transversal projects' in which these discipline-specific results are challenged by specialists from other disciplines (figure 1). As a very first step towards an interdisciplinary synthesis, the senior scientists from all teams published a memorandum naming the specific challenges and target conflicts of importance when deciding about management options (ENTRIA 2014).

Recognising that joint work on specific and pinpointed projects and topics is a major driver of interdisciplinary collaboration, within ENTRIA areas of common interest have been identified and addressed through joint research activities.

As observed through previous research, dose and other regulatory limits, constraints, threshold and reference values (for the sake of simplicity hereinafter referred to as 'dose limits' where these concepts are addressed in their entirety) for the operational and post-operational phases of RWM facilities are an issue of utmost importance and concern when

addressing both technical and governance aspects of disposal options. The scientists involved in the project acknowledged the existence of rather diverse observations concerning such limits in radioecology, radiation protection, disposal research, social science, and technology assessment. Therefore, the topic of dose limits was amongst those identified for more in-depth interdisciplinary work within ENTRIA. Taking up the initiative of the ENTRIA transversal project 'Technology Assessment and Governance', ENTRIA scientists are developing a research paper aiming at an interdisciplinary synthesis of technical, sociology of knowledge, legal, societal and political aspects. The paper comprises a set of 14 propositions addressing technical and non-technical drivers in definitions of dose limits, perceptions of radiation effects and dose limits, and controversies about the meaning and role of such limits.

For the development of this larger paper, the following collaborative working approach was chosen. First, a representative of each participating discipline (political sciences, technology assessment, radioecology and radiation protection, disposal research, law) wrote a short statement paper about what dose limits mean from his or her discipline's perspective. Second, these statements were merged into a continuous text. Third, all of the authors revised and finally agreed on one common draft. Prior to a general assembly of all the ENTRIA scientists, this draft was circulated and then discussed in the plenary meeting. To facilitate discussion, the authors agreed beforehand on the 14 propositions that broke down the essential arguments of the longer text into several bullet points. Some of these propositions are reproduced here. The feedback which the group of authors received in this discussion was integrated in the draft text. Some of the propositions were questioned, discussed and modified during this process. After further revisions and discussion, the group aims to publish a longer and more detailed ENTRIA working paper on interdisciplinary perspectives on dose limits in RWM.

During the work, major challenges concerning interdisciplinary collaboration became evident and means to address them were developed. Obviously, all disciplines involved needed to learn the basics of the other disciplines. Differences in communication culture, terminology and semantics turned out to be challenges. These challenges became particularly evident when addressing a subject like dose limits, which fulfils different tasks in different societal systems.

In this paper, we present selected aspects of the work-in-progress on dose limits within ENTRIA, aspects that are particularly at the interfaces of disciplines. These aspects emphasize the relationship between dose limits and societal debates on low-level radiation health effects as well as the post-closure safety of deep repositories for radioactive waste.

Dose limits and the bigger societal picture

The prerequisite of dose limits is simultaneously the major source of the very contestation of dose limits: they fulfil different tasks for different societal actors. For engineers, dose limits serve as guidelines for technical developments; for public authorities, they are a necessary basis for decision-making about licensing; for the public, dose limits serve as indicators for threats; and for the media (especially in case of exceeding limits), they form an important news value (figure 2).

The dose limit regime, i.e. the collectivity of actors and decision making structures that govern the establishment, enforcement and change of dose limits, has been subject to intense public debate—and with that, has become a popular topic for social science research. For sociologists like Ulrich Beck (1986, pp 85) or Luhmann (1997), dose limits have played an important role in their arguments—especially in relation to their theories on risk. Rather than reproducing their arguments here in detail or analyzing the inter-sociological debate on dose limits as such, this paragraph aims at synthesizing these sociological theorizations of dose limits and at using

Figure 2. Different tasks of dose limits in relation to different societal actors (Graphic by ENTRIA).

these theories for shedding light on the bigger societal picture that plays out in the dose limit regime. To use Ulrich Beck's words: 'Dose limits simultaneously allow toxic emission and legitimize them within the agreed upon limits'.⁶ Fairly, one should add that, at least within some dose limit regimes, these limits should also help to minimize emissions—but that of course depends on the threshold which is set. What is more, the limits serve different purposes for the different actors involved in the dose limit regime. For instance, the implementation of dose limits allows the political system to allocate risks outside of its own system—an aspect that Niklas Luhmann has extensively elaborated on.⁷

