Nuclear Waste State-of-the-Art Report 2022

– Society, technology and ethics

KÄRNAVFALLSRÅDET
Swedish National Council for Nuclear Waste

SWEDISH GOVERNMENT INQUIRIES

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– Society, technology and ethics

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The Swedish National Council for Nuclear Waste

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To the minister and head of the Ministry of the Environment

The Swedish National Council for Nuclear Waste is an interdisciplinary committee that is tasked with advising the Government on issues of spent nuclear fuel, nuclear waste and decommissioning of nuclear facilities, (M 1992:A Swedish National Council for Nuclear Waste. Dir. 2018:18). In February every other year, the Swedish National Council for Nuclear Waste gives its independent assessment of the current situation in the field of nuclear waste. The assessment is presented in the form of a state-of-the-art report. The purpose of the report is to give attention to and describe issues that the Swedish National Council for Nuclear Waste considers important, and to give an account of the Council's views on these issues. The Swedish National Council for Nuclear Waste herewith submits to the Government the state-of-the-art report SOU 2022:7 *Nuclear Waste State-of-the-Art Report 2022 – Society, technology and ethics.*

This report is endorsed by all members of the board and experts in the Swedish National Council for Nuclear Waste. The Swedish National Council for Nuclear Waste's scientific secretary Johanna Swedin has been the project manager for the work on the state-of-the-art report.

English versions of the Nuclear Waste state-of-the-art reports are also available for the years 1998, 2001, 2004, 2007, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018 and 2020.

Stockholm, February 2022

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PART 1

1 Introduction

In accordance with the directives[1], the Swedish National Council for Nuclear Waste (the Council) has been publishing a state-of-the-art report since 1992 (from 2018 on, the report is published every other year).

The chapters in the state-of-the-art report 2022 (SOU 2022:7) intend to both broaden and deepen the perspectives and to highlight the necessity of setting up clear conditions for the continued process with the development of the final repository – for the sake of safety and trust. This is particularly timely and relevant because the Government on 27 January 2022 took decisions to grant Swedish Nuclear Fuel and Waste Management Co's (SKB's) licence application for building a final repository for spent nuclear fuel. The decisions contain a number of conditions, but more conditions will be imposed in the continued handling by the Land and Environment Court at Nacka District Court and the Swedish Radiation Safety Authority (SSM).

The Government's decision came in the absolute final phase of the work with this state-of-the-art report. The Council therefore has not had the decisions as prerequisites in the writing process of the chapters in the report.

1.1 On the decisions and the necessity of conditions

In Chapter 2, *On the Government decisions and the Swedish National Council for Nuclear Waste proposals for conditions*, the Government's decisions are described briefly. Here the Council also gives a number of comments related to the Government's decisions. The Council also highlights its proposals for conditions and regulations, espe-

[1] See Committee terms of reference 2018:18 in Appendix.

cially in relation to those requirements that the Government's decisions contain. The points the Council emphasises in this chapter include the need for transparency, openness and insight in the continued process.

1.2 Socio-technical systems, participation and ethics

In the following Chapters 3–4, issues of importance for conditions regarding participation and information preservation are addressed. These are issues often perceived as situated beyond the field of technology. But all technology is at once both technical and social, and technology is affected by the specific historical and societal contexts it is in. Chapter 3, *Technology in society – socio-technical perspectives on final repositories and safety,* describes the socio-technical perspective in greater detail. The chapter discusses the importance of recognising the socio-technical challenges for the final repository for spent nuclear fuel as a part of the development of safety. An example of an important socio-technical challenge is that society has to be able to manage the project "final repository for spent nuclear fuel" for a long time. The project can take up to a century before the Government gets to consider the issue of a license to closure. The state thereafter is to take over the responsibility for safeguards of nuclear materials, physical protection, information preservation, and so on. The control, other than through inspection and licensing under the Environmental Code and the Nuclear Activities Act, must be carried out in several ways. Efforts are needed, for example, regarding transparency and openness, information preservation, continued risk-related research, and a demonstration repository.

In Chapter 4, *The Aarhus Convention and the public's participation in decision processes relating to the final repository for spent nuclear fuel,* the Aarhus Convention is described, which is an international agreement and an important basis when it comes to issues concerning participation. The Convention is a UN convention that was introduced in Sweden in 2005, concerning among other things the public's participation in decision processes relating to the environment, and access to review of environmental issues. The EU has ratified the convention, which affects Sweden by way of EU law applying in Sweden. The Aarhus Convention determines the public's and in particular environmental organisations' right to information about projects affecting the environment, the right to participate in decision processes regarding the environment, and the right to legal review of environmental issues. In the chapter, the importance of the Aarhus Convention for participation in the stepwise licensing under the Nuclear Activities Act is noted.

Chapter 8, *Small modular reactors (SMR),* describes the ongoing technological development in several countries on different types of small modular reactors (SMRs). In relation to the current large Swedish reactors, it took decades before legislation on nuclear waste management was in place. The Council wants to emphasise that this should not be repeated. Legislation on the management and final storage of the waste from potential SMRs should precede the technical development. SMRs, too, will generate various forms of nuclear waste that have to be managed and finally stored if they become a reality. The final repository for spent nuclear fuel that SKB has been given permissibility to build, will not finally store any other waste than that which is now being produced in the existing reactors in Sweden. In other words, a new final repository, new legislation and new technology would be required in order to handle the waste from potential SMRs.

Chapter 9, *Nuclear waste, the responsibility towards future generations and the non-identity problem,* provides an assessment of ethical/moral theories of our responsibility for future generations. A fundamental issue is whether our responsibility to future generations can be dealt with in the same way as our responsibility for humans living now. Are we obliged to avoid harming future humans in the same way as we are obliged to avoid harming humans alive now? And does one harm an individual only if one makes life worse for that individual? Against the background of an affirmative answer to these two questions, the Government has decided to allow the construction and operation of a final repository for spent nuclear fuel that is safe in the long term. Nevertheless, assume that the final repository is not safe in the long term, and that we harm humans far ahead in time. Have we then acted morally incorrectly? Have we made life worse for those individuals than if we had waited for one hundred years instead? "Obviously!", most will probably answer, but the English philosopher Derek Parfit has a controversial objection. The aim with Chapter 9 is to clarify and address this objection.

1.3 On the canister and the need for research

This state-of-the-art report contains three chapters about continued research etc. on the canister, which consists of a copper shell and a cast iron insert.

Chapter 5, *Corrosion of metallic copper in anoxic water – a scientific controversial in a historic perspective,* describes the scientific discussion, which started in 1986 with a researcher at the Royal Institute of Technology (KTH) describing that hydrogen gas had formed when elemental copper was stored in pure oxygen-free water. This result was interpreted as elemental copper being able to corrode in anoxic water, which went against the prevalent scientific perception and was the beginning of a scientific controversy that still endures. In the end, the controversy is about the question whether copper is a suitable material as the primary barrier for the spent nuclear fuel. In this chapter, the Council summarises the scientific literature that has been published regarding this issue.

Chapter 6, *Trace amounts of absorbed substances in metallic copper and how they affect the mechanical properties of copper*, describes how the mechanical properties of copper are affected by other elements that are included or can be introduced during the fabrication of the copper canister, or later can penetrate into the copper under repository conditions. Certain substances improve the properties of copper as a canister material, while other impair them. On this issue, too, research groups have come to differing results, which are described in the chapter. The Council also provides proposals for continued research on copper corrosion and the influence of tracers.

The two chapters above concern research on the copper in the canister. In Chapter 7, *Embrittlement mechanisms and the cast iron insert,* the Council focuses on the research on properties of the cast iron insert in the canister. In recent years, the Council has several times highlighted that research on the cast iron insert started late and that there are significant uncertainties when it comes to the cast iron insert.

The Council maintains that there is a need for more studies on the cast iron insert. This includes research on the mechanical strength of cast iron and the impact of trace elements and ionising radiation. It is also important to clarify how the interaction between embrittlement mechanisms and the cast iron's permanent deformation under external pressure (creep) affect the mechanical properties of the cast iron insert.

1.4 The Swedish National Council for Nuclear Waste's work and the field of nuclear waste

Finally, there is Chapter 10, *The Swedish National Council for Nuclear Waste's work and the field of nuclear waste,* which forms **Part 2.** Here you will find a description of the Council's work and what has happened within the field of nuclear waste since the Council's report from 2018, that is to say, during the years 2020, 2021, and up to the Government's decisions on 27 January 2022.

2 On the Government decisions and the Swedish National Council for Nuclear Waste's proposals for conditions

On 27 January 2022, the Swedish Government took two historical decisions on the nuclear waste matter and gave permissibility under the Environmental Code (1998:808) and a licence under the Nuclear Activities Act (1984:3) for the construction and operation of a final repository for spent nuclear fuel. [1, 2] In this chapter, the Council starts by briefly describing the conditions included in these decisions. After this follows a description of the proposals for conditions that the Council has discussed earlier. More conditions will have to be considered. The Council also believes that it is important to make specific demands in order to regulate a long-term review.

2.1 The Government's conditions in brief

The decision under the Environmental Code (the EC decision) entails that the Government grants permissibility for a facility for final storage of nuclear material and nuclear waste from the Swedish nuclear power programme, to be built and operated in Forsmark. To this decision the Government adds a special condition that:

> Swedish Nuclear Fuel and Waste Management Co (SKB) shall meet with Östhammar Municipality and Oskarshamn Municipality, competent regulatory authorities, as well as those authorities and organisations proposed by the municipalities, at least once per year to discuss local environmental matters based on the objectives and scope of the Swedish Environmental Code. Within the framework of these meetings, SKB shall continuously provide information on such conditions in the activities at the facility for final storage of nuclear material and nuclear waste

or Clink that may give rise to local environmental impact or that are of importance for the municipality. SKB shall pay the costs for conference rooms and the like. The meetings can be held with the municipalities separately or together. [1a]

In its decision under the Nuclear Activities Act (the NAA decision), the Government gives Swedish Nuclear Fuel and Waste Management Co (SKB) a license to build, own and operate a facility in Forsmark, Östhammar Municipality, for final storage of nuclear material and nuclear waste from the Swedish nuclear power programme. The Government combines this decision under the Nuclear Activities Act with five licence conditions:

1. The facility shall be constructed, owned and operated in principal agreement with what is specified in the application documents.
2. The KBS-3 method with vertical deposition shall be applied.
3. The construction of the facility can commence only after the Swedish Radiation Safety Authority has approved a preliminary safety analysis report (PSAR).
4. The facility can be put into trial operation only after the Swedish Radiation Safety Authority has approved an updated safety analysis report (FSAR).
5. The facility can be put into standard operation only after the Swedish Radiation Safety Authority has approved a supplemented safety analysis report (SAR). [2a]

Further licence conditions apply to Clink. These licence conditions are broadly the same as the conditions that SKB proposed. [2b]

2.2 Conditions on stepwise licensing and the continued process after the decision

The Government writes in its decision under the Nuclear Activities Act that “activities will be subject to a stepwise licensing” and be based on a “reference design” as described in SKB’s licence application. [2c] According to the Swedish Radiation Safety Authority (SSM), the reason for the stepwise licensing process under the Nuclear Activities Act is that SKB is applying for a licence for a “theoretical reference design of the facility, rather than an actual and in all respects fully developed design". [3]

The stepwise licensing process is estimated to last about 17 years for construction and commissioning as well as trial operation, after which it would be possible to start standard operation approximately in the year 2038. [2d] The so-called stepwise licensing process thus comprises only one part of the process of at least 70 years until the issue of a licence for the closure will be examined.

The Government writes that the three steps in the stepwise licensing process lie in the relatively near future, despite the fact that "the time assessments become uncertain in view of the scope of the construction project". [2d]

A stepwise licensing process is based on international practice and the IAEA's recommendations. Stepwise licensing has long been used by the competent regulatory authorities in Sweden for nuclear facilities (nuclear power plants, for example). It is common to the existing nuclear facilities that stepwise licensing has been possible to apply during the construction of the facility. The Authority's review has been possible by progressively inspecting and controlling the construction on site using engineering methods. It has been possible to keep the timeframe for the construction of a facility within a decade. [4]

However, the prerequisites for applying stepwise licensing to a geological final repository for spent nuclear fuel are in part different from those for nuclear facilities in general. For one thing, there is no prior experience to utilise since no repositories are in operation in the world today. (As the only country in the world, Finland has begun to build a final repository). Some other examples of differences are that construction and operation take place simultaneously; that it is not possible to inspect the safety of the barriers; that the actual final repository will not be decommissioned; that the repository has to be safe for at least 100 000 years; and that the final repository is an unusually long-running project to carry out. Since it is a different project than constructing, operating and decommissioning a nuclear power plant, today's legislation is insufficient. A different regulation than the existing one is thus needed because a unique process lies ahead. [4]

In its decision under the Nuclear Activities Act, however, the Government believes that it is not appropriate for the decision to closely regulate how the stepwise licensing process is to proceed, except by means of the three conditions on safety analysis reports that have been described above. [2e]

The Council believes that the stepwise licensing process has to be made more concrete [4] and SSM can impose conditions and control the review process further. SSM is currently working on updating the regulations for final repositories.

The Council has previously raised the issue of the so-called standard operation, i.e., what takes place after the stepwise licensing process. In its state-of-the-art report 2020 [4], the Council emphasises that the construction phase is not one only taking place during the stepwise licensing process until standard operation. If a final repository for spent nuclear fuel is put into standard operation, its construction is not finished. Construction (tunnel excavation, boring of deposition holes) will continue in parallel with operation (placement of buffer and canisters, backfilling, closure of tunnels) until all canisters are deposited, which takes several decades. Under these conditions, it is more difficult to distinguish what constitutes standard operation.

It is also important during the entire time how the repository is being built. The safety analysis reports that shall be updated in the process under the Nuclear Activities Act comprise both SR-Operation safety assessment a safety analysis report for the operation of the final repository and SR-Site safety assessment a safety analysis report on safety after closure of the final repository for spent nuclear fuel.[1]

2.3 Conditions on pilot phase and overall assessments

As a result of what has been written above, the Council wants to stress the following proposals for additional conditions for the process, see below.

[1] SKB. 2011. Application for licence under the nuclear activities act: https://www.skb.com/wp-content/uploads/2017/01/1282973-KTL-ans%C3%B6kan-p%C3%A5-engelska.pdf (hämtad 2022-08-09).

Condition on a well-founded pilot phase

The Council has emphasised that it is unclear what is included in the trial operation, and that this is an example of the “standard stepwise licensing under the Nuclear Activities Act” not being sufficient. It may be necessary to incorporate other new stages and phases. After the decision on permissibility and a licence, the Council believes that conditions have to be established regarding a well-founded and extensive pilot phase in order to allow for any deficiencies in the concept to be discovered early. The continuously ongoing underground activities (excavation, disposal and backfilling and plugging) take place simultaneously. It is therefore important for the phase at least to include emplacement of canisters in two tunnels so as to show that the activities do not negatively affect the engineered barriers or each other. The pilot phase does not correspond to trial operation but is proposed by the Council to proceed for a longer time [4].

Condition on overall assessments

The Government stresses that the licensee under Section 10a of the Nuclear Activities Act is obliged at least every ten years to submit a new, systematic overall assessment (full evaluation) of safety and radiation protection in a nuclear facility. [2f] Overall evaluations, however, have to be clarified and adapted to a final repository for spent nuclear fuel either in conditions or in regulations. The requirement regarding what the assessments are to contain, should regularly be reconsidered. Such “inspection stations” should likely take place more frequently than every ten years. [4]

2.4 Conditions on continued research and demonstration repository

Continued research and analysis of the barriers and the repository environment are needed all the time until the final closure of a final repository for spent nuclear fuel, to improve the long-term safety.

Conditions on continued research and development

The Council establishes that the Government in its decision under the Environmental Code highlights one of the conditions [1c] and the view that the Council has stressed in various contexts, namely:

> ... that it is important that the research projects continue. A very long time remains until the repository is sealed, and new knowledge will be acquired by the repository being constructed. It must also be possible to use future research results, in order for the safety of the repository to be as high as possible. [1b]

The Council highlights this condition in its statement [5] and notes that:

> ... continued research and analysis of the barriers and the repository environment are needed all the time until final closure of a final repository for spent nuclear fuel, in order to improve the long-term safety. Conditions have to be established for this research to be carried out and reported in SKB's research, development and demonstration programme (RD&D programme).

In its decision under the Environmental Code, the Government notes that the Council has emphasised the importance of the RD&D programme in the continued process of stepwise licensing, including research providing comprehensive and adequate material on the cast iron insert. "The Government believes that research on topics including the copper canister's robustness and the cast iron insert must continue to be conducted." [1c] However, the Government considers that this knowledge gathering is already secured through the RD&D programme and the stepwise licensing process in the licence under the Nuclear Activities Act. In this context, the Council wants to emphasise that it is also of crucial importance that research on activities already permitted (by the Government) is included in future RD&D programmes.

In the NAA decision, those conditions are also mentioned that the National Council for Nuclear Waste has emphasised. One of these is that SKB carries out new experiments to specifically study copper corrosion and the properties of the cast iron insert under repository conditions – for example, in a demonstration facility in connection with a final repository for spent nuclear fuel.

In its NAA decision, the Government revisits the RD&D process and emphasises the importance of this process continuing in conjunction with the stepwise licensing process after the decisions:

> In addition to the development taking place within the framework of the stepwise licensing process, the Government establishes that research on uncertainties regarding the canister, the repository environment and the properties of the rock, information and knowledge transfer also are treated within the RD&D Programme that the reactor owners shall prepare or have prepared in consultation with each other every three years, under Section 12 of the Nuclear Activities Act. According to the law, the programme shall provide an overview of all measures that may be needed, and further specify the measures intended to be taken within a timeframe of at least six years. The programme shall be sent to the Government or the authority that the Government determines, to be reviewed and evaluated. [2f]

Condition on demonstration repository

After the decision on permissibility and a licence, the Council believes that conditions have to be established for measurement and monitoring programmes. A monitoring programme can verify calculations and assumptions in the safety assessment. It may also allow for increased transparency. The regulatory authority cannot follow and assess the construction and operation of the safety systems in a final repository in the same way as in a nuclear power plant, as the barriers and the functionality of the final repository can scarcely be assessed. However, one possible way to follow the evolution of barrier systems may be to apply some type of demonstration repository. Also from an international perspective, the measurements and monitoring programmes can provide important new knowledge about final repository processes.

The Land and Environment Court's proposals for possible review periods

Linked to the issue of further research being needed, the Land and Environment Court at Nacka District Court writes in its statement to the Government that one or several review periods[2] may be

[2] The Land and Environment Court may decide on review periods if it believes that an issue has to be studied more before the conditions can be established.

needed in radiation safety matters, and that this should be considered further during a licensing. The court writes that:

> All in all, a review period can be justified in terms of requirements on measures with regard both to the operation of the final repository until closure and to the time after closure of the final repository. [6a]

Regarding the fact that a long time remains until the closure, the Land and Environment Court further writes that:

> During this time, technology development will take place. These circumstances suggest that the issue of more detailed requirements on the closure should be subject to a review period under the Environmental Code. [6a]

(See also proposals for possible review periods concerning information preservation below).

2.5 Conditions on participation, transparency, democracy

The issue of participation is important for every major socio-technical system, not least for a final repository for spent nuclear fuel. Often participation is understood as something that is external in relation to a technical systems. But participation should rather be understood as something that actively develops the socio-technical system. By means of insight and review by more actors, additional questions can be asked, knowledge can be developed, conflicts can arise and the trust in the system can be tested. These are important processes in all societies and in processes that aim to create good knowledge bases. Openness is important both for obtaining confidence from the general public and politicians, and for assessing and improving the final repository concept. Active participation is in line with the Aarhus Convention.

In the Government's two decisions there is one condition linked to participation, which is the condition for permissibility under the Environmental Code when it comes to the municipal meetings with SKB on local environmental issues (see above). However, in 2018 the Land and Environment Court, in its statement to the Government on SKB's application, highlighted the importance of environmental organisations and individuals getting information on and participation in the environmental process as well. [6b]

The Swedish National Council for Nuclear Waste has in various contexts emphasised that it is important that participation and transparency are regulated. More actors than SKB and SSM should be involved in the stepwise licensing process, the overall evaluations and the continued research programmes. The need for broad participation, openness and insight in a continued process exists during the entire, long course of the project and after it (information preservation is important for a long time to come).

The Council has proposed that the Government in a letter of appropriation or similar mandate an agency to form a broadly composed group with different actors such as SSM, county administrative boards, the Swedish Environmental Protection Agency, the municipalities concerned, environmental organisations, SKB, the National Archives, and the state. The Swedish National Council for Nuclear Waste or a similar organisation may have a primary convener role. A broadly composed group should address issues under both the Environmental Code and the Nuclear Activities Act (in contrast to the Government's requirements on SKB's meetings with the municipality regarding local environmental impact under the Environmental Code). This proposed group, together with a number of actors and organisations, can provide information and discuss the project from different angles to improve participation, openness and transparency.

More about the Government decisions and participation is found in Chapter 3, *Technology in society – socio-technical perspectives on final repositories and safety*, in this state-of-the-art report.

2.6 Conditions on information preservation

After the decision on permissibility and a licence, the Council believes that conditions have to be determined about SKB developing strategies for information preservation measures. The conditions have to be developed in good time in conjunction with the design, construction and operation of a final repository. [5]

Related to the latter condition concerning information preservation, the Government emphasises in its NAA decision that:

> … the issue of knowledge and information transfer is an important part of the continued process and observes that the issue is included in the RD&D programme. In view of this, the Government estimates that the issue does not have to be regulated in the license. [2h]

The Council finds that it is of particular importance that the Land and Environment Court and the SSM in their condition formulations take into account the need for conditions on information preservation. In its statement, the Land and Environment Court proposes to consider a review period concerning information preservation. (For more proposals for review periods, see above). [6a]

2.7 Concluding comments on the Council's future role

The nuclear waste issue is not only a technical issue, and the Council has since 1992 worked on it in an interdisciplinary manner. The Council's principal task of studying, shedding light on, and submitting advice to the Government in matters concerning the management and final storage of spent nuclear fuel and nuclear waste, as well as those concerning the decommissioning and dismantling of nuclear facilities, is equally relevant after as before the decision in January 2022. This includes among other things:

A general reviewing role of the KBS-3 concept and processes

The Council has since its origin had a general reviewing responsibility regarding the KBS-3 concept (beyond the RD&D process) and associated processes. After the Government's decisions in January 2022, there is a continued need for such review. This general review is of great importance in the continued licensing under the Environmental Code and the Nuclear Activities Act.

Research programmes

The Council has the responsibility to contribute with an independent review of the RD&D programmes. Research, development and demonstration work will continue, and the Council may be given a continued important role in this work and be an important part of the coming stepwise licensing process (see above).

Participation

It is important to have an actor that has the mandate to contribute to participation, openness and transparency, not least in a future stepwise licensing etc. for the final repository for spent nuclear fuel.

Information preservation for future generations

The Council has got involved in and pursued the issue of the need of developing in good time the work on information preservation. Research so far has shown that processes for information preservation have to cover a wide range of efforts (cultural, legal, technical, etc.), that is to say, that they should be developed from an interdisciplinary perspective. The Council can play an important role in this work, among other things through its seminars and state-of-the-art reports.

Long-term competence management

With a licence to build a final repository for spent nuclear fuel, SKB will proceed from a theoretical reference design to actually building and operating the final repository as it is planned. It is therefore very important for there to be competent personnel in the long term who can carry out the project. The Council's previous investigations (see [4]) have shown that there may come to be a lack of certain skills (which probably will not be possible to be imported), which is important to anticipate as the project requires long-term planning.

Monitoring of practices around the world

The Council should continue to summarise and describe the international development regarding the management of nuclear waste and spent nuclear fuel. This is important since a final repository is to be built according to the principle "best available technique". There are advantages to a council having a wide perspective following developments in other countries, both when it comes to other final repository concepts and variants within the KBS-3 concept.

Decommissioning and dismantling of nuclear facilities

Monitoring this is one of the Council's responsibilities, according to the current directive, and becomes more and more timely now that several reactors are going to be dismantled.

Upcoming processes – SFL and SFR

Other parts of the process for final repositories where the Council's competence continues to be of relevance, are the extension of the Final Repository for Short-lived Radioactive Waste (SFR II) and the site selection process for a Final Repository for Long-lived Waste (SFL).

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3 Technology in society – socio-technical perspectives on final repositories and safety

All technology is developed in a specific historical and social context, and its function will always be as dependent on its material components as on people's understanding and use, that is to say, on the social. A final repository for spent nuclear fuel (the final repository) and the processes for planning, development and implementation of the KBS-3 concept are examples of how people, organisations, artefacts, infrastructure, research, culture, norms and regulatory frameworks have interacted and are interacting over time. The final repository is thus being developed as a composition of social and technical processes. An established definition of technology is that *technology is compositions that function*. [1] In this chapter we understand these compositions as socio-technical combinations. [2] We use a socio-technical perspective and discuss how it can help us to understand in a broader way the challenges that the final-repository project faces.

We start with mobile telephony as an example of all technology being both technical and social at the same time.

3.1 The mobile phone – technical and social

All technology – from the sewing needle to biomedical applications and nuclear power facilities – is at the same time both technical and social. The mobile phone – a technical gadget that many of us use – may serve as an example of what we mean by this.

Technology is created with a certain aim, often to solve a specific problem. Its dissemination and use is not always predictable nor in line with the initial ideas of what the technology was intended for. The first mobile phones were not mobile phones in a proper sense, but radio transmitters that facilitated wireless communication at a distance, for example, created for the military, rescue services and police. The commercial mobile phone that was launched during the 1980s weighed almost 10 kilos, and businessmen could use it between meetings when seated in a car. Its weight and high cost limited the spread of the technology, and the calls were not of a particularly high quality either.

Today, approximately 40 years later, the mobile phone is something completely different both from a technical and a social perspective – small, light, possible to afford for most users, and it has developed from being analogue to digital. The mobile phone has furthermore changed our social life, how we communicate and participate with the surrounding world – everything from reading the morning newspaper, communicating with workmates or friends via speech, text or moving picture, looking for dinner recipes and for keeping track of our sleep and physical activities. The mobile phone is an example of what is commonly called a "technological innovation" and therefore also always entails innovation of social identities and roles, decision-making processes and institutions that develop along with the new technology.

Technical gadgets such as mobile phones are designed and developed by technological expertise. Users of technology do not have to know how the technology functions, only how it is used. However, the more complex the technology is the more dependent the users become of experts when something goes awry. It is not uncommon when technology fails, to blame this on the "the human factor". The users *expect* the technology they have paid for to function, and when it does not, it will lead to indignation and often mass-media attention. During the launch of Apple's iPhone 4, this was exactly what happened. It turned out that when the telephone was held in a certain way "death grip", the calls were dropped and did not function as a telephone at all. In his reply to the criticism, Steve Jobs, Apple's co-founder and head visionary, repeated the message that "we are not perfect" and that the engineers at Apple were working intensively to foresee problems and to solve those *before* they arose, and to handle rare mistakes like this one. He backed up his statements with information about how much resources were dedicated to this and how many tests were made of the function of the present antenna that was the cause of the problem. [3] Even though the statements by Steve Jobs admit the shortages of the technology, they also state a strong faith in the experts' ability to solve problems.

There is also a more complex narrative about the history of the mobile phone. Common standards for mobile telecommunications have been developed and have facilitated far more functions than those we initially used in our common mobile phones. To be able to adopt those common standards (3G, 4G and 5G), actions had to be taken by international, European and national bodies. When mobile telephony of the third generation was established at the end of the 1990s, this had been preceded by EU decisions to adopt the new technical standard, and in Sweden the Government took the decision that 90 percent of the Swedish population should get coverage. This decision by the Government in turn led to the building of numerous telecommunication towers often with local protests not to get them in the neighbourhood, and completely new social questions appeared beyond the technical. Municipalities and committed citizens wondered: What are we to do with this technology? What benefit does it have for us? Are there risks? What happens with local codetermination?

It has been highlighted in media that the production of mobile phones leads to plenty of dangerous waste and that the metals that are used are being mined in countries where both child labour and violations of human rights occur. It is not easy to survey how benefits and risks, connected with a certain technology, are distributed over temporal and geographic borders. Often negative consequences are being understood as "unintentional consequences", a language that links the design and development of the technology to a "creator" with certain intentions. But the good and bad sides of technology need not be understood as part of the developer's intentions at all. They can be a consequence of us living in a globalised world, which means that decisions and actions are distributed across many actors and regulatory frameworks and protections for the health of workers and the environment differ between countries. In a globalised world the effects of our actions are diffused in both time and space.

There can also be basic uncertainties about the consequences of specific technologies for people and the environment (for an explanation of different types of uncertainty, see the Swedish National

Council for Nuclear Waste's State-of-the-art report 2018 [4]). Cell-phone towers and mobile phones generate non-ionising radiation, in the microwave frequency and worries about harm full health effects have been of concern relating to the local heating close to the cell phone antenna or other hypothetical effects. However, radiation from mobile telephony has such low effect that the heat generated has not been shown to have any verified detrimental effects. Another concern, however, has been if electromagnetic fields of the cell-phone towers can cause negative health effects by other mechanisms. Regarding 3G and 4G technologies, potential negative health effects have been evaluated in several epidemiological meta-studies and could not be verified. Effects of a certain type of exposure are often difficult to study – in today's society we are exposed to various confounding factors (through indoor and outdoor environment and through food), and our lifestyles will vary (which have a clear connection to our health).

In parallel with environmental and health consequences, there are also a number of social consequences of our flipping, googling and constant availability through our mobile phones. The large changes to our social behaviours that the mobile phone has caused – from the fact that it is seen as entirely normal today to talk straight out into the air when one walks alone, to children's (and grownups) increased vulnerability due to on-line bullying – were difficult to anticipate 30 years ago. New problems that arise require new solutions in the form of societal provisions and decisions (e.g. prohibitions against mobile phones in school) and new technical components (e.g. wireless headphones and safety filters).

The mobile phone is thus a composition of common technological standards such as physical components, circuit boards, light-emitting diodes, metals, base stations in the form of towers and antennas on one hand and on the other political decisions, trade-offs of benefit and risk, regulatory frameworks and investments, telephone operators and users. The mobile phone is a gadget that does not function on its own as an isolated artefact, but must be composed with all these networks of things, people, organisations, standards and infrastructures.

3.2 A socio-technical perspective on a final repository for spent nuclear fuel

> Research on the role of science and technology in society – how science and technology come into being, is disseminated, applied and questioned, and changed – exists in several fields of study, such as sociology of knowledge, research on professions, organisational studies, research on governance, and studies of social movements (e.g. volunteer movements in environment and gender equality).

To enable a discussion of a final repository for spent nuclear fuel from a socio-technical perspective, we first list some concepts and research results from the research field STS – Science and Technology Studies. STS is a research field whose *main focus* is to study the role of science and technology in society. STS research includes many perspectives, but a common denominator in the field is that the development, dissemination and use of science and technology are seen as intimately included/integrated in societal processes.

The researchers Hess and Sovacool [5] give an overview of the STS research and its relevance for the energy issue. Among other things, they take up the following concepts that have been developed since the field's establishment during the 1980s [5]:

Socio-technical systems are ensembles of people, artefacts, infrastructure, research, culture, norms and regulatory frameworks, and natural resources. The development and process of the final repository is a clear example of such a system and we will develop that below. Research into socio-technical systems puts the technical artefacts – the gadgets such as e.g. the mobile phone – in a context and asks questions about their origin and development, production, resources and infrastructure, benefit and risk, users and dissemination, regulatory frameworks and decision-makers.

Interpretive flexibility means that scientific knowledge and technological design are shaped through social processes that involve negotiations over their meanings and purpose. What meaning science and technology get, can therefore vary between different groups and also over time. Science-based controversies, which see researchers as actors on both sides and where scientific arguments constitute an important ingredient, are nothing unusual. During an ongoing controversy, interpretive flexibility is opened, but it can also be closed, which means that the interpretive flexibility is being limited. We will later provide several examples of science and technology being given different meaning, in relation to final repositories.

The politics of design highlights the fact that technical artefacts reflect societal values and ideas about the user. An example is the view on whether the spent nuclear fuel should be retrievable or not. This relates among other things to how we are to look at it, as a resource or as waste, and whether we believe that future generations may have to repair the repository.

Distributed agency or the agency of objects is a concept that has been developed in the actor network theory (in the following ANT). That objects have agency should not be understood as things being proper actors just as people or organisations with intentions, aims and interests. But objects can make things happen, and people can delegate tasks to technology; one example is automatic door openers. Another example is that we delegate final storage of the spent nuclear fuel to the KBS-3 method.

The issues that are treated in the other chapters of the present state-of-the-art report 2022 can also be seen from a socio-technical perspective. Socio-technical systems are compositions of people, artefacts, infrastructure, and regulatory framework. The Aarhus Convention (chapter 4) is a part of the international regulatory framework that supports the participation of the public and environment organisations, and thereby can contribute to a change of the composition of actors. The ethical issue that is treated in chapter 9 relates to the values upon which we consciously and unconsciously build our technical decisions, in this case the responsibility for future generations. The view of opportunities and risks with small modular reactors (SMR) is an example of all technology being developed in a specific historical and social context, see chapter 8. Chapters 5, 6 and 7, which are about interpretations of the research situation and scientific controversies, are additional examples of interpretive flexibility. This means, as we have mentioned above, that scientific knowledge and technology are shaped through social processes that involve negotiations over the meaning and purpose of the knowledge.

3.2.1 Separation and integration of the technical and the social

ANT studies, which we mentioned above, are interested in the relationship between the technical and the social. One of the prominent figures in ANT study, Bruno Latour [6] claims – despite these existing compositions of technology and the social – that there is a strong tendency in modern society towards separating them. Latour explains this tendency with modern society's high degree of specialisation. Professions and institutions have developed which have been specialised in "the one" (natural sciences, medicine, technology) or "the other" (law, social sciences, psychology). Within the universities, these specialised fields are split across different faculties, and within municipalities and the industry, experts find themselves in either technical departments and environmental offices or in departments for personnel and communication. The specialisation and division lead to professions developing languages, perspectives, approaches and communities that make it more difficult to communicate across and between these borders. But Latour claims that despite this tendency towards separation, it is almost impossible in practice to separate the technical and the social. In practice, the social and the technical are therefore integrated, but that can occur in different ways.

In a study that compares processes for final storage of nuclear waste in four countries – Belgium, Slovenia, Great Britain, and Sweden – four different variants of socio-technical combinations are identified that all prioritise the technical above the social. [2a]

1. Social aspects are being hidden. Technical experts can take decisions that involve social priorities and values, but without making this visible and transparent to others. That means that the project is presented as *more technical* than it actually is, since the social aspects are hidden and embedded in the experts' decisions.
2. Social aspects are subordinated. Social aspects may be added at a late stage, after a well-developed technical project already is in place. That results in technical solutions that are developed by experts being given priority, and potential contributions from "social actors" becoming subordinate.

3. Processes are separated. Participatory processes are often disconnected from decision-making processes. Examples are given from Belgium and Slovenia, where partnerships were established. But in both the countries these became quite short-lived. During the time for the site investigations, the Swedish Nuclear Fuel and Waste Management Co (SKB) had tight contacts and discussions with Östhammar and Oskarshamn. But SKB's decision to select Östhammar was disconnected from the many previous consultations with the two municipalities.
4. Integration that hides separation. There are far-reaching attempts to integration in Belgium and Slovenia, among other things examples of involving citizens more in security matters and monitoring programmes, but where the decision-making actor has guarded old boundaries and ignored what one has arrived at in the partnerships. Since the dialogue and the collaboration still have taken place, the process can be *presented* as an integrated process despite its being separated in practice.

3.2.2 Civic epistemologies, technologies of hubris and technologies of humility

As is apparent above through the STS research, technology is not isolated artefacts produced by experts – but complex compositions. Therefore, experts cannot handle them on their own, but there is a need for public insight and scrutiny. Sheila Jasanoff [7] has highlighted in her research how technology is complex compositions of natural resources that are needed for its production, legislation and regulatory framework, and assessments of benefit and risk. Jasanoff has also taken particular interest in the relationship between expertise and democracy. She thinks that we need societal structures that make sure that important expertise is utilised, but is not seen as once and for all given.

To utilise scientific knowledge and technical development and at *the same time* retain a humility for the fact that the latest knowledge or development is not the only and final solution, is an art that a single individual expert authority or decision-maker cannot handle. It is an attitude towards science and technology that only can be developed *between* decision-makers and citizens, something Jasanoff calls *civic epistemologies*. Also in those cases where the handling of an issue is largely transferred to experts, which is the case for many environmental and health matters, only the people who live and operate in a society, and who are affected by the consequences of the experts' decision, can assess how the handling works. Problem conceptions change over time and in relation to the experts' initial problem or approach. The function, risks and benefit of technology can be reassessed when the compositions change – something may be added, for example, a different climate, a new scientific discovery, or a new regulatory framework. If these complex compositions change (which they do, since society is not a controlled and isolated laboratory, nor a neat drawing table), it is probable that the new problems that arise are not in the field of expertise of the original developer – other skills can become important in the re-evaluation of the benefits and risks of the technology. Large technical systems are often handled through prediction and control. Researcher Jasanoff [8] argues that these so-called technologies of hubris have to be supplemented by technologies of humility. Technologies of humility is approaches that can give better prerequisites for reflection and the possibility to evaluate the unknown and uncertain as well.

3.2.3 Socio-technical challenges and democratic control

The issue of democratic decision-making and transparent processes in repository processes is connected to technologies of humility. The aims of the EU-project *International Socio-Technical Challenges for implementing geological disposal* (InSOTEC) included identifying socio-technical challenges with regard to final storage of spent nuclear fuel. The final report of the project states that the need of long-term governance of the implementation of a geological final repository constitutes one of the major socio-technical challenges and that this has not been discussed much. But how is it possible to establish governance processes that facilitate democratic decision-making and transparent processes over several generations? The researchers in InSOTEC describe some observations and understanding in relation to long-term governance of a geological final repository [9]:

- Stepwise decision-making is needed, and it is important that technical questions are discussed publicly at all stages. Broad participation should also include those with deviating opinions, and apply in all phases of a planning and implementation process.
- Conflicts can be constructive by emphasising potential weaknesses in a suggested technology, which may need to be adjusted and improved. Participation is not only about creating trust, but can also contribute to the development of the technology.
- The complex socio-technical matter of carrying out geological final storage requires interdisciplinary perspectives. Several perspectives are needed that are not only parallel but that also interact with each other. It is important to incorporate different values and understandings.
- We cannot anticipate all problems and changes that can arise over the time it takes to build a final repository. Therefore, flexibility and the will and ability to develop the technology are required to avoid lock-in. For example, research programmes should continue during the whole implementation period, and they should be interdisciplinary and open for insight from society.