If we apply an interdisciplinary perspective, taking a closer look at the implementation process for dose limits and the actions required in the event a threshold is exceeded and if we contemplate, in the next step, the perspectives on this process and actions of different groups of people, we see that the dose limit system incorporates a high potential for conflict among these different actors. In most of today's dose limit regimes, calculations of numerical limits include safety margins and safety coefficients. Thus, a temporary exceeding of dose limits often does not prompt alarm or concrete action by scientists, public experts or public authorities. However, this non-action can lead to the public perception that these scientists, public experts and authorities belittle the situation and do not respect rules that have been put in place. This can lead to a call for stricter limits and a loss of trust in these actors (figure 3).

Dose limits and debates about the health effects of ionizing radiation

When we look at the specific case of dose limits in the field of ionizing radiation, we can clearly see how these dynamics may play out. A loss of trust has already occurred in many countries in relation to the nuclear complex, especially in the case of Germany; this is true for the industry as well as for the government and sometimes for scientists as well. This loss of trust must be considered in the contexts of the long, contentious history of nuclear technology

⁶ Beck (1986), p 85. (translation by the authors of: 'Grenzwerte lassen den Giftausstoß zugleich zu und legitimieren ihn in eben dem eingeschränkten Umfang'.)

⁷ See for example: Luhmann (1997), p 210. 'By imposing dose limits, the political system can avoid that technological risks, even risks in general, are transformed into political risks'. (translation by the authors of: 'Das Politische System kann durch Vorgabe von Grenzwerten vermeiden, daß alle technologischen, ja alle Risiken überhaupt, direkt in politische Risiken transformiert werden'.)

Figure 3. Conflicts caused by the internal logic of the dose limit system (Graphic by ENTRIA).

and the close connection of its civil and military applications, as both contexts are inherent parts of the debates about dose limits for ionizing radiation. Throughout this long struggle over applications of nuclear technology, and specifically over nuclear power, in some countries dose limits—and in particular the excess of dose limits—have become a central point of attention. Thus, the debate about dose limits is often not a debate about a specific numerical dose limit but a proxy for the debate about national or even international nuclear technological regimes.⁸ At the same time, the longtime downplaying of radiation risks by some pro-nuclear activists has resulted in a loss of trust in regulatory systems, as the industry and the state are seen as belonging to the same techno-political regime.

Taking this broader historical context of the nuclear debate into consideration, and focusing in particular on the case of Germany, we can formulate the propositions given in box 1.

The situation described by these propositions plays out for the entire nuclear sector and has created severe societal conflicts. But what are the specific implications of these settings for nuclear waste management, in particular with regard to deep geological disposal?

Dose limits, nuclear waste governance and the specific case of post-closure safety of deep repositories

In general, RWM activities and operating facilities are regulated like other nuclear installations. Standard radiation protection measures and rules apply, and dose limits stipulated in these rules have the same role and face the same problems as elsewhere in the nuclear

⁸The term 'techno-political regime' was shaped by Gabrielle Hecht in her book 'The Radiance of France: Nuclear Power and National Identity after World War II' (Cambridge, MA: MIT Press, 1998). Hecht used this term to explain the different approaches employed by the Commissariat à l'Énergie Atomique (CEA) and Électricité de France (EDF) with regard to nuclear policies in the post-war period. Our use of the term differs from her use insofar as we do not make a distinction between different regimes within one state. Nevertheless, our use of the term describes the same 'linked sets of individuals, practices, artefacts, programs, and ideologies' as described by Hecht (p 56).

Box 1

ENTRIA propositions:

Regulatory systems using dose limits are being put into question by various actors both with regard to elements concerning techno-scientific issues and governance issues.

The strategy of addressing this loss in trust with concepts like ‘better educating the public about risk’ did not increase trust in the system, as the initiators of these campaigns were not considered trustworthy.