3.3 Socio-technical challenges, long time perspectives, and the Swedish final repository

The Swedish final repository for spent nuclear fuel is a very clear example of a socio-technical system. Historically, for instance, we can see the interpretive flexibility that has existed, that is, how the perception of the waste and the responsibility to take care of it in Sweden has been reassessed. To solve the most urgent problems, on a few occasions during the 1950s and 1960s, radioactive waste was dumped in the Baltic Sea, the Gothenburg archipelago and the Atlantic. [10a] It then took almost 30 years of nuclear development work before the requirements for the handling of the waste from nuclear power and final storage of the spent nuclear fuel was reflected in policy and legislation.

Political (*the politics of design*) and societal changes have then been driving technological development and research (see more detailed descriptions of the processes e.g. in [11, 12]).

The historical changes of the regulatory framework have influenced the handling of the spent nuclear fuel and the knowledge that has to be developed. The Environmental Impact Assessment (EIA) legislation and the Environmental Code [13] began to apply in 1998 when the process to find a method and place for a final repository for spent nuclear fuel already had been initiated. The new law introduced new societal values having to be taken into consideration – for instance, that several alternative methods for final storage are to be developed, and higher demands on involving affected groups and an interested public. This can be compared with the Nuclear Activities Act [14] from 1984, which focuses on radiation safety and above all involves the exchange of information between the implementer of nuclear activities and experts at reviewing authorities (regulator).

The following section gives some examples of current socio-technical challenges in relation to the final repository for spent nuclear fuel.

3.3.1 New issues arise twenty years later – the example of the LOT experiment

The KBS-3 method entails that there are three barriers that are to work together for the purpose of enclosing the spent nuclear fuel, namely the copper canister, the bentonite clay, and the rock. In the Äspö Hard Rock Laboratory, which is SKB's unique research facility (there are only a few similar ones in the world), 500 metres below the ground, experiments are conducted to study under realistic conditions, for example, how the bentonite clay interacts with the rock. One of SKB's experiments that received a lot of attention is the so-called Long Term Test of Buffer Materials (LOT), see box below.[1]

The LOT experiment is a topical example of interpretive flexibility and the necessity of openness towards the possibility of the initial problems and the questions changing. The LOT experiment has been discussed a lot, not least in connection with the Government's permissibility assessment.

[1] Also see chapter 5, section 5.5. about the LOT experiments.

On the LOT experiment:
The arrangements in the LOT experiment consist of seven packages that were installed between 1996 and 1999. The packages consist of 4 m long copper canisters with electric heaters surrounded by bentonite clay in boreholes at a depth of approximately 450 m in the rock on Äspö. Copper plates (coupons) were embedded in the bentonite clay close to the central copper canisters (at somewhat increased temperature).

LOT was a bentonite experiment, and the issue of copper corrosion under repository conditions was not central during the experimental design. In its report, SKB points out weaknesses with the LOT experiment with regard to copper. [15, 16] In the first uptake after 1 year, copper (Cu) was not checked at all. In the second uptake after 6 years, some analyses of Cu were conducted, but a report where the results were presented did not come until some years later. In the third uptake of two packages, which was carried out in 2019 after 20 years, several analyses on Cu were conducted, though. One final package of the experiment remains to be taken up. For reading more about the experiments, see reference [17].

Environmental organisations have asserted in the discussion that it is possible to find out whether copper is a suitable encapsulation material. They consider it possible in the two 20-year experiment packages to retrieve detailed results concerning copper corrosion from the most corroded surfaces, and they think that SKB has not wanted to publish these results. [18]

The LOT experiment and the discussions 20 years after the experiment was initiated show that it is not given which issues will be relevant or which actors will raise them. The copper issue was not in focus in the LOT experiment twenty years ago, and we do not know which issues and technologies will be questioned in the future. The discussions of the LOT experiment also show that assessments of science and technology are about trust as well, which must be maintained continuously (cf. civic epistemologies). Also, in those cases where the handling of a question is largely transferred to experts, it is only others who can assess how the handling works. The environmental organisations have expressed a lack of trust and even a suspicion that there is something to hide, when the results of the LOT experiment are not presented publicly.

The National Council for Nuclear Waste has stressed in a pronouncement to the Government [16] that it is important that SKB gives an account of how the now ongoing experiment S3, which is a part of the LOT experiment, will be completed, analysed and presented.

The Council has proposed that the Government set as a condition in connection with its decision about permissibility for the operation of a final repository for spent nuclear fuel, that SKB conducts new experiments to study the copper corrosion during final repository conditions specifically. These experiments should be conducted with the type of copper that is intended to be used in the final repository. The experiments can be carried out, for example, in a demonstration facility in connection with the final repository for spent nuclear fuel. In the Government's decision of 27 January 2022, it was established that: "research on topics including the copper canister's robustness and the cast iron insert must continue to be conducted". [37a] No particular condition was formulated; instead, reference was made to SKB, in future RD&D programmes and the stepwise licensing process, having to give an account of the remaining results from the LOT experiment, make new safety assessments, and also conduct further research on copper corrosion. At the same time, it is clear in the decision that the continued research "mainly aims to optimise the KBS-3 method". [37b]

3.3.2 The century perspective – at least seventy years of construction time

The example with the LOT experiment shows that the issues that are in focus can change over the course of only twenty years. Now that the Government has given the go-ahead for construction and operation of the final repository under the Environmental Code and the Nuclear Activities Act, at least seventy years (according to SKB's planning) of research, testing, building and operation await before the repository is finished and can be closed. Before closure, however, the licensee for the final repository must apply for a new licence from the Government. [38a] Thereafter the state is to take over the responsibility (including for nuclear safeguards and physical protection) and the project will probably take more than a century to carry out.

In its pronouncement to the Government in 2018, the Land and Environment Court at Nacka District Court takes up a time perspective of seventy years (the time that SKB considers to be needed), which they call the construction time and which "the parties have not devoted a lot of attention to". [19a]

The Council has particularly pointed to the necessity of giving careful attention to the century perspective. The Council noted e.g. in its pronouncement on SKB's research programme RD&D 2019 [20, 21] (RD&D stands for research, development and demonstration) that the programme lacked a discussion about flexibility and best available technology. There was no account of how SKB plans to follow up research and utilise research results from international research during the time it takes to build, operate and close the repository – at least seventy years. [21a] The Council has also highlighted the century perspective in other contexts, not least that there are several challenges concerning the implementer's (SKB) organisation, that competence management is needed and that the financing has to be sufficient. Furthermore, the Council considers that SKB should do research on how unpredictable societal changes such as economic, political and social external changes can influence the final repository project. (See [10, 21, 22, 23], for example.) It is important to be prepared for surprises, changes that are unexpected, since all prognoses and plans for the future of necessity are fallible.

The Land and Environment Court additionally believes that: "It should be considered whether the long time to build the final repository makes it justified to impose special requirements on the activity", for example by a "control programme that takes into particular account the long construction period". [19b]

By being able to impose conditions, the Land and Environment Court and the Swedish Radiation Safety Authority (SSM) have key roles in the continued process. The court can also judge whether a review period for an issue is needed, i.e., whether it has to be studied more before the conditions can be determined.

3.3.3 The process over the coming century – what do we know?

When we look back a hundred years, we can see that a lot has happened. Therefore, it is rather likely that things will happen – new research results, developed technology, a changed climate, or new legislation – that entail re-negotiations of the meaning and purpose of previous assessments of science and technology. The century perspective reminds us that it is important to recognise that the role of science and technology is not given once and for all, but that there is an *interpretive flexibility*. Therefore, it is logical and wise that continued planning and research processes, too, take into account that such changes will occur.

Questions

At present there are many questions about what the continued process will look like. One question is which actors are to be given insight. This is a question that regards what societal and democratic values we want a continued process based on the KBS-3 method to contain. To how large an extent do we rely on experts being able to handle the coming process, and to what extent is public scrutiny needed? And what development and research process means that we feel confident with delegating the storage of the spent nuclear fuel to the KBS-3 method? How can a process for the coming seventy years, now after the Government's decisions on permissibility and licence, incorporate a humility towards future new technical knowledge or development upending all or parts of the KBS-3 method? Is it of importance to have a width of skills in the future process, in addition to technology and natural sciences, such as e.g. ethics, decision-making and risk management?

The regulation is presently not completely clear with regard to what the continued process looks like after the decision on license and permissibility for the applications on final storage of the spent nuclear fuel. This applies, for instance, to what is included in a stepwise licensing process under the Nuclear Activities Act. [24]

We know, however, that there remain both concretisations and additional conditions for the continued practical work for SKB with research, planning, construction, operation and closure. The remaining conditions will be based on two different laws – by the Land and Environment Court under the Environmental Code, and by the Radiation Safety Authority under the Nuclear Activities Act. In its 2022 decision on permissibility under the Environmental Code, the Government found that the condition proposals that have been formulated (by SKB and in the Land and Environment Court's pronouncements) can be handled by the Land and Environment Court in the continued licensing process. [37a]

What the process with conditions under the laws looks like:

The Environmental Code

- The Government assesses permissibility and can then decide on specific conditions in order to satisfy general interests (permissibility conditions), EC Chapter 17 Section 7.
- The Land and Environment Court grants a permit and combines the licence with conditions.

The Nuclear Activities Act

- The Government decides on a licence and conditions for the license.
- The Radiation Safety Authority decides on potential additional conditions under the Nuclear Activities Act and the Radiation Protection Act, and assesses according to the Government's license conditions.

Below, we take a closer look at some questions about the continued process, on the basis of the century perspective and in relation to participation and continued research programmes.

Participation

The question of participation is important for each socio-technical system. Often participation is understood as something that is external in relation to a technical system, that which we have described above as a separation between the technical and the social. But participation should rather be understood as something that actively develops the socio-technical system. By means of transparency and review by more actors, additional questions can be asked, conflicts can arise and the trust in the system can be tested. These are important processes in democratic societies, but also in processes that aim to create good knowledge bases.

It is quite clear that SKB, as the implementer, and SSM, as the regulator/reviewing public authority, will have distinctive roles. The process is therefore partly transparent since the actions of authorities are public. But the transparency is also limited, partly due to the fact that SKB is a private company. Furthermore, SKB has the ambition to sell its competence, through SKB International, to other countries that want to have support in their work on final storage. It can also be difficult to obtain insight into what the interaction between SKB and SSM looks like, and which trade-offs are made in the course of the process. There is a risk that social dimensions are hidden and that the process is presented as more technical than it is, if there are no open forums with requirements to formulate technical details in an easily accessible way and on the basis of a clear context (e.g. trade-offs between social values, legal requirements or the use of research funding).

Below, we describe what has emerged about participation up to and including the Government's 2022 decision in the two legally separate processes under the Environmental Code and under the Nuclear Activities Act.

The Environmental Code participation

SKB has had concrete but limited proposals for conditions [26] regarding how different actors' participation may be included in the continued process under the Environmental Code:

– One condition proposal from SKB is that SKB during the license period, at least once a year, is to meet Östhammar and Oskarshamn municipality and qualified supervisory authorities, as well as authorities and organisations that the respective municipality can suggest. They will then treat local environmental issues on the basis of the Environmental Code.

– Another condition proposal from SKB is that SKB during the time up until closure of the final repository will carry out surrounding world monitoring, which is presented to the Government, Östhammar municipality and relevant supervisory authorities at least each fifth year. The surrounding world monitoring will according to SKB's proposal focus on information preserving and monitoring of the final repository.

In its pronouncement to the Government 2018, the Land and Environment Court emphasises the importance of a broad participation:

> ... the participation of environmental organisations and individuals in the case has been important for highlighting the issue of permissibility in a comprehensive way. During the continued assessment, a discussion is needed about how environmental organisations and individuals can be given an opportunity for continued information about and participation in the environmental process. [19b]

In the Government's decision under the Environmental Code, from January 2022, the Government considers that good communication and insight by Östhammar and Oskarshamn municipalities are essential, but that SKB's first condition proposal above suffices.[2]

After the Government's decision, the Land and Environment Court has the opportunity to formulate additional requirements/conditions under the Environmental Code.

The Nuclear Activities Act participation

There is no clear regulation today of participation under the Nuclear Activities Act, which the proposal in the report on a new Nuclear Activities Act demonstrates. According to the report, the investigation assesses that the phases of the stepwise licensing process have to be united with regulations that allow insight and an opportunity for influence.

> ... there should be a clearer set of requirements against which the licensing process is to take place, and how consultation with the public and other interested parties is to be designed. [27]

[2] See also Chapter 2.

SKB has not had any condition proposals for participation under the Nuclear Activities Act.

In the Government's decision on participation under the Environmental Code, which has been described above, SKB is to provide information about local issues (e.g. groundwater reduction and protected species) to the municipality of Östhammar and Oskarshamn. But in the decision under the Nuclear Activities Act, the Government is of the opinion that the general interest and Östhammar municipality's wish to be an active party in the stepwise licensing process do not have to be regulated in a licence under the Nuclear Activities Act. Instead, the Swedish Radiation Safety Authority assumes responsibility for ensuring that Östhammar municipality's "insight can be carried out in a satisfactory way". [38b]

SSM thus has to clarify how insight and participation in the continued process under the Nuclear Activities are to be achieved, including in stepwise licensing processes with updated safety analysis reports and in periodic overall assessments[3] thereafter.

Funding of participation

Not only regulation for participation has to be revised, but so do matters concerning the funding of participation for various actors. The Council has discussed that the funding should be revised in order to facilitate for municipalities and environmental organisations to participate in the process with regard to the Environmental Code and the Nuclear Activities Act even if an activity obtains a license. [28] An investigation was appointed in 2021 with the aim to revise the possibility of long-term funding for the participation of municipalities and non-governmental organisations (NGOs) in matters concerning the assessment of a final repository for spent nuclear fuel and radioactive waste, and for other work on following the nuclear waste issue. [29]

[3] In the Nuclear Activities Act, there are today requirements for overall assessments (full evaluations) which are specified in ordinances and regulations. At least every ten years, the licensees are to make an integrated analysis and overall assessment of the facility's safety and radiation protection. Read more in [24].

Broad participation in the continued process is requested

After the Government having issued a license on 27 January 2022, there still remains important development and research as a part of the continued process for the final repository. Furthermore, insight into the work on the implementation of the repository is needed. The Council therefore considers that there is good reason to continue with transparency and openness so as to achieve a high quality in knowledge grounds and decisions. The Aarhus Convention emphasises that people's knowledge and expertise can contribute to improving the quality of environmental decisions.

Several actors have pointed out the importance of a broad continued participation also after a license (see e.g. above the Land and Environment Court and the Nuclear Activities Act inquiry). The international group from the *Organisation for economic cooperation and development* (OECD)/Nuclear Energy Agency (NEA) that reviewed SKB's safety analysis, SR-Site, also wrote about participation. The international group was of the opinion that SKB should keep concerned municipalities as well as national interest groups involved during all stages of the project. [25a]

There are no economic resources secured yet for other actors' participation, either, nor are there self-evident forums for a *broad participation*. It is positive, however, that the work with the RD&D programmes maintains the possibility of insight according to the existing model.

The Council is of the opinion that a broader and more active participation is needed, and has proposed that a broadly composed group should be formed, by means of appropriation directions or the like, that is tasked with handling issues under both the Environmental Code and the Nuclear Activities Act. [30, 31]

The Council has also pointed out that mandatory involvement of concerned actors in the stepwise licensing process, overall assessments, and the RD&D Programme should be regulated.

Research programmes

Every third year, SKB presents its plans for continued research and technology development in a special research programme (RD&D). SKB has been preparing RD&D programmes since 1986, and during all these years they have been reviewed by the concerned actors and approved by the Government. This formal process of review and response has kept issues alive and creates a democratic process focused on the safety of SKB's final repositories.

The Council underlines that: Research and development is an ongoing process, which not only provides new knowledge, but also gives rise to new questions. Previously accepted knowledge is reconsidered, and new technical solutions are developed. The Council furthermore points out that the principle of best available technology is fundamental in the Environmental Code and also is a concept that is focused on the future. [21b]

The Council has been discussing for several years that it is important for research, development and demonstration programmes in accordance with the Nuclear Activities Act to continue for a final repository for spent nuclear fuel, also after a licence. SKB writes in a statement in 2021 that the Council's wish can be satisfied, if necessary, through a Government condition (under the Environmental Code) that relates to relevant research within the scope of the RD&D process. [32] The Government decision of 2022 establishes that continued research is needed, but no special conditions concerning this were formulated, as a stepwise licensing process is upcoming and the RD&D process is expected to progress even after the decision on permissibility under the Environmental Code and a licence under the Nuclear Activities Act.

The Council has in its review statement on RD&D 2019 also strongly emphasised the importance of openness, transparency and comprehensiveness in SKB's research, since these ultimately contribute to the long-term safety of the final repository. The comments from various consultative bodies and the responses from SKB contribute to improving SKB's research and development activities. The consultative bodies from different sectors of society can highlight perspectives and issues that are important for the execution of the projects and, not least, raise issues of relevance for general society. [21c]

Participation and transparency furthermore contribute to a documentation for the future – which show which critical issues have been raised by different social actors. This creates a social memory of importance for future generations when it comes to the radioactive waste.

The broad transparency and participation that the RD&D process has permitted so far, is thus also needed in the future.

3.3.4 The long-term safety – 100 000 years

The decisions that have been taken by the Government in 2022 is to permit the construction and operation of that proposal for a technical solution which SKB has developed, i.e., the KBS-3 method. In the balance for the decisions there were many questions and perspectives of both technical and social nature.

It is a decision taken under uncertainty, in view of the fact that there is a fundamental uncertainty about the future when the technology needs to enclose the radioactive waste. A repository has to be "safe" for up to a million years, and at least for 100 000 years, which is the time it takes before the waste corresponds to the radiation levels in the natural uranium ore used to produce the fuel.

An important issue for future safety and societies is the societal memory. How can the technical information and the knowledge of the final repository developed in our time "travel" through time to be understandable for people and societies in the future? A future that in all probability has changed with regard to language, culture, technology, scientific knowledge, rules, and governance. This is an issue where both technical solutions (e.g. time capsules) and social ones (recurrent events, monuments, etc.) are discussed.

The so-called safety assessments which SKB carries out are a major issue for long-term safety. It is not possible to know on the basis of previous experience that a final repository can isolate the waste from humankind and environment for so long a time, and it cannot be controlled in retrospect. Instead, different safety analysis are made to assess the safety. In a safety analysis, of necessity quite a lot of theoretical assumptions are made (about environmental events, human intrusion, etc.), and it is based on models that are simplifications of reality. The safety analysis are included in safety analysis reports that are to be updated and approved by SSM before construction, trial operation, and standard operation, as part of a so-called stepwise licensing process under the Nuclear Activities Act.