As ionizing radiation is broadly considered a health threat without any threshold, there is a strong societal demand for zero-emissions of nuclear facilities. This demand also holds for facilities for deep geological waste disposal.

industry. When it comes to deep repositories for radioactive waste (often called ‘geological’ repositories, i.e. facilities located at a depth of several hundred meters below surface), at least two additional challenges arise: (i) such repositories are underground nuclear facilities; consequently, they are subject to multiple (and in specific cases perhaps conflicting) regulations (e.g. mining and nuclear regulations) (OECD/NEA 2013b); (ii) all what has been said so far applies to the operational phase of a repository (which includes waste emplacement, repository closure and perhaps an interim phase during which the facility is kept open). However, the ultimate goal of such a facility is to provide safety in the long-term, i.e. during the post-operational phase after closure.

While challenge (i) has no bearing on the issue of dose limits, challenge (ii) poses some specific aspects of concern, which will be discussed in the following paragraphs.

With respect to the post-operational phase, the conflicts described above are not only negotiated for the here and now, but for timescales and planning processes that reach far into the future. For some aspects, this leads to a somewhat paradoxical situation. There is a widespread agreement that today’s safety standards (and thus dose limits) should apply to all future generations,⁹ taking for granted that contemporary concepts like legal personhood will still be valid hundreds of thousands of years from now.¹⁰ However, the very idea of deep geological disposal is based on the conviction that society will fundamentally change over the generations to come. Therefore, radioactive waste should be disposed of in a way that it would not become a threat due to loss of knowledge, changing societal settings, changing values, etc. Thus, the facility itself needs to be designed and laid out in a way that it will continue to function in a regime different from that of an operating nuclear facility. The idea is, therefore, that ‘protection’ in the usual sense, i.e. in a sense that society and organisations can take active measures to ensure safety and security, cannot be relied on in the long term due to the uncertainties of society’s evolution. This means that within the concept of deep geological disposal sits an attempt to create an almost unchangeable solution for ever changing societies. This goes along with the recognition that changes concerning the needs

⁹ On inter-generational justice, see Kristin Shrader-Frechette: Mortgaging the Future: Dumping Ethics with Nuclear Waste, in: Science and Engineering Ethics (2005), Volume 11.

¹⁰ On legal figures and deep timescales, see Vincent Ialenti, Adjudicating Deep Time: Revisiting the United States’ High-Level Nuclear Waste Repository Project Yucca Mountain, in: Science and Technology Studies (2014), Volume 27.

and aspirations of future societies cannot be predicted and therefore we need to live with the possibility that, from a future perspective, today's RWM policies and decisions may not be considered appropriate.

ICRP (2013) describes the phases an underground repository undergoes as a process with different periods concerning 'oversight'. While direct and indirect oversight take place during the pre-operational and operational phases, only indirect oversight will be carried out during the post-operational phase, after repository closure. During this phase, at some undetermined point in time, indirect oversight will also cease. Therefore, the intent is to provide 'passive safety': 'Safety after closure of the repository is provided by the passive safety functions of the geological environment and the engineered barriers placed around the waste, as well as the stability of the waste form itself'. (OECD/NEA 2013a).

The guiding principle for deriving regulations (including dose limits) for this phase is that 'individuals and populations in the future should be afforded at least the same level of protection as the current generation' (ICRP 1998). Motivations for deriving dose limits include

- "1. Acceptability of levels of risk.
2. Comparison with numerical radiological protection criteria used for current practices.
3. Comparison with existing levels of natural radiation.
4. A combination of these." (OECD/NEA 2007)

ICRP (2013) recommends 'that either a dose constraint of 0.3 mSv yr^{-1} (for the expected evolution scenario) or an annual risk constraint of 1×10^{-5} be used for potential exposures from the emplaced waste'. However, there is wide variation in national regulations, not only with respect to the numerical values, but also with regard to terminology and interpretation (terms being used include constraint, limit, and target—applicable to annual individual effective dose, annual conditional radiological risk, or annual aggregate risk) and the ways conformity with criteria has to be assessed (see the review of national regulations described in OECD/NEA 2007).