One way to follow up socio-technical assumptions made in a safety assessment is to use monitoring programmes when a final repository is built and operated, at least up to final closure of a repository. A monitoring programme can be designed so that information regarding ongoing processes in the rock is collected, for instance, its mechanical and thermal behaviour or hydrology, and that the engineered barriers are studied, such as the bentonite clay and the copper canisters. Monitoring programmes are being developed in a number of countries, among them France and Finland (read more in [33]). Furthermore, at the request of the French parliament, Andra (the authority in France responsible for final storage of high-level waste) has developed a final repository project where the waste is retrievable. [34] SKB did not plan for monitoring in its application in 2011, but the company has changed its attitude during the course of the licensing process. In SKB's RD&D Programme 2019, there is a separate section on monitoring, where it is described that the monitoring will contribute to verifying SKB's understanding of the evolution of the repository, supporting assumptions made in the analysis of post-closure safety, as well as identifying any previously unknown processes and events. [20a] But no description is provided of how different stakeholders can be involved in the design of a monitoring programme.

The international group from OECD/NEA underlines in its review that SKB should draw up a comprehensive testing and monitoring programme to confirm that the proposed repository works as planned. The group considers that the programme should continue until final closure and that it is an issue of the regulatory authority's and the public's trust. Furthermore, the group is of the opinion that SKB has to show that the company is sufficiently open to gathering new data down at repository depth, even if such information might challenge existing models and results from the tests that until now have been carried out from the surface for many years. [25b] The Government does not set any conditions about monitoring programmes in its decision from 2022, but such conditions may be formulated by the Land and Environment Court and by SSM.

Socio-technical challenges in the long time perspective

How can we understand socio-technical challenges in relation to the long time perspective? Jasanoff [8a] describes that various methods for predictions have been designed in fields where there are large uncertainties, for instance, risk assessments. SKB's risk analyses and assumptions about "worst-case scenarios" can be included in that which Jasanoff calls predictive "technologies of hubris". According to Jasanoff, there are three considerable limitations with these methods: 1) they focus on the known at the expense of the unknown and do not always show the existing uncertainty and ambiguity; 2) they can be difficult to understand for non-experts and therefore also difficult to criticise and openly debate; and 3) they are not able to highlight challenges arising outside their own boundaries (for instance, other parameters and variables than those that are included in the models). Jasanoff argues that also technologies of humility are needed which recognise that assumptions can be incorrect, and which are more open towards reassessing the questions that are raised and towards which knowledge thus must be included. Jasanoff's concepts of technologies of humility cannot be summarised in a single method, but rather involve an understanding of the complexity in socio-technical systems, the necessity of openness and a readiness to change the initial assumptions, and a willingness continuously to include more knowledge that potentially may turn that which we hold for true on its head. The monitoring programmes can be a part of such a system that is flexible, recognises socio-technical complexity, and is open to the possibility that initial assumptions may have to be revised or even be overturned.

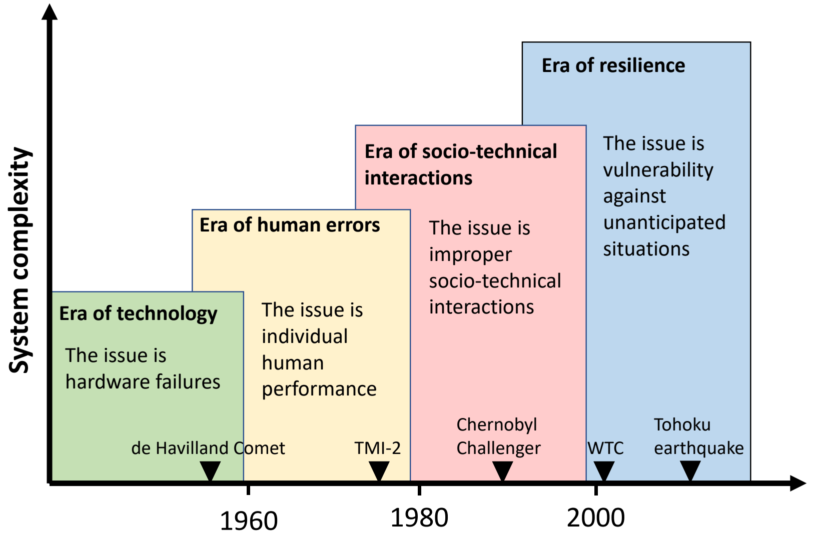
3.4 Keeping future challenges for the final repository present today

Socio-technical perspectives are of practical importance

All technology is developed in a specific historical and social context and a final repository is not an isolated artefact produced by experts – but is based on complex compositions of things, people, organisations, standards, and infrastructures (a socio-technical system). Regardless of how long a time perspective we consider – 20, 100, or 100 000 years – there will be socio-technical challenges for the final repository. Research on STS has shown this clearly. Also research that has evaluated accidents has shown that the social parts of technical systems combined with the technical have been the cause in several cases. This is true for the Fukushima Daichii accident, for example. [35]

As a result of the understanding that complex socio-technical systems have failed and that unexpected accidents have occurred, there is a discussion of how risks have been handled historically and what is needed in the future. Historically, a development is seen from viewing technical failures as just technical, i.e., when the systems were not so complicated (see figure 3.1). Concurrently with the increased complexity of the systems, the human factor has also been seen as a cause. Then it was established that also poorly functioning socio-technical interplay could cause accidents (e.g. the Chernobyl accident) and the idea of a safety culture was introduced. Today it is discussed how engineers and technical systems can be created that can recover from unexpected events such as terrorist attacks and earthquakes. We need new approaches on socio-technical systems today that handle risks in and beyond the socio-technical system. [36]

Figure 3.1 Changes in the view on what causes accidents and faults in complex socio-technical systems (the figure is freely recreated after [36a])



The figure shows changes in the view of what causes accidents and faults in complex socio-technical systems.

The socio-technical perspectives are therefore of great practical importance and have to be consciously given attention in the continued final repository process.

The socio-technical from a Swedish perspective – conclusions

It is important in the continued work to give attention to the complexity in a socio-technical system, and that the final repository project is not presented as more technical than it actually is. More perspectives and a consciousness of this being a complex socio-technical project mean that the strategies to handle the challenges become more adequate.

- The latest knowledge or development is rarely the only and final solution. Problem conceptions change over time, and it is important to be prepared to change the initial assumptions. There can also be fundamental uncertainties. Therefore, research programmes are important during the entire time up to final closure.
- The Council has on several occasions in its reviews emphasised the character of the final repository process, which is not only research-dependent but also has the character of a long-term project, that is to say, with “a century of challenges.” This means that special emphasis must be placed on the dynamic and unpredictable character of the research process. One way to follow up the socio-technical assumptions that have been made in a safety analysis, is to use monitoring programmes at least during the time while a final repository is being built.
- It has to be clarified what the governance of the continued processes will look like after the Government’s decision in January 2022, with what transparency and with what opportunities for broad participation. It is necessary to create preconditions for long-term governance processes that facilitate democratic decision-making and transparent processes spanning several generations.
- It is important to retain transparency and flexibility throughout the project. Open processes with transparency, so that information persists about which trade-offs have been made, can also be seen as a way to take responsibility for future generations. The question of information preservation thus becomes dependent on constant maintenance, rather than a final solution that we can devise here and now.

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4 The Aarhus Convention and the public's participation in decision processes relating to the final repository for spent nuclear fuel

4.1 Introduction

The preceding chapter describes that the final repository for spent nuclear fuel is socio-technical and stresses among other things that participation is important in an implementation process. This chapter describes the Aarhus Convention, which is a basis for participation in environmental law issues. The Aarhus Convention was negotiated within the framework of the United Nations Economic Commission for Europe (UNECE) and entered into force in 2001. It is a new type of environmental convention, as it connects the protection of human rights with the protection of the environment in a way this has not been done before. The convention is legally binding for the nations that have signed it.

The Aarhus Convention focuses on the public's and in particular environmental organisations':

- right to information about the environment
- right to participation in decision processes concerning the environment
- right to legal action in the review of environmental issues

The convention is aimed at administrative decisions, i.e. a statement from an authority, intended to have determining character for administrative bodies or individual's actions and thereby to be action-dictating. At hand may be a licence to carry out a certain measure or a prohibition. It is thus "the exercise of authority to determine for an individual on favour, right, obligation, disciplinary punishment or other comparable circumstance" that qualifies as the exercise of public authority. [1] Other activity that the authority is engaged in is not included in the exercise of public authority, for instance contracts or business activities.

The exercise of public authority can consist of both favourable and onerous decisions. An individual cannot appeal a favourable decision, but only decisions that formally are negative (thus it does not matter whether the individual perceives the decision as onerous: if it formally is favourable, it cannot be appealed, see Section 22 of the Administrative Procedure Act).

However, the Aarhus Convention gives the environmental organisations, which have to meet certain criteria, a right to speak for public interests, that is, to appeal rulings and decisions on licences and approval of environmentally hazardous activities and on exceptions to protection of areas. They also have the right to appeal decisions on measures related to the authorities' supervision.

In the preparatory work for the Swedish Environmental Code, the issue of public interests is addressed. There one conclusion is that nature has a value in itself, in addition to the value it has as a resource for humankind.

This chapter first describes in general terms the background to the convention and its rules. Thereafter, the implementation of the convention's provisions in Swedish law is presented. The chapter is rounded off with examples of how the Aarhus Convention may be applied in relation to the development of the final repository for spent nuclear fuel.

4.1.1 Background

Matters of legal procedure have long been considered to be a national matter. The public's right to participate in decision processes and in the context of environmental issues being examined legally was not regulated by international law to any appreciable extent.

Still, there have been bright spots that have led to the Aarhus Convention, and these are described below.

The Nordic Environmental Protection Convention of 1974

The Nordic Environmental Protection Convention is a result of the 1972 United Nations Conference on the Human Environment.[1] It is a regional agreement between the Nordic countries Norway, Sweden, Denmark and Finland (i.e., excepting Iceland). The convention contains, among other things, principles stating that damages and disruption that may occur in any of the other states are to be dealt with in the same way as damage and disruption in the current state during an assessment of whether an activity is to receive licences and similar. Citizens, including environmental organisations in the concerned states, also have the right to bring an action to court and before the authorities in such a case. The purpose is to remove the obstacles that parties' national borders can create.

The Rio Declaration in Brazil 1992

It was only at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, Brazil, in 1992 that the matter of the public's participation in the review of environmental matters gained international attention. More than 150 states agreed upon the so-called Rio Declaration [2], which in its Principle number 10 formulated the issue of the public's participation in environmental issues in the following way:

– Environmental issues are handled best with participation of all concerned citizens.
– On a national level, each individual should have access to information on the environment that is held by public authorities, including the information on hazardous materials and activities in their communities.

[1] It was signed on 19 February 1974 and came into force on 5 October 1976.

- States should facilitate and encourage the public's awareness and participation by making information on environmental issues publicly available.
- The public should be provided access to legal and administrative handling in accordance with each country's legislation, including corrections and other measures.

The Rio Declaration, however, is not a legally binding document and, since the charter is formulated in a general way, leaves several issues concerning the execution unanswered. Even though the Rio Declaration does not clearly regulate the issue of environmental organisations right to speak, it was of importance, since ideas were presented in it that later (by way of the ministerial conference in Sofia) would serve as a basis for the design of the Aarhus Convention.

Ministerial Conference for the environment in Sofia 1995

In 1995, a conference with Ministers of Environment was held in Sofia, Bulgaria, where they agreed on several guidelines for increasing the public's influence in environmental matters. The provisions in the Rio Declaration served as a basis for these guidelines. The Ministerial Conference in Sofia was the starting point for the work on developing a new convention on the environment, and the ministers agreed that the time was ripe for a legally binding document. The work later led to what came to be called The Aarhus Convention. [3]

The Aarhus Convention 2001

Based on the guidelines from the Ministerial Conference in Sofia, some thirty countries and a coalition of several international and regional environmental organisations started negotiating the Aarhus Convention's contents and design: A convention about access to information, the public's participation in decision-making, and access to legal review in environmental issues.

A result was presented after two years of negotiations, and on 25 June 1998 the Aarhus Convention was opened for signing in the Danish city of Aarhus. The Aarhus Convention was negotiated within the framework of the United Nations Economic Commission for Europe (UNECE) and is a regional convention for all European countries. It is also open for the USA and Canada, though, as well as the previous soviet republics in Central Asia.

The convention was signed by the EU and 34 more states and came into force in October 2001. Today (as of January 2022), the convention has been ratified by 47 states and the EU. [4]

4.2 The Aarhus Convention

A new type of environmental convention

The Aarhus Convention constitutes a new type of environmental convention, as it connects the protection of human rights with the protection of the environment in a way this has not been done before. The convention addresses the fact that a prerequisite for our fundamental human rights is that there is suitable environmental protection. It asserts that each human has the right to live in a healthy environment and that a larger social participation by the public in turn creates a better environment. The goal is to contribute to protecting current and future generations' right to a good environment.

The EU has implemented the Aarhus Convention through Directive 2003/4/EC on the public's right to environment information, and directive 2003/35/EG on the public's participation in preparing plans and programmes and the right to legal review. EU Regulation (1367/2006/EC) provides opportunities for environmental organisations to request review and legal review of administrative measures and administrative negligence within the EU's institutions.

The convention is legally binding for all states that have ratified it as a party. Each party has the obligation to facilitate the principles of the convention. The parties shall also present a national report, which always includes a consultative and transparent process.

The EU has the task to ensure compliance, not only in the Member States, but also for its institutions such as various types of authorities and organisations.

The three pillars of the convention

The Aarhus Convention is based on three different pillars:

1. *The public's right to information on environmental issues*
   Access to information means that every citizen should have a right to gain broad and simple access to environment information. Public authorities must provide all the information required, and collect and disseminate it in a speedy and open manner. They can refuse to do so only in specific situations, for example in matters relating to national defence.
2. *The public's right to participate in environmental decision-making processes*
   The public must be informed about all relevant projects and it must have the chance to participate in the decision-making process and in the legislation process. Decision-makers can utilise people's knowledge and expertise and thereby improve the quality of the environmental decisions and, not least, guarantee the legitimacy of the decision.
3. *The public's right to take legal action in environmental issues*
   The public has the right to be consulted, within the framework of current law, and in other respects participate in a licensing process and appeal licensing decisions and inspection decisions. The public also has the right to participate in legal or administrative Government procedures if a party breaks against or fails to follow environmental legislation and the convention's principles.

Different types of actors

The convention makes a distinctions between "the public", "all civil society actors" and "the public concerned", that is, those persons or organisations who are affected by or interested in the environmental decisions (for example environmental organisations). Public authorities are the addressees of the convention, namely governments, international institutions, and privatised bodies that have public responsibility or act under control of public bodies.

The private sector, for which disclosure of information is dependent on voluntary, non-compulsory, practice, and organisations acting in a legal or legislative capacity, are not affected by the convention's information requirements.

Other important provisions are for instance the principle of "non-discrimination" (all information has to be disclosed without taking into account the applicant's nationality or citizenship), the convention's international nature, and the importance of promoting the public's environmental education. [5, 6, 7]

The environmental organisations right to speak for public interests

The Aarhus Convention regulates in article 9 (1–3) the environmental organisations' right to speak for public interests.

Environmental organisations which meet certain criteria under the Environmental Code have the right, within the appeal period, to appeal judgements and decisions on licences and approval of hazardous activities as well as exceptions for protection of areas. They also have the right to appeal decisions on measures related to regulatory supervision by the authorities.

The criteria in Sweden under Chapter 16 Section 13 of the Environmental Code are that the organisation is a non-profit association or other legal entity with the main purpose of protecting nature-conservation or environmental-protection interests, and that it has been operating in Sweden for at least three years and has at least 100 members or in another way demonstrates that it has support from the public.

Environmental organisations that fulfil the national criteria are provided an extensive standing[2] for environmental organisations, regarding all actions and omissions that the regulatory authorities have made in various licensing processes.

Environmental organisations also have access to legal review of the authorities' decisions and omissions in various inspection cases. The environmental organisations are also given access to legal review when it comes to the authorities' right to act directly against an activity operator through a civil process. Article 9.3 of the convention concerns the possibility for the public, including environmental organisations, to contest a private-law claim which an activity operator asserts, the correctness or inaccuracy of which will be examined by the court.

[2] Standing here – to stand before a court – i.e. to appeal etc.

4.3 Implementation of the Aarhus Convention in Sweden

The implementation in Swedish law

The Aarhus Convention was introduced into Swedish law in 2005. [3a] While the rights that the Convention gives the public to a large extent already were guaranteed in Swedish law when the Convention was introduced, a certain number of Swedish laws were complemented, such as the Swedish Environmental Code, the Roads Act, the Aviation Act, and the Minerals Act. However, the Aarhus Convention was not implemented in all the relevant laws, for example not in the Swedish Forestry Act (1979:429).

Various organisations in Sweden have criticised the Government for not having implemented the Aarhus Convention in its entirety. Among other things, there are no provisions in Swedish legislation that give environmental organisations the right to appeal an inspection decision or to request that a permit decision be reconsidered. An example is given below of an inadequate implementation, where a judgement in the highest instance affected the application of law in Sweden.

National law versus Union law – Example: Swedish Forest Agency's licence decisions

The fact that the Aarhus Convention was not separately implemented in the Swedish Forestry Act, led to a case where an environmental organisation was not given the right to appeal a decision by the Swedish Forest Agency to allow logging of a forest area that according to the environmental organisation was worth preserving. The decision to deny the environmental organisation the right to appeal was tested all the way up to the Supreme Administrative Court, which came to the conclusion that the Aarhus Convention was to be applied. The environmental organisation thereby gained the right to appeal the Forest Agency's licence decision according to the judgement in the Supreme Administrative Court. [8]

The case in question concerned national circumstances, but was also tangent to Union law right by virtue of the logging areas' location next to a Natura 2000 area.[3] According to a judgement in the EU court [9], when a Convention provision can be applied both to situations covered by national law and to situations covered by Union law, there is a clear interest that the provision be interpreted in a uniform manner, regardless of under which circumstances it is to be applied. The procedural law should to the extent possible be interpreted in such a way that an environmental organisation as the one in the case in question is given an opportunity to bring an action to the court against a decision that may be in violation of the Union's environmental legislation.

The Supreme Administrative Court's judgement is thus indicative for the application of law in other cases that relate to regulatory decisions with the support of a legislation where the Aarhus Convention has not been implemented via a direct provision.

4.4 The application of the Aarhus Convention in the context of the construction of a final repository for spent nuclear fuel

Stepwise licensing of licence conditions

On 27 January 2022, the Government granted licences under the Nuclear Activities Act:

firstly, to construct, own and operate a facility in Östhammar Municipality for final storage of nuclear material and nuclear waste from the Swedish nuclear power programme,

secondly, to construct a facility part adjacent to the existing Central interim storage facility for spent nuclear fuel, Clab, for encapsulation of nuclear material and nuclear waste, called Clink.

A number of conditions have been incorporated in the licences, entailing among other things that:

– the *construction* of the facility can commence only after the Swedish Radiation Safety Authority has approved a preliminary safety analysis report (PSAR).

[3] Natura 2000 is a network of protected areas in the entire EU. In Sweden there is more than 4 000 Natura 2 000 areas.

- the facility can be put into *trial operation* only after the Swedish Radiation Safety Authority has approved an updated safety analysis report (FSAR).
- the facility can be put into *standard (regular) operation* only after the Swedish Radiation Safety Authority has approved a supplemented safety analysis report (SAR).