German Safety Requirements for the disposal of heat-generating waste (BMU 2010) allow for likely evolutions of the repository system (see below for a discussion of scenarios) an additional exposure of individuals of only $10 \text{ } \mu\text{Sv}$ per year (effective dose). For less likely evolutions the additional exposure must not exceed 0.1 mSv per year. The former is being justified with reference to the trivial dose according to (ICRP 2007b), the latter with reference to the lower probability and the risk constraint of $1 \times 10^{-5}/\text{a}$, as mentioned in (ICRP 1998) and later adopted by (ICRP 2013). No numerical criterion is stipulated for unlikely evolutions and for inadvertent human intrusion. However, these requirements are not applicable to repositories for 'waste with negligible heat generation' (equivalent to low and intermediate level waste LILW). For the Morsleben LILW repository, the governmental advisory body SSK (Radiation Protection Commission) recommends limits of 0.1 mSv (likely evolutions) and 1 mSv (less likely evolutions) (SSK 2010).

The ways conformity with criteria has to be assessed typically comprise addressing uncertainties about the future by the systematic development and postulation of scenarios, i.e. descriptions of potential evolutions of the repository system with the aim to illustrate and bound the credible evolutions of the repository system (OECD/NEA 2012a, 2015).¹¹ Scenarios have a range of roles in repository development, including to show (or to test whether) safety

¹¹ In addition to scenarios caused by natural (e.g. geological) features, events or processes, scenarios related to future human actions such as inadvertent intrusion into the repository are also addressed. Due to the unpredictability of societal and technical evolution, there are particular difficulties in defining protection standards for such scenarios. The same holds for 'low probability, high consequence' situations in general. This issue, however, goes beyond the scope of this paper.

criteria are met for a range of potential evolutions of the disposal system. This is being done using numerical models of the repository system, by means of which the containment potential of the repository or, on the contrary, potential releases of toxic substances and thus impact on the environment, can be estimated. Naturally, the compliance timeframes considered (typically up to several hundred thousand years) imply that such calculations are associated with uncertainties. Moreover, there is a wide variation of such uncertainties when considering the system components. While the containment capability of the host rock and the engineered barrier system can be reasonably predicted over the periods of concern, groundwater flow patterns near the surface are less predictable. ‘Surface environmental processes and radiological exposure modes are not generally considered to be parts of a deep geological repository system, but are relevant for evaluating dose and risk. These are less predictable still, being affected by ecological change, human activities and individual habits, which are highly uncertain, even on a timescale of a few years’. (OECD/NEA 2004)

In other words, this is a paradoxical situation in which there are poorly predictable system components which are not crucial for safety (i.e. the biosphere), but are crucial for its assessment using criteria such as dose limits. This is one of the reasons for the ICRP’s statement that:

“... effective dose loses its direct connection to health detriment for doses in the future after a time span of a few generations, given the evolution of society, human habits, and characteristics. Furthermore, in the distant future, the geosphere, the engineered system and, even more so, the biosphere will evolve in a less predictable way. The scientific basis for assessments of detriment to health at very long times into the future therefore becomes uncertain, and the strict application of numerical criteria may be inappropriate. In the very long term, dose and risk criteria should be used for the comparison of options rather than a means of assessing health detriment.” (ICRP 2013)

Thus, calculated doses remain a measure of performance necessary for repository development. The modern concept of the post-closure safety case acknowledges their role but puts numerical calculations of potential radiological consequences into the context of a much wider set of evidence and arguments stemming from geoscience and engineering. This includes the use of additional or complementary indicators (see discussion in the concluding section of this paper) as well as substantiation of the robustness of the system (meaning that key safety-relevant characteristics are unlikely to significantly change over the timescales and for the scenarios of concern).¹² Consistently, international recommendations and national regulations stipulate requirements going far beyond compliance with numerical criteria (IAEA 2011a, 2011b, 2012).

For example, the aforementioned dose criteria stipulated by the German Safety Requirements for the disposal of heat-generating waste (BMU 2010) are addressed in just four of the more than 40 requirements (less than one page in a total of 22). Two further requirements (less than two pages) address the ways conformity has to be assessed as well as an alternative option to show conformity (see discussion of alternative and complementary indicators further below). However, the media and political debate prior to the release of the final version (BMU 2010) was almost entirely focused on the issue of numerical criteria (the only other topic of interest being retrievability) (Hocke and Röhlig 2013).