Each such safety analysis report that the Swedish Radiation Safety Authority (SSM) receives, will be safety reviewed and examined by the authority and will result in a decision that may entail that the licensee can continue with the construction of the facility. The final safety analysis report will be submitted by the licensee when it is time for a final closure of the final repository. This process, as far as the final repository is concerned, will continue for about 70 to 80 years, according to the Swedish Nuclear Fuel and Waste Management Co's (SKB's) plans.

During this long time period, which is at issue, it is reasonable to assume that continued research and technology development will take place, for instance relating to the integrity of the copper canister and the stabilising capacity of the bentonite buffer. The design solutions that were thought of at the time of application may have to be changed over time. Problems may arise during the construction phase and lead to other solutions having to be resorted to. Doing this kind of licensing of large nuclear facilities, which takes place stepwise, is also recommended by the IAEA.

For a licence, which is associated with conditions, to remain valid, it is necessary that the licensee fulfils the licence conditions. This means that progressively supplemented safety analysis reports must comply with the requirements that are described in SSM's regulations (SSMFS 2008:1 and 2008:21). If SSM finds that the requirements according to the regulations are fulfilled, SSM takes a principal decision, which may entail that the safety analysis report can be accepted and construction work can continue.

SSM will thus take a number of decisions, where the authority, on each occasion, is to assess the long-term safety when it comes to the final repository, and continuously examine whether the KBS-3 method can be considered to be acceptable. Ultimately, the aim is to protect human health and the environment in the long term against damage and other detrimental impacts.

SSM decisions are administrative decisions that can be appealed

Much suggests that the decisions regarding the preliminary safety analysis reports in a stepwise licensing process, which SSM takes on each occasion, are administrative decisions which entail the exercise of public authority. A positive decision entitles – in this case SKB – to continue to construct a final repository.

According to Administrative Procedure Act by Hellners & Malmqvist [10], there are certain formal requirements to be met for an authority measure to be counted as a "decision". In order to be counted as a decision, the measure must have the character of a statement that endures at the time of the examination of the appeal. In practice, it has usually been emphasised that a decision can be appealed when it has some form of legal effect, i.e., it is binding for someone and is enforceable. Res judicata suggests that a decision is considered appealable. Also refusing a request from someone who is a party is usually a decision that is appealable. Even when a decision is not enforceable, does not entail a refusal of a party's request, and is not affected by res judicata, it may affect someone's personal or economic situation in such a way that it should be possible to be appealed.

Who has the right to appeal?

Then the question is who has the right to appeal SSM's decisions regarding the preliminary safety analysis reports related to the construction of the final repository for spent nuclear fuel. SKB, obviously, and persons residing nearby. The Environmental Code – Chapter 16 Section 13 – gives environmental organisations the right to appeal judgements and decisions about licences, approvals or exemptions that are decided under the Environmental Code, and Section 5 b of the Nuclear Activities Act specifies that i.a. Chapter 2 of the Environmental Code shall be applied during review of cases. The fact that SSM in its review of cases under the Nuclear Activities Act shall take into account some of the material provisions of the Environmental Code, does not necessarily entail that the special procedural rules that under the Environmental Code apply to non-profit organisations are applicable to the decisions that SSM takes.

Concerning the issue of who has standing, another point of departure is found in the three basic principles of the Aarhus Convention – mentioned above – regarding:

1. the public's right to gain access to environmental information that authorities possess,
2. the public's right to participate in decision-making processes that have an impact on the environment, and
3. the public's access to legal review in environmental issues.

The final repository facility for spent nuclear fuel in Östhammar, just as the above legal case with a decision by the Swedish Forest Agency to allow logging of a forest area, affects a Natura 2000 area. This suggests, with the guidance of the Supreme Administrative Court's judgement, that an environmental organisation would have the right to appeal SSM's decision regarding preliminary safety analysis reports.

References

1. This is a general concept, which is used widely in administrative law. The concept was introduced by the older Administrative Procedure Act (1971:290). See prop. 2016/17:180, p. 47, which describes this.
2. The United Nations Conference on Environment and Development, the Rio Declaration, was held in Rio the Janeiro, Brazil, from 5 to 30 June 1992.
3. The Aarhus Convention (cf. Directive 2003/4/EC of the European Parliament and of the European Council of 28 January 2003 concerning the public's access to environment information, and suspension of the European Council's Directive 90/313/EEC (EUT L 41, 14/02/2003 p. 26, Celex 32003L0004).
   3a. The Aarhus Convention. Prop. 2004/05:65. Available at: www.riksdagen.se/sv/dokument-lagar/dokument/proposition/arhuskonventionen_GS0365 (retrieved on 09/02/2022).

4. Read more about “Aarhus Convention – your right to environmental information” on the Swedish Environmental Protection Agency’s website: https://www.naturvardsverket.se/en/environmental-work/international-cooperation/conventions/aarhus-convention (retrieved on 19/05/2022) [in Swedish: www.naturvardsverket.se/om-miljoarbetet/internationellt-miljoarbete/internationella-miljokonventioner/arhuskonventionen--din-ratt-till-miljoinformation (retrieved on 11/01/2021)].

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9. EU court’s judgement in Case no. C-240/09.

10. Hellner, T. & Malmqvist, B. 2010. *Förvaltningslagen: med kommentarer [Administrative Procedure Act: with comments].* 3rd ed. Norstedts Juridik. Stockholm.

Laws and regulations

Administrative Procedure Act (2017:900).

Act (1984:3) on Nuclear Activities (Nuclear Activities Act).

Environmental Code (1998:808).

Forestry Act (1979:429).

SSMFS 2008:1 The Swedish Radiation Safety Authority's Regulations concerning Safety in Nuclear Facilities (SSMFS 2008:1).

SSMFS 2008:21 The Swedish Radiation Safety Authority's Regulations and general advice concerning safety in connection with the final storage of nuclear material and nuclear waste (SSMFS 2008:21).

Directives and EU regulation

Directive 2003/4/EC, on the public's right to environmental information.

Directive 2003/35/EC, on the public's participation in preparing plans and programmes, and the right to legal review.

EU Regulation (1367/2006/EC).

5 Corrosion of metallic copper in anoxic water – a scientific controversial in a historic perspective

5.1 Introduction

The KBS-3 system consists of three barriers, copper canister with a cast iron insert, bentonite clay and the bedrock. The barriers shall together prevent the spread of decomposition products from the nuclear waste to the biosphere, and the copper canister constitute the primary barrier. The scientific reasoning for the choice of a 50 mm thick copper canister as the primary barrier in the KBS-3 system has been in focus regarding the long-lasting safety of the final depository. The issue dominating the scientific discussion so far is the choice of copper as canister material, whether it fulfils the safety requirements for the long-lasting integrity of the container. The main issue has been whether metallic copper may corrode at the conditions expected in the final repository, specifically, if anoxic water may corrode metallic copper. This issue has been heavily debated during the last 35 years, since Hultquist proposed it in 1986. [1] A large number of experimental and theoretical studies on this subject has been reported in open peer reviewed scientific journals, and in technical reports from the Swedish Radiation Safety Authority (SSM), the Swedish Nuclear Fuel and Waste Management Company (SKB) and Posiva, the Finnish counterpart to SKB. The aim has been to prove or disprove the hypothesis that metallic copper may corrode (oxidize) in pure anoxic water. This has caused a scientific controversial which is still on-going, and it has put doubts about the suitability to use copper as protecting material in the canisters for deposition of used nuclear fuel in the bedrock ca. 500 m down into the ground.

The Swedish National Council for Nuclear Waste (the Council) organised in November 2009 an international conference on copper corrosion in pure anoxic water with almost 300 participants from all around the world. [2] One year later, the Council organized a round-table discussion at MIT, Cambridge, MA, USA, with invited experts. At this meeting, the results from the conference in 2009 were summarised, and the planned experiments proposed by SKB were discussed. The Council organized an international symposium ("New insights in to the repository's engineered barriers") in 2013 concerning copper corrosion in pure anoxic water. [3] The Council also organized a domestic symposium in 2014 with scientists from the Royal Institute of Technology (KTH) in Stockholm and Uppsala University, who have taken active part in the studies of possible corrosion of copper in pure anoxic water, as these have reported different results, see below, with the aim to solve the scientific controversial. The outcome of the symposium did result in neither consensus nor possibilities to find a common view on the issue.

In this chapter, we have summarized the literature dealing with the possible corrosion of metallic copper in pure anoxic water. The results from reported studies are summarised in chronologically order to allow the reader to follow how this controversial has developed. The publications are divided in peer reviewed scientific journals and technical reports from SSM, and companies with responsibility to safely deposit nuclear waste, SKB and Posiva. However, contributions from conferences without a peer review system are not included. We give also a brief scientific background with the aim to give the reader an insight to established chemical and physico-chemical rules, and to pin-point the scientific details of the on-going scientific controversial. In Appendix 4,[1] a more detailed description of the chemical reactions responsible for corrosion of metals, and in which way the surfaces of metal oxides are affected by the presence of water.

[1] Appendix 4: "Redox reactions (electron transfer reactions) and the chemistry of the surfaces of metal oxide in presence of water".

5.2 Fundamental chemistry

Corrosion of metals is a reduction-oxidation (redox) reaction where electrons are transferred from one compound to another. This means that one compound releases electrons (reducing agent), it oxidizes, and the other compound accepts electrons (oxidizing agent), it reduces. Redox reactions are examples of chemical equilibria. This means that there is a balance between reactants and products, which are determined by chemical and physico-chemical parameters describing the ability of the participating chemical compounds to react with each other. A chemical equilibrium is written in the following way:

$$R1 + R2 \rightleftharpoons P1 + P2$$

where R1 and R2 are the reacting compounds, P1 and P2 are the products formed, and the double arrows shows that it is a chemical equilibrium (the final distribution of reactants and products in a chemical reaction). A chemical equilibrium can either be shifted to the right, at equilibrium there is more of the products than the reactants, or to the left, at equilibrium there is more of the reactants left than products formed (little or nothing has happened). The physico-chemical parameter giving information whether the equilibrium is shifted to the right or to the left is the standard electrode potential. It describes the ability of a chemical compound to be oxidised or reduced. Metallic iron is an example of a compound which oxidizes easily (fairly strong reducing agent), while it is very difficult to oxidize metallic gold (very weak reducing agent). Likewise, oxygen is easily reduced (strong oxidizing agent) while it is difficult to reduce the hydrogen in water (very weak oxidizing agent) to hydrogen gas. Metallic iron corrodes (oxidizes) easily of oxygen in air, while metallic gold does not. Metallic copper is oxidized by oxygen in air to mainly copper(I) oxide, Appendix 4. This results in that metallic copper in contact with air forms a dark surface layer of copper(I) oxide, a couple of tenths of millimeter thick. Further oxidation of metallic copper in presence of water and dissolved compounds leads to the formation of blueish-green copper(II) compounds.

The reaction discussed in this chapter is the one between metallic copper, Cu, and pure anoxic water, H_2O, to form copper(I) oxide, Cu_2O, and hydrogen gas, H_2,

$$2\,Cu(s) + H_2O(l) \rightleftharpoons Cu_2O(s) + H_2(g) \qquad \text{(reaction 1)}$$

where (s) denotes a compound in solid state, (l) denotes liquid and (g) a gas.

According to the standard electrode potentials for the compounds in reaction 1, which are determined with high accuracy and precision, the equilibrium of this reaction is significantly shifted to the left. It can therefore be assumed that only extremely small amounts of copper(I) oxide and hydrogen gas will be formed before the reaction reach equilibrium and the reaction ceases, for details see Appendix 4.

5.3 Literature survey – oxidation of metallic copper in pure anoxic water

In this sub-chapter, the scientific publications on copper corrosion in pure anoxic water are presented in chronological order. The presentation is divided in publications in peer reviewed scientific journals and technical reports from SSM, and in technical reports from SKB and Posiva.

5.3.1 Publications in peer reviewed scientific journals and agency reports

The first article reporting that metallic copper was corroded by pure anoxic water was published in 1986 by Hultquist. [1] The corrosion was observed indirectly by the evolution of hydrogen gas. The experiment was performed at elevated temperature, 50 and 80 °C, and sodium chloride was added as inert salt. It was assumed that metallic copper was corroded to copper(I) oxide in the reaction $2\ Cu(s) + H_2O(l) \rightleftharpoons Cu_2O(s) + H_2(g)$.

A year later another research group made a similar study in distilled water at 25 °C with the purpose to compare the results with those reported by Hultquist. [4] They concluded that metallic copper was not corroded under the conditions they have used. [4] Hultquist and coworkers replied to this report by trying to find possible differences in the experimental set-ups to explain the different observations. [5] In this reply paper they put forward a hypothesis that copper and water reacted on the copper surface to split water molecules into a hydrogen atom, H, and $CuOH\cdot$ and $Cu_2OH\cdot$ radical complexes; a radical is a chemical species with an unpaired electron and thereby very reactive, and denoted by a dot ”·”. As an argument they put forward that $CuOH^+$ and Cu_2OH^+ ions have been detected in water exposed copper surfaces by SIMS. However, it is important to stress that ions as $CuOH^+$ and Cu_2OH+ are different species with different chemical properties than the radicals CuOH· and Cu_2OH·.

Eriksen et al. reported in 1989 a study to compare new data on corrosion of copper in pure anoxic water. [6] They were not able to detect any hydrogen formation in their experiment, which lasted for 61 days. The only corrosion product they found was copper(I) oxide, most likely from reactions with initial oxygen content in the experiment. They also did put forward arguments based on established thermodynamic data that metallic copper cannot be oxidized by water.

Möller reports a two-year study where copper wires were immersed in oxygen-free water in test tubes sealed with palladium and platinum foils. [7] Oxidation of the copper surfaces were observed in equal amounts in all samples, most likely from traces of oxygen present from start. These observations are opposite to those reported by Hultquist [1].

Beverskog and Puigdomenech reported revised Pourbaix diagrams for copper in the temperature range 25–300 °C and the pH range 0–14 in 1997 in a review article. [8] Copper(I) oxide, Cu_2O(s), and copper(II) oxide, CuO(s), are stable up to 200 °C, while at 300 °C only CuO(s) is stable. It can be noted that solid copper(I) hydroxide, CuOH(s), was excluded in the calculations due to lack of data.

In 2007 Szakálos, Hultquist and Wikmark reported new more carefully performed experiments on corrosion of metallic copper by water. [9] They reported that hydrogen gas was formed in a system containing only metallic copper and oxygen-free water at 20 °C in a glass container hermetically sealed with a palladium membrane. In this experiment hydrogen gas was detected over the long experimental time 10 500 hours (1.20 years). The hydrogen production rate was determined to 0.37 $ng \cdot h^{-1} \cdot cm^{-2}$ during the first 7 000 hours thereafter the hydrogen gas production slowed down slightly. In a second experiment, two compartments of stainless steel with pressure meters separated with a palladium membrane only allowing hydrogen gas to pass from one compartment to the other. The water was contained in a glass vessel in order for the water to not come in contact with the stainless steel. In this experiment, it took 1 200 hours to pump off the initially present oxygen at 20 °C. Thereafter the temperature was raised to 62 °C, and significant amounts of hydrogen gas were detected. After 2 100 and 2 275 h the temperature was raised to 73 and 85 °C. At each temperature increase, the hydrogen pressure increased significantly. The observed hydrogen gas pressure at 73 °C was approximately 2 000 times larger than the steady-state pressure of $5 \cdot 10^{-7}$ bar. A secondary ion mass spectrometry (SIMS) study of copper surfaces exposed to oxygen-free and oxygen-containing water and to dry oxygen gas, showed that Cu_2O was the solely product formed in in dry oxygen gas, and while a mixture of copper oxides and hydroxides with an O:H ratio close to unity were found in presence of water. [9] It was proposed that a corrosion product with formula H_xCuO_y, with x and y close to unity, which could be described as "protonated" copper oxide was present on the outer surface, together with $H_xCuO_{0.5}$, "protonated" copper(I) oxide, closest to the metallic copper. [9] The authors claim that the initial form of hydrogen is atomic in a proposed reaction $Cu(s) + yH_2O \rightleftharpoons H_xCuO_y + (2y\text{-}x)H_{ads}$, where hydrogen atoms are adsorbed to the copper surface, H_{ads}. A fraction of the Hads is recombined to hydrogen gas, $H_2(g)$, and the other fraction is entering the copper metal. [9] If the hydrogen gas is removed or eliminated the corrosion process can continue. [9] To summarise, the authors propose that water is catalytically split in atomic hydrogen, H, and a hydroxyl radical, OH, where the latter immediately reacts with metallic copper to form H_xCuO_y. The hydroxyl radical is known as a very reactive species.

In a comment to the study by Szakálos, Hultquist and Wikmark, Johansson under-lined that oxidation of copper by water is not thermodynamically allowed, and that the proposed corrosion product H_xCuO_y is unknown to science. [10] Johansson finds it remarkable that H_xCuO_y should be more stable than known copper oxides, and it requires strong experimental support for this stability. [10] He also questioned the accuracy of the reported experiments by Szakálos et al. and did put forward alternative reasons for the hydrogen production. In a reply to Johansson's comment, Szakálos et al. claimed that their experiments have been performed in correct way, and that Johansson's proposed alternative explanations for the hydrogen production were incorrect. [11]

Rosborg and Werme reports the first results of long-time experiments of copper canisters placed in the Swedish bedrock similar to those conditions in a nuclear waste repository, LOT experiments. [12] Details of the LOT experiments are given below.

Hultgren et al. maintain their position in paper in Catalysis Letters in 2009 [1,5,9,11] using first principles simulations in new hydrogen gas evolution studies there they claim:

a) There is an evolution of hydrogen in reaction with copper metal in liquid water at room-temperature which is evidence for corrosion of copper by water. This hydrogen evolution takes place up to a pressure which greatly exceeds the hydrogen pressure in air,

b) Early experimental results, favoured hydroxide formation, and our first principles simulations concerning copper stability are consistent with our present experimental results which involves catalytic properties of a copper hydroxide,

c) Contrary to the accepted view, pure water does indeed corrode copper,

d) By linking together exposures with widely varying durations of copper to liquid water without or negligible O_2, a realistic extrapolation is made to predict that more than 1 m thickness of copper is required for a 100 000 year lifetime at room-temperature. [13]

To extend the time-line they have examined copper coins from the historic warship the *Vasa*. [13] It has been proven that water at the sea-bottom around the Vasa was saturated with hydrogen sulfide. [14] Hydrogen sulfide is known as a compound able to corrode copper. [15]

Werme and Korzhavyi replied on this paper claiming that Hultgren et al. have used hydroxide ions, OH^-, instead of hydroxyl radicals, OH, which cause a significantly different result in the calculations. [16] The hydroxyl radical, an extremely reactive oxidant, is able to oxidize copper as well as gold. New calculations presented in the paper show that chemical species containing copper, oxygen and hydrogen are all less stable than copper(I) oxide and should therefore not be formed. [16]

In a comment to the reply by Werme and Korzhavyi, Hultgren et al. states that they have used the hydroxyl radical in their calculations, and they still claim that stability of the CuOH phase (written as HxCuOy by Hultquist et al.) is present in the system and stable. [17] They agree that the corrosion copper coins, found in the *Vasa*, was caused by sulfur compounds. Hultquist et al. remain in their position that “water can corrode copper”.

Bojinov et al. reported a study on the corrosion of copper in pure anoxic water using a number of electrochemical techniques. [18] The following conclusions were drawn from the study:

a) The oxide layer formed during the pre-treatment of the Cu metal sample and the initial period of consumption of the residual oxygen has been essentially reduced by a voltammetric sweep.

b) No increase in the concentration of soluble copper species with immersion time has been found, thus it can be claimed at the applied conditions, no sustained corrosion of copper metal has been observed

c) Calculations on the basis of the proposed kinetic model lead to the conclusion that at the rest potential, most part of the CuOH intermediate has been produced by reduction of Cu(II) species. Thus, its production is not directly related to corrosion of Cu in the present experimental conditions.

Hultquist et al. reported a new study using the same methodologies as in previous studies. [19] Besides previously reported results they report that the hydrogen formation is dependent on the hydroxide concentration in water, thus pH in water, that the mode of corrosion depends on the concentration of hydrogen in the copper sample, and thereby the sample thickness.

Johansson et al. reported a simulation study “On the formation of hydrogen gas on copper in anoxic water”. [20] Their results show that water can be split on a copper surface into a hydrogen atom and a hydroxyl radical which bind to a copper atom in the surface. The hydrogen atoms combine to hydrogen molecules which can leave the surface. This process can proceed until the copper surface has a complete monolayer of hydroxyl groups. The desorption of hydrogen gas is slower in water than in gas phase, and that hydrogen desorption is a slower process than water cleavage on copper in water. At full coverage of hydroxyl groups on a copper surface should produce

2.4 ng hydrogen gas/cm^2. It was assumed that the copper corrosion reaction ceases after full coverage.

Becker and Hermansson did repeat the experiments reported by Hultquist et al. [9,13] to confirm/disconfirm whether pure anoxic water is able to corrode metallic copper. [21] They concluded that the amount hydrogen gas formed was less than expected compared to the amounts of formed metal compounds (Cu, Mn, Fe, Co, Ni, Ag, Zn, etc.) in the aqueous solution. They concluded that copper may corrode in pure anoxic water. The authors reported that their hydrogen gas analysis could only be used qualitatively, and that the amounts of hydrogen gas was below the detection limit of the applied method and thereby uncertain.

King and Lilja published in 2011 a review article summarizing and evaluating the results of studies of corrosion of copper in pure anoxic water. [22] They underline that the studies reported by Hultquist et al. [1,7,11,13,15,17,19] have not been reproduced by any other scientists. They also claim that even if the results reported by Hultquist et al. are correct, the impact on the copper canisters in a repository should be limited. [22] In a reply to this paper, Åkermark criticizes the authors for not regarding flaws in some of the experiments showing contradictory results to those of Hultquist et al. [23] Åkermark did also bring up that the LOT experiments have shown much larger corrosion rates than anticipated. In a reply to Åkermarks's reply, King, Johansson and Lilja described the LOT experiments in more detail than in the original paper and concluded that a corrosion rate of 0.15 µm/year was observed, and that the main corrosion products were copper(I) oxide, Cu_2O, and malachite, $Cu_2CO_3(OH)_2$, and significant diffusion of copper into the surrounding bentonite clay, with an estimated corrosion rate of 3 µm/year. [24] This is consistent with copper corrosion at aerobic conditions. The oxygen originates from bentonite pore water. King, Johansson and Lilja remain in their position:

> … the observations of Hultquist and co-workers are interesting, but since no experimentally verifiable corrosion mechanism linked to the hydrogen evolution has been put forward, there is, as yet, insufficient evidence to justify incorporating such an effect in our canister lifetime prediction models. [24]

King, Lilja and Vähänen published a review paper "Progress in the understanding of the long-term corrosion behaviour of copper canisters" in 2013 without reporting any new studies. [25] Their conclusion is that metallic copper does not corrode in pure anoxic water.

Betova, Bojinov and Lilja reported a renewed electrochemical study of copper in deoxygenated neutral aqueous solution with a borate buffer to stabilize pH (7.3) and ionic strength. [26] They reach in principle the same conclusion as in their previous study, [18] proposing that the copper surface is covered by three types of adsorbates, water, hydroxyl groups and copper(I) hydroxide; latter can be an intermediate structure of copper(I) oxide.

Hultquist et al. reports a long-term experiment, ~19 000 hours, where copper was immersed in oxygen-free distilled water and the hydrogen pressure has been measured. [27] The copper corrosion products were examined ex-situ by scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS) and secondary ion mass spectrometry (SIMS). XPS indicated a corrosion product containing both hydroxide and oxide, and SIMS showed that oxygen is mainly present in the outer 0.3 µm surface region and that hydrogen penetrates to larger depths in the substrate well below the corrosion product.

Boman et al. reported a study on corrosion of copper in oxygen-free water with emphasis to use as clean chemicals as possible and sensitive analytical tools as XPS, AES, ICP-MS and XRF after six months of treatment. [28] No other compounds except extremely small amounts (less than a monolayer) of copper(I) oxide were detected. Only very small amounts of copper in the aqueous phase, 4–5 µg, and on glass-ware walls, less than 0.02 nm, after six months of exposure. The collected gas was to 99 percent hydrogen gas. The amount of hydrogen gas was significantly larger than the related copper formation in the experiment. The amount gas formed in the experiments was the same in water with and without metallic copper present. They put forward a hypothesis that the hydrogen detected may come from the stainless steel in the experimental set-up.

Cleveland et al. reported that in the absence of hydrogen, copper would corrode in the order of 1 nm/day in deionized water with an O2 concentration on the order of, or less than, 1 ppb, using impedance spectroscopy, slow-scan linear sweep voltammetry, thermodynamic calculations for the environment under study, and kinetic simulations. [29] This study was criticised in a comment by Spahiu and Puigdomemech, as they questioned if the experiments have been completely oxygen-free. [30] In an answer to this comment, Cleveland et al. admitted the criticism, but claimed the general conclusions drawn from the originally reported experiments are correct. [31]

Hultquist reported a study where desorption of water from copper surfaces exposed to water vapor without oxygen at three temperatures. [32] Hultquist concluded that oxygen is taken up by copper in both surface and bulk, which did equal the half of the amount out-gassed hydrogen. [32]

The content of the SSM report by Hultquist et al. [27] was also published in Corrosion Science. [33] Hedin et al. responded to this paper where they questioned a/ the account of the reported experiments, b/ the conclusions regarding continuing bulk reactions drawn from studies of surface reactions and c/ the proposed model by the authors for corrosion. [34] In a reply to Hedin et al., Hultquist et al. reject the concerns raised. [35] In a final reply from Hedin et al. the criticism in their first reply remains. [36]

Betova, Bojinov and Lilja have in two continued electrochemical studies, using various techniques, the aim to find the reason and mechanism behind the hydrogen formation in anoxic copper-water systems. [37,38] They claim that hydrogen evolution from copper is a surface catalytic reaction which is not directly related to any corrosion process of metallic copper. This claim is based on no sustainable increase in soluble copper concentration, and no continuous hydrogen formation. They have also found [18,26] that the formation of copper(I) compounds containing oxygen and hydrogen results from reduction of soluble copper(II) ions and oxidation of metallic copper.

The study reported in ref. 28 was continued in time to 29 months.[39] In this continued and complementary study the conclusions by the authors remain from the first study. An important claim is:

> The detection of hydrogen gas (from a corresponding reduction step) and the measurement of its pressure would appear to be a scientifically dubious basis for claiming that copper corrodes appreciably in water when other sources of hydrogen evolution are present; specifically, stainless steel and the components used in the pressure gauges.

Szakálos et al. reply to this study stating that the oxygen and hydrogen control was unsufficient and that the pretreatment of the copper samples could seriously affect the studies. [40] In a reply to Szakálos et al., Ottosson et al. remain in their position that their studies were performed in a correct way, and that the different views are misunderstandings. [41]

Hedin et al. reported another study [42] with the aim to repeat the studies reported by Hultquist et al.,[11,15,19,27,33] using as clean chemicals and instruments as possible, and critically evaluate reported experiments and results. The new experiments by Hedin et al. show that

a) No hydrogen evolution above the experimental background was observed from copper immersed in pure O_2-free water in the glass contained system, for a range of copper qualities and surface treatments. The only example of a continuing hydrogen evolution was due to outgassing from that particular copper quality.

b) No hydrogen evolution above the experimental background was observed from copper immersed in pure O_2-free water.

They state in the results of their study

> … give no support for the existence of a sustained corrosion of copper in pure O_2-free water at an extent above the sensitivities of the experimental methods used.

He et al. reported that the copper open-circuit potential and corrosion rates in anoxic water were very sensitive to the residual O_2 concentration in solution. The corrosion rates ranged from submicrometer to micrometer per year, depending on the residual O_2 concentration level. [43] The corrosion products were predominantly cuprous oxide (Cu_2O). Minute amounts of hydrogen were detected from the autoclave as test cell, however, they cannot be simply correlated to copper corrosion because of complications from the autoclave material corrosion.

Senior et al. observed an initial hydrogen release of copper samples in pure water, but it stopped after ca. 70 days. [44] The copper samples were chemically cleaned at the start of the experiment but not protected from air.

5.3.2 SKB and Posiva reports

The first SKB report on copper corrosion in a deep geologic repository was published in 2001. [45] In this report, the thermodynamics of copper corrosion in dry air, most air and in repository conditions prior, under and after water saturation are presented in great detail. The surface of copper canisters, at the time of deposition into the repository, is expected to be oxidized to a compact layer of copper(I) oxide of less than 1 mm, on which surface traces of further oxidation products as basic copper(II) salts as malachite, $Cu_2CO_3(OH)_2$, are present. The expected amount of oxygen in the deposition hole can add another 0.3 mm of copper(I) oxide before all oxygen is consumed. An up-dated version of this SKB report was published in 2010. [46] In a separate report "Critical review of the literature on the corrosion of copper by water", the reported findings by Hultquist et al. on the corrosion of copper metal in pure anoxic water was critically evaluated and compared with publications trying to repeat the studies by Hultquist et al. [47]

In a new attempt to reproduce the studies by Hultquist et al., the VTT Technical Research Center of Finland, on behalf of SKB, reported such a study in 2013. [48] Copper foil samples were exposed in deaerated deionized water in Erlenmeyer flasks in a glove box with inert atmosphere. Four corrosion experiments (Cu1, Cu2, Cu3 and Cu4) were started, as well as a reference experiment standing in air, and the experiments were terminated after three and a half years. Cu1 and Cu2 had gas tight seals, whereas Cu3 and Cu4 had palladium foils as hydrogen permeable enclosure. The test vessels were stored during the experiments in a closed stainless steel vessel to protect them from the trace oxygen of the gas atmosphere and light. There were no visible changes in the copper surfaces in any of the tests in the glove box, in contrast, the copper surfaces looked shiny and unaltered. The Cu3 test was terminated after a reaction time of 746 days. The analysis of the Pd-membrane showed the presence of H_2 in the test system. If the measured amount of $7.2 \cdot 10^{-5}$ mole H_2 was the result of formation of Cu_2O this would correspond to a 200 nm thick corrosion layer. This was not in agreement with the measured layer thickness using SIMS, 6 ± 1 nm. A clear weight loss was observed for the Cu3 test vessel throughout the test period suggests evaporation of water through the epoxy sealing to the closed steel vessel. If this occurred, the anaerobic corrosion of steel surface in humid oxygen-free atmosphere could be a source of hydrogen. A similar weight loss was not observed for the parallel test (Cu4). The reference test standing in air showed visible development of corrosion products.

In a parallel study at Uppsala University on behalf of SKB to reproduce the results reported by Hultquist et al. were reported in 2013 (Swedish) and 2014 (English). [49] The results from this study were reported in the scientific journal Corrosion Science in 2017, [39] as described above. A subsequent study, where further precautions have been taken, was reported in 2016, [50] and in Corrosion Science in 2018, [41] as described above.

In another study performed at Microbial Analysis Sweden AB, Göteborg, Sweden, hydrogen evolution in carefully sealed glass test tubes with different copper qualities in pure anoxic water, pH adjusted water, and water with added sodium chloride, and with copper surfaces cleaned or treated in different ways. [51] The hydrogen and oxygen concentration in the gas phase were analyzed with gas chromatography. The experiments lasted for 1.0–2.3 years. The general conclusion was hydrogen evolution was detected in the same order of magnitude independent from copper being present or not, and that the hydrogen evolution could not be related to copper corrosion. [51] This study continued with the same general conclusions as reported in a later report. [52]

In a technical report from 2019 SKB writes:

> Regarding copper corrosion in pure, oxygen-free water, it is concluded that there is no reason to assume that this corrosion mode occurs to an extent that exceeds that predicted by established thermodynamic data. The conclusion is based on a thorough evaluation of available scientific evidence on the matter. It was also concluded that data used by a few researchers to claim corrosion extents many orders of magnitude in excess of established scientific views, would cause corrosion of only around one millimeter of copper during the one million year period covered by the safety assessment. Based primarily on the former of these two conclusions, corrosion of copper in pure, oxygen-free water is not further considered in the report, since established thermodynamic data predicts a corrosion depth under repository conditions that is completely negligible during the assessment period. [53]

In a technical report from experiments performed by Posiva, the longest lasted more than 6 years, on possible corrosion of copper in pure anoxic water it was observed that hydrogen was detected in some experiments, but no copper corrosion products were detected. [54] Very thin layers of copper(I) oxide were shown to dissolve with time, as shown by both XPS surface analysis and chemical analysis of the aqueous phase. Different kind of copper qualities did show different hydrogen release with the Cu-OFP quality showing detectable hydrogen release, while 6N-Cu did not. In experiments with and without water present did show the same results for both copper qualities. [54] This shows that hydrogen is present in some copper qualities and its release is very slow.

5.4 Relationship between reported experiments and conditions in the final repository

The experiments cited in section 5.3 are performed in beakers, bottles or autoclaves with copper foils or wires surrounded by a large volume of water. Thin foils and wires have high surface area/mass ratio. Surrounding water can continuously transport away possible corrosion products and gases from the copper surfaces. In the repository, at ideal conditions, the copper canisters are imbedded in water saturated bentonite clay, and thereby, they are in contact with a limited amount of ground water, and the possibility to transport from the copper surface is very limited. The canisters has low surface area:mass ratio. The water in contact with the copper surface is mainly bound to bentonite clay, and possible corrosion products can only very slowly be transported away by diffusion. However, the conditions will be very different if the bentonite clay has eroded and groundwater is in direct contact with the copper surface. At such conditions, there is an increased risk for corrosion with sulphide compounds, and the flow rate of groundwater to the canister surface and the sulphide concentration in the groundwater will determine the amount of copper corrosion.

Copper corrosion with sulphide is the most relevant process for formation of hydrogen gas at repository conditions. [55] Due to the limited access of sulphide ions at the canister surface only low concentrations of hydrogen are expected to be formed. The amounts of hydrogen gas formed by sulphide corrosion and radiolysis is small, and thereby, also the amount of hydrogen gas able penetrate into metallic copper. The impact of hydrogen and other trace elements on the mechanical properties of metallic copper is described in Chapter 6 in this report.

In a final repository it is not possible for formed hydrogen gas to easily escape as diffusion through water saturated bentonite clay is very slow, <1 nm/year. At the expected conditions in final repositories, hydrogen gas will quickly obtain equilibrium conditions at the copper surface, and thereby the required conditions for reaction (1) to take place. This results in very slow corrosion rates according to reaction (1) as only extremely low concentrations of hydrogen gas and copper(I) ions can be accumulated in the system before the reaction ceases. The process is controlled by the very small equilibrium constant of reaction (1), the equilibrium is strongly shifted to the left, as well as the slow diffusion rates of hydrogen gas and copper(I) ions through the water saturated bentonite clay at the expected conditions in final repositories. For the assessment of copper corrosion at the expected conditions in a final repository, the corrosion rate of metallic copper in pure anoxic water is mainly of scientific interest rather than of real importance as the copper canisters will come in contact with ground-water containing dissolved minerals, and not pure anoxic water. [53,56] This means that other corrosion reactions than reaction (1) will be dominating at the conditions in a final repository as sulphide corrosion, radiation induced corrosion and stress corrosion. [53,56] These will therefore be most important ones for the assessment of the long-time integrity of the copper canisters. The copper canisters will be exposed to a reducing sulphide environment, and the copper corrosion will depend on the access to sulphide ions on the copper surface, which will covered by a sulphide film, rather than an oxide and/or hydroxide film.

5.5 LOT experiments and prototype experiments

SKB started in 1996–1999 seven long-term experiments to study primarily the physical, chemical and mechanical properties of the bentonite buffer under repository conditions, ”Long-term test of buffer materials”, LOT. [57] Another aim was to study copper corrosion by analysing the copper tubes and copper coupons imbedded in the bentonite clay. As the copper tubes used in the LOT experiments did not contain used nuclear fuel, heaters were installed to mimic the temperatures expected in the repository. There are two series of LOT experiments, A, with a temperature of ca. 120 °C, and S, with the temperature expected in an operational repository of ca. 90 °C, A0, A1, A2, A3, S1, S2 and S3. Experiments A0, A1 and S1 were terminated and analysed after one year, A2 after six years, and A3 and S2 after 20 years in 2019. The remaining experiment S3 will according to plan be terminated in 2023. As the LOT experiments were not designed for detailed copper corrosion studies, no characterization of the copper samples were performed before the start of the experiments, and the conclusions possible to draw concerning copper corrosion processes are therefore limited.

The overall results of the copper corrosion in the LOT experiments give no conclusive information whether copper corrosion has taken place early in the experiments and then ceased, or if it is still on-going. The reported results on copper corrosion are scattered and no conclusion of the corrosion as function of time can be drawn. [57] However, it is evident that that copper corrosion increases with increasing temperature, [57] as there are significantly more corrosion products in the A experiments than in the S ones.

Furthermore, SKB has besides the LOT experiments also performed experiments with full size copper canisters but without presence of used nuclear fuel or heating at conditions similar to those expected in the final repositories, "Prototype experiments". [58] The copper canisters were stored for seven years at these conditions. SKB reports local corrosion, 3–5 mm in depth, and the detected copper compounds were copper(I) oxide and malachite, $Cu_2CO_3(OH)_2$.

5.6 Formation of hydrogen in chemical experiments

In many of the reported experiments studying corrosion of metallic copper, hydrogen gas formation has been used as evidence for copper corrosion. An important rule in chemistry is the law of mass balance, thus the same weight of the chemicals going into a chemical reaction must be found in the products. To be regarded as copper corrosion, the formation of hydrogen formed must be balanced with the amount of copper used and copper compounds formed. There are a number of explanations to formation of hydrogen gas in the reported experiments. Water molecules may split on a copper and/or copper oxide surface causing hydrogen formation without copper corrosion. Hydrogen formation can also take place at corrosion of other parts of the experimental equipment, and due to degassing of previously absorbed hydrogen gas, which may release at increased temperatures and/or reduced pressure. A decrease in the hydrogen gas formation with time in an experiment may be an indication of alternative processes. It is therefore of utmost importance to secure that the experimental equipment does not release hydrogen gas from other sources than the chemical system under study. It is also important to use a range of analytical methods that in different ways detect the concentration of chemicals formed and/or used, and the law of mass is fulfilled.