¹² ‘Robust systems are characterised by a lack of complex, poorly understood or difficult to characterise features and phenomena, demonstrated quality control, and an absence of, or relative insensitivity to, detrimental phenomena arising either internally within the repository and host rock, or externally in the form of geological and climatic phenomena that introduce processes with the potential to compromise safety’. (OECD/NEA 2013a). Robustness measures include the use of the multi-barrier concept.

Thus, it can be concluded that dose values for which criteria (i.e. dose limits) apply for technical specialists are just one piece of the compilation of evidence which is associated with (sometimes considerable) uncertainties and has to be understood in context of assumptions and scenarios. However, dose values are still a valuable and even indispensable tool for technical specialists with regard to both legal security and optimisation of the technical system. For other actors within the radioactive waste debate, however, such values are perhaps the central or even the only safety information. This sometimes goes along with the phenomenon that some actors assign meanings to dose limits which are not necessarily consistent with the rationale behind the proposals made by other actors concerning these limits. These differences in assessments of dose limits and in the attributions of meanings to them clearly reflect the inherent issues of the dose limit concept discussed earlier in this paper.

Debates about such limits are further complicated by the fact that communication concerning dose limits for the post-operational phase often does not address the ways in which models for estimating dose values for this phase are designed. Given the uncertainties described above (ICRP 2013), when calculating dose values, a cautious approach is used in which the members of the (hypothetical) potentially exposed group receive doses at the upper end of the conceivable range. This cautious approach assumes that the group is rather small. However, when transferring a calculated annual effective dose into an annual individual risk, and assuming a linear relationship between dose and likelihood of health detriment ('linear no threshold hypothesis' LNT, ICRP 2007a), this calculated risk value neither carries information about the size of the potentially exposed group, the indicative character of the underlying calculation, nor about the use of the LNT hypothesis.

If this information is not accounted for, it can lead to the conclusion that increased dose values are associated with accepting (perhaps many) additional casualties. Referring to an earlier draft of (BMU 2010) in which a risk criterion was proposed, a German daily newspaper stated: 'By this, many additional fatalities by cancer caused by a repository are possible, since the radioactivity released from underground might spread over large areas with thousands of inhabitants. Once initiated, the release might span over tens of thousands of years and would affect many future generations. After all, highly radioactive waste will remain hazardous for one million years.' (TAZ 2009, 'Cancer and atomic waste repositories. Every thousandth individual may fall ill', translation from (Hocke and Röhlig 2013)). Discussion of this kind finally led to the dose criteria as quoted above¹³ (BMU 2010) as well as to stipulating an alternative option for showing conformity which uses the concept of collective dose.¹⁴

The elaboration on the regulatory and societal contexts of dose limits and on their perceptions by different actors have led to the ENTRIA propositions shown in box 2.

Outlook

In recent decades, the *technical* problems associated with dose calculations in the long term, especially the uncertainties described above, have led to the consideration of what are usually

¹³ Likely evolutions: additional exposure of individuals of only 10 μSv per year (effective dose), less likely evolutions: additional exposure must not exceed 0.1 mSv per year.

¹⁴ ICRP (1998) addresses the issue of collective dose by saying: '[...] the Commission recognises the problems of estimating collective dose over long periods of time in the future'. 'Conventionally, collective dose is a further input into optimisation of protection but it is of limited use in the context of the disposal of long-lived radioactive waste [...]. However, consideration of the number of people potentially involved and the distribution of individual dose in time can be of some help'. The approach taken in (BMU 2010) can be seen as an attempt to do the latter, i.e. to consider the number of potentially involved people. The uncertainties mentioned by ICRP, related to the need for additional 'predictions about future population distribution' (EU 2003), are bounded by providing advice about the calculation of collective dose.

Box 2

ENTRIA propositions:

(Dose) limits do not stand alone but are woven into various sets of regulations. However, different actors perceive and judge the relevance of these contexts most differently.

(Dose) limits are the result of scientific, societal and political negotiations and stipulations. They are based on knowledge, perceptions and interests.