5.7 Conclusions of importance for copper corrosion from the literature survey

By isolating the issue whether pure anoxic water can oxidize (corrode) pure copper metal, the following statements can be made from the scientific evidence put forward in reported publications as described above:

- Form thermodynamic point of view, the equilibrium of the reaction $2\ Cu(s) + H_2O\ (l) \rightleftharpoons Cu_2O(s) + H_2\ (g)$ is shifted very far to the left, and any substantial corrosion with only pure metallic copper and pure anoxic water as reactants is not possible as the very low concentrations of hydrogen gas and copper(I) ions formed will cease the reaction.
- Hultquist and co-workers claim in series of studies that pure anoxic water can oxidize pure copper metal by the formation of a solid compound, H_xCuO_y, which needs to more thermodynamically stable than copper(I) oxide, Cu_2O, see Scheme 3 in Appendix 4. The solid compound H_xCuO_y has not yet been characterised by chemical analysis or physico-chemical methods, and its existence has been questioned. The compound $Cu(OH)_2(s)$ is well-known and characterized, but it is thermodynamically less stable than Cu_2O. This is the reason to that copper(I) oxide is

the main product at copper oxidation in air. The compound CuOH has been claimed from theoretical simulations to be unstable and decompose according to the following reaction scheme 2 CuOH(s) $\rightleftharpoons$ $Cu_2O{\cdot}H2O(s)$ $\rightleftharpoons$ $Cu_2O(s) + H_2O(l)$. [59

- A number of attempts to repeat the studies by Hultquist and co-workers using as controlled conditions and pure chemicals as possible have been reported. However, a majority of these have not been able to obtain the results reported by Hultquist and co-workers, as described above.
- Hultquist and co-workers have not been able to show that the formed hydrogen in their experiments is mass balanced with the copper corrosion products.
- In spite of these efforts, the literature survey shows that the scientific controversial is still on-going.

Governmental decision

The Swedish government decided to allow the construction of a final repository for used nuclear fuel after this survey was completed. The governmental decision includes [60]:

> … SKB has satisfactory complemented the matter with the required information concerning uncertainties about the ability of the copper canister to long-lasting protection as required by the Land and Environmental Court in a statement to the government.

The Swedish government assess that the activity “fulfills the requirements on best available technology in the Environmental Code”. The Swedish government claims also that “it is of utmost importance to continue the research on important issues, as e.g. the integrity of the copper canister”, and points out that SKB within the continued RD&D program and the stepwise licensing process issued by SSM ”to account for remaining experiments within the LOT program, perform new safety analyses and to perform more research on copper corrosion”.

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Appendix 4

Reduction-oxidation (electron transfer) reactions and the chemistry of the chemistry of metal oxide surfaces in contact with water.

6 Trace amounts of absorbed substances in metallic copper and how they affect the mechanical properties of copper

The mechanical properties of metals are strongly dependent on whether they are pure or mixed with other elements. A well-known example is steel (cast iron), which in addition to iron contains carbon (graphite) and metals such as chromium, nickel, vanadium and molybdenum. Depending on the composition, the steel has different mechanical properties and thereby different technical applications. When a metal is combined with another element, the pure metal's very well-ordered atomic structure is disturbed, but it is difficult to predict how the mechanical properties change. For instance, copper to which very small amounts of phosphorus are added, has better mechanical properties than pure copper, and is therefore better suited for use in the canisters for final storage of spent nuclear fuel. On the other hand, if the copper contains oxygen and hydrogen, its mechanical properties deteriorate.

In Chapter 5, the issue of potential corrosion of copper in pure, oxygen-free water is discussed, in relation to the copper canister in the KBS-3 concept for a final repository for spent nuclear fuel. This chapter describes the current state of knowledge on how different – very low – concentrations of hydrogen, oxygen, sulfur, and hydroxide ions in copper can be expected to affect the copper canister's mechanical properties and thereby the safety under the expected repository conditions. The chapter is concluded with the Swedish National Council for Nuclear Waste (the Council) making proposals regarding the need for further research in the area.

6.1 The copper canister and hydrogen uptake in copper

In order to ensure that the copper canister meets the requirements with respect to mechanical properties, limit values have been defined for how large the content of hydrogen and oxygen in the copper is allowed to be. These are given in parts per million (ppm) of weight, and are 0.6 ppm for hydrogen and 5.0 ppm for oxygen. [1] The solubility of hydrogen in copper is strongly dependent on temperature and pressure. At normal atmospheric pressure (1 atm) and room temperature, the hydrogen solubility at chemical equilibrium is 0.0001 ppm. Under these conditions, hydrogen is thus almost insoluble in copper, but at 1 000 °C, the solubility is 1.2 ppm. [2] The solubility of gases such as hydrogen and oxygen is directly dependent on the concentration (pressure) of the gas in question.[1] Due to various corrosion processes, hydrogen gas will be in contact with the copper canister in the final repository. Under repository conditions, however, the oxygen content in contact with the copper canister will be very low and therefore no uptake of oxygen takes place.

6.1.1 Processes that can lead to hydrogen uptake

Different processes could potentially lead to hydrogen uptake into the copper canister, for instance corrosion, radiolysis and irradiation. In corrosion and electrochemical hydrogen charging, it is difficult to determine the prevailing hydrogen gas pressure. [3] In order to quantify the hydrogen uptake from corrosion, one has to experimentally measure the hydrogen content in the metal. Under repository conditions, where both the hydrogen gas pressure and the cathodic current density are low, the occurrence of molecular or atomic hydrogen in the copper surface is calculated to be small.

During electrochemical hydrogen charging, so high hydrogen contents may occur that hydrogen gas bubbles form in copper, for instance on oxide particles or in copper material. Hydrogen bubbles may arise and grow when hydrogen accumulates, and the internal gas pressure in these hydrogen-induced voids may increases to a critical

[1] This is described by Sievert's law: $c = \mathrm{k}\,p^{1/2}$, where c_{H_2} is the atom concentration of hydrogen (H_2) dissolved in the metal, p is the partial pressure (in atm) and k is a system-specific constant that is temperature dependent.

value (approximately 1 000 times normal atmospheric pressure, 1 000 atm). [4, 5] At that point the yield strength of copper is exceeded, and plastic deformation occurs around the voids. During electrochemical hydrogen charging, formation of hydrogen bubbles may take place close to the surface, but deeper penetration of hydrogen, via migration (diffusion) of atomic hydrogen, occurs only very slowly. Hydrogen penetration cannot be expected to extend so far that it affects the copper canister's mechanical properties under repository conditions.

One mechanism for fracture is the formation of voids on the atomic level in the metallic copper, where hydrogen atoms from slow sulfide corrosion[2] can collect. This is called hydrogen-induced stress corrosion cracking and arises when the hydrogen has a local impact on the atomic level at interfaces in the material (grain boundaries) and in the crack tips. Due to the limited availability of hydrogen sulfide and hydrogen sulfide ions at the copper canister surface, however, it is expected that only low concentrations of hydrogen gas arise. As the maximum amount of hydrogen gas from such sulfide corrosion[3] is limited, the probability of hydrogen leading to the occurrence of cracks or affecting the mechanical properties of the copper canister is small.

Corrosion processes on grain boundaries and in crack tips may occur only locally, with only a local supply of hydrogen. A general hydrogen embrittlement of the copper canister shell can therefore not be expected, and it cannot be assumed to affect the integrity of the canister. In general, the long-time hydrogen content in the copper canister is in balance.[4]

6.1.2 Experimental studies of hydrogen uptake in copper

The section above describes the theoretical as well as chemical and physical foundations for hydrogen uptake in copper under repository conditions. The following text discusses a number of studies that have led to different views of the importance of hydrogen up-

[2] When the hydrogen sulfide and hydrogen sulfide ions react with copper, copper(I) sulfide and hydrogen are formed.
[3] Hydrogen gas can also be formed by radiolysis of water, but again in limited amounts.
[4] By diffusion and desorption (degassing), according to Sievert's law, which depends on the temperature, the hydrogen content in copper, and the hydrogen pressure both around the canister and in the pores in metal.

take in the copper canister, and the potential impact on the canister's long-term safety function.

A study investigating the hydrogen uptake under optimal conditions used copper in both the parent material and the weld metal. [6] After a 10-day exposure at 250 °C and 1 000 atm pressure, it was shown that the weld metal (FSW, Friction Stir welding, welded in air) contained oxide particles and absorbed more hydrogen (up to 4 weight-ppm) than the parent metal (less than 0.6 weight-ppm). Such a hydrogen uptake in copper material does not affect the ductility or the mechanical strength of copper. [6] The experimental temperature and pressure conditions were extreme compared to the conditions in a final repository.

In contrast to the conclusions in the above study, a review report [7] describes that there is a potential for local fast corrosion and embrittlement processes in copper canisters in a repository environment, as well as for hydrogen embrittlement and stress corrosion cracking. It is stated that copper is embrittled mainly by hydrogen but also by sulfur, which leads to fracture of the copper canisters if they are subjected to mechanical stresses. The combined effect of sulfur and hydrogen may give rise to fast-growing stress corrosion cracking and fractures in the copper canister under mechanical tensile stresses. The review report presents experimental results obtained with a piece of copper from SKB's Äspö Hard Rock Laboratory [8] and concludes that hydrogen penetrates through the copper canister wall after 7 years of exposure. The hydrogen analyses were carried out with SIMS (Secondary Ion Mass Spectrometry) and were applied to a piece of copper from a distance ring that had been placed on top of the copper canister and not to copper from the canister itself. However, the report lacks a detailed description of the performance of the experiment (for instance it lacks a full account of instrumentation and the reasoning behind the interpretation of data), which makes the assessment of the scientific relevance of the study difficult. This applies for instance to the hydrogen analyses done with SIMS, which is not a reliable analysis method for measuring light atoms such as hydrogen. The results have been presented (Figure 3.12, reference [7]) as an atom ratio between hydrogen and copper (H/Cu), and a ratio of 0.01, for instance, would yield an average content of hydrogen in the canister wall of about 160 ppm. The average value of the hydrogen content in six different samples from the same distance ring in another study (carried out with LECO Rhen 602 equipment) was 0.43 ppm, however. [8] In the review report it is also stated that the hydrogen content increases from about 1 ppm to 6–40 ppm in copper foils that were exposed to pure, oxygen-free water for a few years. At such hydrogen contents, and especially at 160 ppm, a copper sample ought to exhibit severe defects, such as large hydrogen bubbles and cracks, [2] but that was not reported. Therefore, it is desirable for the results in the review report to be re-examined by other laboratories, preferably by using modern SIMS in combination with other measurement methods that can verify the results achieved, for instance thermal desorption spectroscopy (TDS) and high-resolution electron microscopy, the latter to study hydrogen bubbles.

The aforementioned review report also suggests another mechanism for hydrogen uptake in copper, namely the so-called "hydrogen sickness". There, hydrogen atoms that are formed when the copper corrodes migrate into the metallic copper and react with copper oxide inclusions in the weld metal, which in turn gives rise to small blisters of steam on grain boundaries. When these blisters grow in number and the pressure increases, stresses occur which in the end lead to the metal cracking. The method that is now planned to be used for closure welds of the copper canisters, however, is carried out in an atmosphere where argon is used as a shielding gas to counteract undesirable reactions and where the surfaces are carefully cleaned, two measures which together counteract the occurrence of copper oxide inclusions. Since a reaction between hydrogen and copper oxide inclusions furthermore only occurs at high temperatures (over 300 °C), hydrogen sickness is not an expected failure mechanism for the copper canisters under repository conditions. [10]

6.1.3 Experimental studies of the uptake of oxygen, sulfur and hydroxide ions

In addition to hydrogen, some other substances that can affect the copper canister are subject to specified limits, too. Studies on the migration of different elements in copper have shown that oxygen and sulfur do not move appreciably in copper at the relevant temperatures (below 100 °C) in the final repository, owing to their low solubility and a very good capability of copper to form stable compounds of copper oxide and copper sulfide. [9] For temperatures below 500 °C, there are no experimental data for either oxygen or sulfur, as their diffusion has not been possible to measure. The conclusion was that only atomic hydrogen can diffuse in copper under repository conditions, and that it takes at least 1 000 years at room temperature for hydrogen to penetrate through the 50 mm thick wall of the copper canister, which is explained by the low solubility and diffusivity of hydrogen in copper. [2]

In the aforementioned review report it is argued that the KBS-3 method for a final repository for spent nuclear fuel will not work due to the fact that hydroxide ions or sulfur atoms penetrate into the copper material, causing hydrogen embrittlement and stress corrosion cracking. [7] This claim is contrary to the results of other studies that have shown that sulfur and oxygen atoms are not mobile in metallic copper. [9] The suggestion that corrosion can occur inside the copper material on the basis of the penetration of hydroxide ions [7] is contradicted by the fact that a corrosion process is an electrochemical reaction, which normally takes place on a metal surface. Furthermore, as was the case for the results on hydrogen penetration discussed above, the review report's results concerning hydroxide ions (Figure 3.13, reference [7]) also build upon unpublished SIMS analyses of the surface of a piece of copper from a distance ring from the Swedish Nuclear Fuel and Waste Management Co's (SKB's) Äspö Hard Rock Laboratory, see [8]. The conclusion that the 50 mm thick copper shell can be penetrated by hydroxide ions within a few hundred years therefore cannot be said to build upon clear scientific data that have undergone customary peer review.

Since the above SIMS measurements in the review report were carried out in parallel with other published measurements, however, certain comparisons can be made. In an experiment with 15 years of exposure of copper in distilled water, the depth of hydrogen penetration in the surface layer was estimated to be 2–5 micrometres [11], and in another experiment it was measured at 10 micrometres. [12] After 7 years of exposure to similar conditions, the review report presents, with the same measurement method, that the hydroxide ions penetrated copper to a depth of 1360 micrometres, which indicates the unlikely result that diffusion of hydroxide ions in copper would be much faster than hydrogen diffusion in copper. [7] As SIMS is a sensitive analysis method for studying surfaces on the scale of nanometres, the choice of methodology may have affected the results in the review report. In order to critically review the SIMS experiments and the arguments about the penetration of hydroxide ions and internal corrosion in the copper in greater detail, however, relevant information on the experimental methodology employed in the SIMS measurements must first be published.

6.2 Summary and proposals

In this chapter the Swedish National Council for Nuclear Waste has presented the current state of knowledge concerning the impact of hydrogen and hydrogen uptake, oxygen and sulfur atoms and hydroxide ions on the copper canister's mechanical properties and thereby on the long-term safety under repository conditions.

The Swedish National Council for Nuclear Waste believes that further research (within the framework of RD&D Programmes created according to Section 12 of the Nuclear Activities Act, and within the stepwise licensing process) regarding copper corrosion and related mechanisms should be carried out for:

- mechanisms for 1) hydrogen uptake in copper, 2) formation of hydrogen bubbles in copper, and 3) hydrogen transport in copper through the canister wall;
- hydrogen uptake (also the penetration of hydroxide ions and sulfur atoms) in the copper materials from the long-term exposures done in SKB's Äspö Hard Rock Laboratory with modern SIMS and other measurement methods (such as thermal hydrogen desorption spectroscopy and electron microscopy);
- the effects of gamma radiation on all corrosion processes and corrosion mechanisms; and
- mechanisms for fracture and deformation (creep) during slow sulfide corrosion, so-called hydrogen-induced stress corrosion cracking, due to the local impact of hydrogen.

Supplementary studies are also needed under actual repository conditions, for instance regarding prototypes for copper canisters and different copper samples exposed to bentonite clay (similar to the LOT experiments). In these studies, different physical-chemical parameters (such as oxygen concentration and redox and corrosion potential) should be carefully monitored over time to broaden the scientific understanding related to the assessment of the long-term safety of the copper canisters.

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7 Embrittlement mechanisms and the cast iron insert

In the 2020 state-of-the-art report, the Swedish National Council for Nuclear Waste (The Council) gave an account of what was then known about the cast iron insert in the copper canister in the planned final repository for spent nuclear fuel, and what knowledge deficiencies existed within the area. The Council emphasised the necessity of continued research. Since then, new information has been added, and for the purpose of presenting the state of research, the Council arranged a seminar on cast iron in November 2021 in Stockholm with about 50 participants. The seminar discussed how casting of the insert is done, summarised the chemical composition, microstructure and mechanical properties of the cast iron, as well as various embrittlement mechanisms that may occur during the long deposition time. The seminar also gave an insight into the Swedish Radiation Safety Authority's (SSM's) review of the cast iron insert.

In this chapter the Council wants to give an account of the updated state of knowledge concerning embrittlement mechanisms of the cast iron insert that can affect its mechanical properties in a negative way, and to what extent this may affect the safety under the expected final-repository conditions.

7.1 Introduction

The copper canister and the cast iron insert are the primary barriers in the KBS-3 concept and therefore crucial for the long-term safety of the repository. The Swedish National Council for Nuclear Waste has previously identified research needs within the area, concerning among other things corrosion, creep, formation and effects of hydrogen, the damage tolerance of the cast iron insert, and the reliability of the non-destructive testing[1].

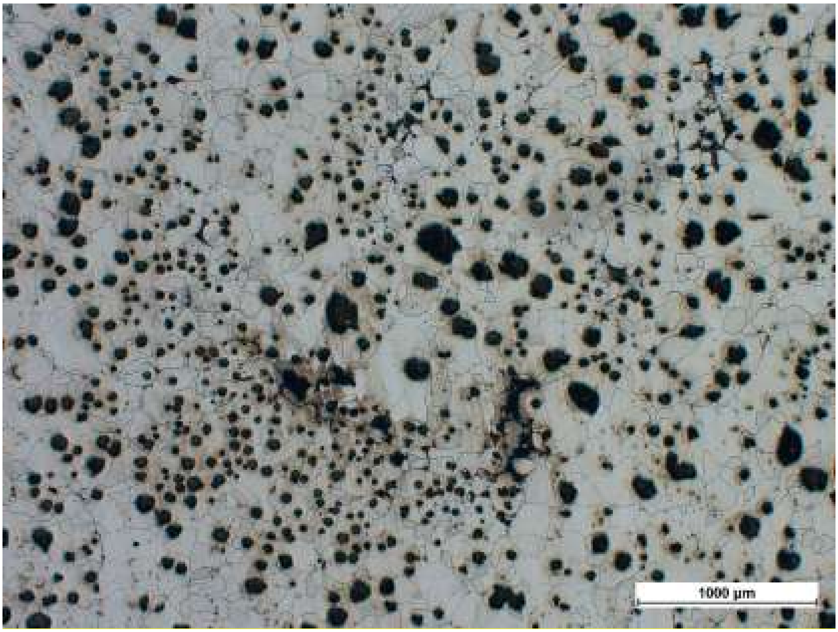
Regarding the mechanical properties of the cast iron insert, there is still uncertainty about how microstructure and chemical composition may affect the fulfilment of applicable performance requirements. Variations in the cast iron's composition and temperature during casting can affect its ductility and fracture toughness within wide limits and may degrade the cast iron insert's load-bearing capacity, which in turn may affect the copper canister's mechanical properties, damage tolerance and long-term safety. Furthermore, different impurities, for instance copper, in the cast iron insert affect the cast iron's mechanical properties under gamma and neutron irradiation, what is called radiation-induced embrittlement. Another embrittlement mechanism of cast iron is static and dynamic strain ageing, so-called blue brittleness. These different topics are described in the following text, which highlights new knowledge and presents the needs for further research.