Classical concepts of (dose) limits are not helpful when addressing societal controversies about RWM.

termed ‘complementary’ or ‘additional’, sometimes even ‘alternative’ indicators (IAEA 1994, 2003, 2005, EU 2003, 2009, OECD/NEA 2012b). Many of these considerations, especially the early ones, focus on the migration of radionuclides (e.g. on concentrations in compartments, fluxes out of compartments, travel times etc. either formulated in units of activity per nuclide or in Sievert by using the radiotoxicity of the nuclides).¹⁵ While the calculation of such ‘content and concentration related indicators’ and ‘flux related indicators’ (terminology based on OECD/NEA 2012b) is associated with (sometimes considerably) less uncertainty than the calculation of dose values, it is challenging to formulate criteria (limits) for them: What is an ‘acceptable’ iodine-129 flux at several hundred meters depth? Comparison with values occurring in nature is possible in some cases but leads to new complications. Is ‘occurring in nature’ equal to ‘being acceptable?’ Should limits be based on local, regional, or global data collections? What about radionuclides which do not occur in nature? Moreover, the question whether the use of such indicators might have advantages with respect to governance or communication with non-specialists needs further investigation (OECD/NEA 2012b).

In addition to ‘content and concentration related indicators’ and ‘flux related indicators’, more recent work also addresses what is sometimes called ‘status of barriers related indicators’, examples being groundwater age, container lifetime, transport times through the engineered barrier system components and the geosphere, state of stress in the near-field rock (containment zone), swelling pressure (buffer and backfill) and ionic strength (geosphere groundwater) (OECD/NEA 2012b). From a technical point of view, such indicators are helpful for repository development since, by judging the performance of components, they aid in optimising the repository. But again, it is an open question whether, or to what extent, they might be helpful in broader contexts (e.g. governance or communication).

Despite numerous attempts to address the issue of indicators complementary or alternative to dose, the types of indicators mentioned above have not found their way into national regulations (an exception being the Finnish regulations (STUK 2009)). In the German Safety Requirements (BMU 2010), the additional use of certain ‘status of barriers related indicators’ is required in order to demonstrate the integrity of the geological barrier. Also, an alternative to the conventional compliance demonstration using annual effective dose (see above)

¹⁵ There is considerable variation concerning the predictability of processes and, thus, the (un)certainly of calculated indicators dependent on the compartment (system component) for which these indicators are formulated (e.g. engineered barrier system, host rock, hydrogeological system, surface environment). As a rule of thumb, the timeframe of predictability increases with depth and varies over several orders of magnitude (from a few years for human activities and habits up to 10^5 – 10^6 years for the host rock) (OECD/NEA 2004).

is offered based on the concept of a ‘confining rock zone’, the integrity of which has to be ensured over the assessment timeframe of one million years. It has to be shown that the radionuclides released from this zone lead for likely evolutions to no more than 0.1 person-mSv and for less likely evolutions to no more than 1 person-mSv. The Safety Requirements give advice about how this collective dose has to be calculated. The approach was further tested in the Preliminary Safety Assessment Gorleben VSG (GRS 2013). There is still considerable need for clarification concerning the calculation of the dose values for different scenarios (point source versus plane source, liquid or gas as radionuclide carrier) as well clarification of the exact role this type of assessment should have in a Safety Case.

So far, this debate has been focused on technical issues. In the opinion of the authors, however, the question about complements or alternatives to classical dose concepts should also be addressed from the viewpoints of acceptability, governance, law, communication, perception, and acceptance—thus, in an inherently interdisciplinary way.

Considering the various political, societal, ethical, economical and technical conflicts that are entangled in the debates about nuclear waste management, it will not be sufficient to simply replace ‘old’ criteria with ‘new’ ones—especially when this is done in a top-down decision-making process which does not take into consideration the contentious history of the current dose limit regime. It is likely that such top-down changes would create distrust rather than promote confidence that the ‘new’ criteria are ‘better’ (i.e. more reliable, better suited to ensure safety) than the ‘old’ ones.

An inclusive debate (in terms of the debaters as well as the debated topics) within a deliberative governance system seems, at the moment, the best way to arrive at an acceptable and accepted solution for the management of nuclear waste and the search for disposal sites. In this setting, the topic of criteria (limits) requires specific attention: for a long time, debates about dose limits have served as a kind of a proxy war to dispute national and international nuclear techno-political regimes. It may be worth considering whether coming to an acceptable and accepted agreement on criteria (limits) might appease the debate on nuclear waste management in some regard and, with this, open up spaces for new dialogue between established front-lines.

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