7.2 Design analysis and manufacturing requirements for the cast iron insert

The cast iron insert is the canister's load-bearing component and must comply with specific requirements regarding strength. The insert is made of ferritic nodular cast iron[2], whose special properties make it a common material for the construction specifically of large components (the canister's cast iron insert weighs 13.6 tonnes). The mechanical properties of the nodular cast iron depend mainly on the microstructure of the cast iron matrix (ferrite and pearlite content), the form, size and spatial distribution of the graphite, and slag inclusions, porosity and casting defects (Figure 1), which in turn are affected by the chemical composition, process control, and heat treatment. [1–6]

[1] Non-destructive testing is a way to inspect quality requirements without risking to deform or destroy the product that is tested.
[2] Ductile Cast Iron (DCI), grade EN-GJS-400-15C (SS-EN 1563).

Figure 7.1 Distribution, shape and size of graphite nodules in nodular cast iron's ferritic matrix



The figure shows distribution, shape and size of graphite nodules in nodular cast iron´s ferritic matrix.

Swedish Nuclear Fuel and Waste Management Co (SKB) has presented wishes for the requirements to be relaxed that are made on the mechanical properties of the cast iron insert regarding elongation to fracture, yield strength, and fracture toughness. [7, 8] These wishes refer to the centre of the cast iron insert and would lead to altered requirements on the mechanical properties and defect size also in the other parts of the insert. If the requirements and acceptance criteria for the mechanical properties and defect size of the nodular cast iron are lowered, new analyses of damage tolerance for different loads are needed, in particular for the central parts of the insert, where the mechanical properties can be worse due to the microstructure and graphite distribution, potential defects, and slag inclusions from the casting process. SKB has also proposed a reduction of the requirements and the scope of non-destructive testing. [7, 8] If the requirements concerning the testing for quality assurance of different parts of the cast iron insert (the bottom slab, the top, and between the channel tubes) are lowered, quality assurance of these parts must be secured via new acceptance criteria.

7.3 Quality control

The cast iron insert's critical defect size may not exceed a depth of 4.5 mm if a shear movement of 50 mm takes place in the surrounding rock in the final repository, which imposes high demands on both fabrication and non-destructive quality control. [1–3] The planned methods for quality control of cast iron inserts and copper canisters are still preliminary. If the canister's technical design requirements are changed, a new design and defect analysis is needed. The requirements on the canister's mechanical properties and permissible defect size are today predetermined (deterministic), and the acceptance criteria vary between different parts of the cast iron insert. Unavoidable variations in material properties must lie within the limit for damage tolerance, but at the same time the quality assurance is dependent on the detection capability of the non-destructive testing methods that will be used.

7.4 Temperature

The maximum temperature in the copper canister is reached in a fuel assembly in the centre of the canister (calculated to 230 °C, to be compared with the maximum permissible temperature of 300 °C). [9] Due to the cast iron's favourable thermal conductivity, the temperature in the cast iron insert will decrease from the centre out towards the canister's copper shell. The effect of this temperature gradient must be considered as well in the assessment of effects on the properties of the cast iron insert. The temperature in the cast iron insert's centre is at most 60 °C higher than in the copper shell. [9] The peak temperature in the copper shell (about 90 °C) and on the inner surface of the buffer (about 80 °C) is reached after about ten years. The thermal evolution in the copper canister affects the chemical and metallurgical processes in the canister during a relatively short time period, i.e., a few thousand years. The temperature in the copper shell exceeds the ambient temperature for about 7 000 years after deposition, after which the temperature gradually decreases to the rock's temperature. During the initial period of elevated temperature, different ageing mechanisms (both static and dynamic strain ageing) may occur in the cast iron, and these may have a great effect on the strength and fracture toughness of the cast iron insert.

7.5 Strength

The canister must resist shear loads that may occur due to earthquakes and glacial conditions, and isostatic loads that are caused by swelling pressure from water-saturated bentonite clay that serves as a buffer material around the canister. The canister must withstand a maximum isostatic load up to 45 MPa (i.e., about 450 times normal air pressure), which is the sum of the maximum swelling pressure and the maximum groundwater pressure. The cast iron insert's pressure-bearing properties are defined for isostatic load and for asymmetric loads due to uneven swelling of the bentonite.

The cast iron insert must withstand a maximum external load of 15 MPa at an elevated temperature of about 125 °C for the first one thousand years. Furthermore, the canister must withstand shear loads that arise when fractures in the rock intersecting the deposition holes experience secondary shear movements as a result of major earthquakes in the vicinity of the final repository. The canister must remain intact even after a 50 mm shear movement at a velocity of 1 m/s for all locations and angles of the shearing fracture in the deposition hole, and for all relevant temperatures down to 0 °C. [1–3, 9] These shear movements may cause significant plastic (permanent) deformation that remains in the cast iron after the affecting force has stopped. A 50 mm shear movement gives rise to a plastic deformation in the cast iron insert of 1–2.5 percent. [1–3, 9] Shear movements can take place during the entire deposition period, but are expected mostly to occur in conjunction with glacial periods. The probability of large earthquakes occurring in the vicinity of the final repository is small, according to the safety assessment, and therefore shear movements of 50 mm through the deposition holes are expected to be rare.

To characterise which fractures in the rock have to be taken into consideration in the choice of deposition holes, documentation of the properties of the rock during the construction is important, both homogeneity and mechanical stresses, so as to reject deposition holes where 50 mm shear movements could occur. [10] However, it cannot be ruled out that a few canisters will be exposed to shearing of 50 mm or more due to earthquakes also within a timeframe of 1 000 years, and that canister damages can occur as a result of this.

7.6 Embrittlement mechanisms of the nodular cast iron

The effects of gamma and neutron radiation on the mechanical properties of the cast iron insert are affected by impurities (e.g. the copper content) in the cast iron, so-called radiation-induced embrittlement. The effect of irradiation on the material properties of the nodular cast iron insert have been both calculated [11] and studied after electron irradiation. [12] At the investigated radiation doses, only small effects in terms of an increased yield strength and a reduction of the ductility were observed. Under the conditions in the final repository, radiation-induced precipitation of copper and other radiation damage in the cast iron cannot be ruled out. It has not been sufficiently analysed how this may affect the mechanical properties such as embrittlement of the cast iron. Research on radiation-induced embrittlement of the cast iron should therefore continue in order both to supply the safety assessment with new data that shed light on the risks of radiation-induced embrittlement, and to permit the establishment of acceptance requirements for the contents of copper and other impurities in the cast iron insert.

The cast iron insert will also be exposed to hydrogen that may be produced in several ways. According to the technical design requirement, the copper canister is allowed to contain up to 600 g water, which enables several hydrogen-generating processes [3]; for instance, hydrogen is formed via oxygen-free iron corrosion and radiolysis of water. No complete description is yet available of how hydrogen affects the cast iron insert. Stress states, hydrogen content and temperature may together increase the risk of hydrogen embrittlement and creep of the cast iron insert.

There are very few scientific studies of hydrogen embrittlement of nodular cast iron and of how small variations in the composition and microstructure of the cast iron may affect such a process. [13–17]

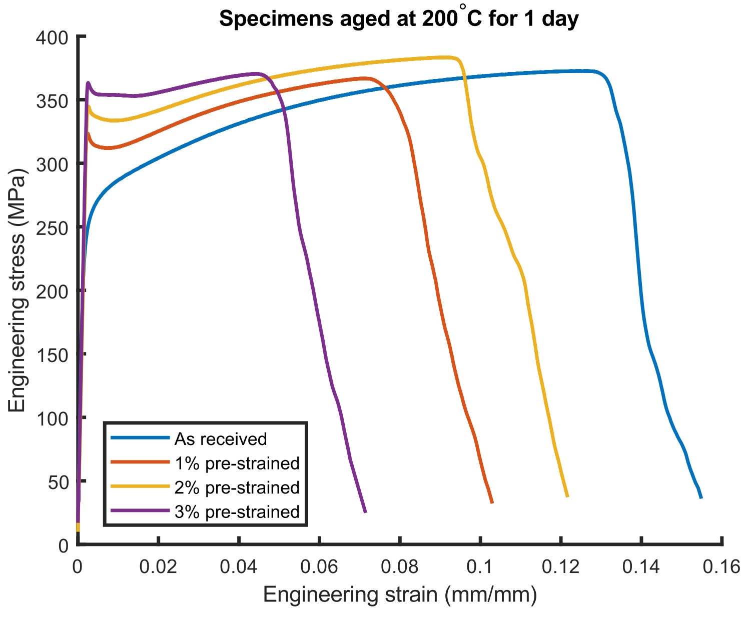
Research has shown that hydrogen not only occurs on the graphite-matrix surfaces (see Figure 1), but also inside the graphite nodules. In nodular cast iron, the porosity affects both the hydrogen content and the diffusivity in the material. The ductility of nodular cast iron is drastically affected by hydrogen, and brittle cleavage fracture surfaces occur around graphite nodules. Graphite-matrix interface separation takes place before fracturing, and the prerequisites for brittle fracture growth increase with a decreasing strain rate.

Static and dynamic strain ageing, so-called blue brittleness, is an embrittlement mechanism of nodular cast iron that was described only recently, and that should be characterised for the conditions that exist in the final repository. Even though the matrix in the nodular cast iron where plastic deformation occurs consists of ferritic iron, nodular cast iron has no sharp yield strength after heat treatment. [6, 18–20] The reason for this may be that deformation is initiated continuously in the graphite nodules already below the proportionality limit (i.e., the highest stress where the stress and strain practically are proportional) and that is why the material does not exhibit a sharp yield strength. Strain ageing in cast iron is qualitatively comparable to the corresponding process in common structural steel [18], and the effects of strain ageing on the ductility and strength of the cast iron insert are important to characterise. Strain ageing (blue brittleness) is a hardening and embrittlement mechanism that takes place during specific combinations of plastic deformation and temperature conditions in steel and cast iron. If the embrittlement occurs after deformation, it is called static strain ageing, and if it takes place at the same time, it is called dynamic strain ageing. This phenomenon occurs from room temperature to 250 °C, with particularly the concentrations of carbon and nitrogen in the materials having a significant importance for the embrittlement. Carbon and nitrogen atoms diffuse and accumulate around dislocations in the crystal lattice and in the grain boundaries in polycrystalline material, causing embrittlement in iron. [18–20]

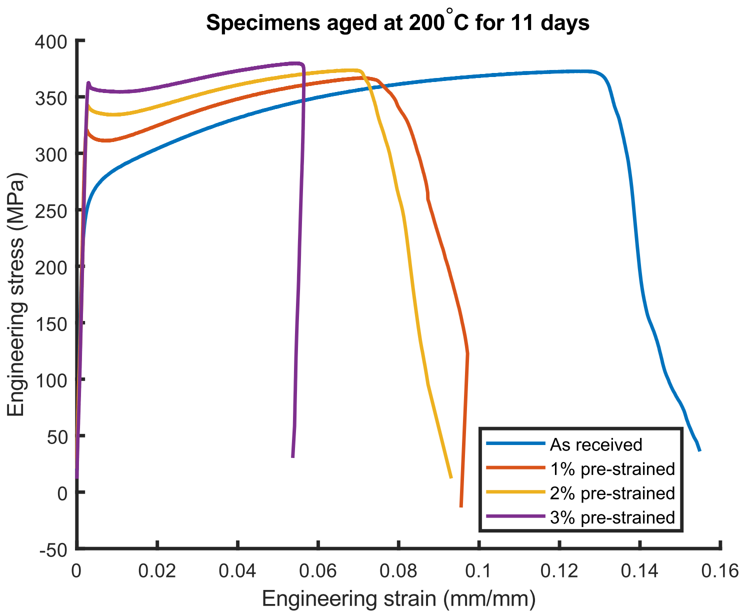
Static strain ageing in cast iron may occur as a result of plastic deformation. Static strain ageing leads to certain characteristic changes in the material properties of cast iron, such as increased yield strength and reduced elongation to fracture. If permanent plastic deformation of the cast iron insert arises, for instance due to a shear movement in the rock, strain ageing occurs independent of the temperature in the final repository. After 1–3 percent of plastic deformation at room temperature, static strain ageing of nodular cast iron was studied with tensile testing after different times (1–84 days) and at different temperatures, from 20 to 400 °C. [19] Nodular cast iron is very sensitive to strain ageing at all investigated temperatures and degrees of plastic deformation, which leads to a markedly increased yield strength and a drastic reduction of the material's ductility (elongation to fracture) (Figure 2). Even though the ductility of nodular cast iron is drastically affected by static strain ageing, ductile fracture surfaces arise, and no change of fracture mechanism was observed. [19] This means that strain ageing results in a faster localisation of plastic deformation to a shear band with a ductile fracture mechanism. It is also clear that both dynamic and static strain ageing of cast iron are possible and can have a great impact on the mechanical properties of the cast iron insert if plasticising loads occur in the final repository.

Figure 7.2 Stress–strain curves of nodular cast iron, after a plastic deformation and ageing

a)



b)



The figures 7.2 a and b shows stress–strain curves of nodular cast iron, after a plastic deformation and ageing.

Note: Stress–strain curves of nodular cast iron, after a plastic deformation of 1–3 % at room temperature and after different periods of time at 100 °C:

a) 1 day and b) 11 days. An increased yield strength and reduced elongation to fracture are characteristic consequences of static strain ageing. [19]

The cast iron insert must withstand load over a long period of time, and thus time-dependent strain can occur due to the cast iron undergoing creep deformation, a process that increases in extent with increasing temperature. Creep in the cast iron insert may be affected by the complicated geometry of the inner parts of the insert. The creep tendency is also affected by the hydrogen content and the residual stresses from the casting process. Limited studies of creep testing of the cast iron insert [21] have been carried out, but it is important to continue the creep testing of cast iron in order to rule out the possibility that creep could serve as a damaging mechanism under final-repository conditions.

There are no published data describing how different combinations of blue brittleness, radiation-induced embrittlement, hydrogen embrittlement and creep affect the properties of the cast iron. The nodular cast iron insert may undergo both static and dynamic strain ageing at low temperatures as a consequence of a shear movement that results in a permanent plastic deformation. Residual stresses in the structurally complicated insert may also affect this process. Hydrogen affects the mechanical properties of the cast iron, which can lead to brittle fracture of the nodular cast iron insert. However, limits of the acceptable hydrogen content have not yet been specified, and the critical hydrogen content that causes brittle failures in the nodular cast iron has not yet been determined.

7.6.1 Influence of embrittlement on the damage tolerance of the cast iron insert

The cast iron insert of the canister must be able to retain its mechanical functions for the loads that occur in the final repository without permanent plastic deformation occurring (except for large shear loads). According to the requirement specifications, the cast iron insert must be able to be subjected to asymmetric loads due to non-uniform water saturation of the bentonite buffer, and to isostatic loads after full saturation of the buffer, without permanent plastic deformation of the insert occurring. In the final repository, shear movements from an earthquake may occur in rock fractures intersecting the deposition hole. These shear movements may cause significant permanent plastic deformation of the cast iron insert; a 50 mm shear movement may cause 1–2.5 percent of plastic deformation. [1–3, 9] The ductility, fracture toughness and permissible defect size are essential to characterise regarding the integrity of the canister at plastic deformation of this extent. The strength of the cast iron insert at maximum isostatic load may also be affected drastically if the canister is first exposed to a shear movement that causes a permanent deformation (static strain ageing).

The mechanical damaging mechanisms for the cast iron insert under deposition conditions of which the safety assessment gives an account only include plastic collapse (buckling) through crack initiation and stable ductile crack growth when the ultimate strength has been reached. [1–3, 9] Brittle cleavage fracture has been excluded, for the reason that cast iron has been assumed to be a ductile material under all expected conditions in the final repository and over the entire relevant temperature range. [1] It is known that the nodular cast iron can show a ductile-to-brittle transition at low temperatures and moderately high strain rates. [6] Material testing has been carried out to a limited extent at temperatures from zero degrees to room temperature, and only at high strain rates. [1] Based on these limited data, SKB has concluded that brittle cleavage fracture of the cast iron insert is not likely under the final-repository conditions. Analyses of the mechanical properties of the cast iron are mostly done at room temperature, however, and measurements have not been carried out regarding the area for strain ageing. A drastic reduction of elongation to fracture and fracture toughness after strain ageing at elevated temperatures, as well as at room temperature, is possible. When analysing the strength of the cast iron insert, plasticising loads and ageing effects must be described as well, and attention must be given to relevant temperatures. Data on temperature and ageing dependence of the mechanical properties of the cast iron insert, such as an increased yield strength, reduced elongation to fracture and fracture toughness, have to be studied in order to reduce remaining uncertainties. If the load-bearing cast iron insert fractures through a brittle fracture mechanism, it is possible that the copper shell fractures as well, resulting in leakage of radionuclides.

7.7 Conclusions

The text above sheds light on areas where further research about the effects on mechanical properties of the cast iron insert is needed, in order to verify the specifications of quality requirements in production and in order to draw conclusions regarding the long-term safety of the repository. Furthermore, acceptance criteria for the different manufacturing defects will have to be developed.

The Swedish National Council for Nuclear Waste believes that there are significant knowledge gaps regarding the cast iron insert and that further research is needed. This is true for mechanical properties, microstructure, and chemical composition of nodular cast iron. Additional uncertainties related to the cast iron insert properties in the final repository concern embrittlement mechanisms that could impair the strength of the cast iron insert.

The Council proposes that continued research should take place within the framework both of the RD&D Programme produced according to Section 12 of the Nuclear Activities Act and of the stepwise licensing, in order to clarify:

- how radiation-induced embrittlement affects the mechanical properties of the cast iron insert and how different impurities (e.g. copper and hydrogen) affect this process,
- how hydrogen embrittlement affects the mechanical properties of the cast iron insert and whether this could lead to brittle fracture. The maximum amount of hydrogen that is allowed to be formed in the insert must be specified, and the critical hydrogen content causing brittle fracture in the nodular cast iron must be determined.
- whether blue brittleness of cast iron (static and dynamic strain ageing) is an embrittlement mechanism that must be considered when it comes to the requirements on mechanical properties of the cast iron insert,
- how the interaction between these embrittlement mechanisms and creep affects the mechanical properties of the cast iron insert.

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8 Small modular reactors

Summary

Interest in so-called small modular reactors has increased considerably within the nuclear power industry over the past years. The purpose of this chapter is to describe small modular reactors in order to give the reader the preconditions for getting acquainted with the question of what the waste from these reactors looks like and how it is to be taken care of. The chapter will first introduce small modular reactors, followed by a historical background that describes the emergence of the systems, and an account of these systems in different countries. Different reactor technologies are then described, as these are crucial for the design of the fuel to the various reactors. Finally there is a description of different types of waste from the systems, and waste studies from some countries are summarised.

8.1 Introduction

8.1.1 What is meant by "small modular reactors"?

"Small modular reactors (SMRs)" is a collective term for various types of nuclear power reactors. As the name suggest, they are relatively small, compared to present-day commercial systems, with the word "small" relating to both the size and the power output. According to the International Atomic Energy Agency IAEA's definition, the power referred to ranges from a few megawatts (MW) up to a maximum of 300 MW.

Concerning the word "modular", the Generation IV International Forum [1] thinks that modularisation of a nuclear facility means that its design and manufacturing process allows for prefabricated modules to be transported and installed on a given site. Similar definitions exist elsewhere (see [2] for an overview). This means that the reactors do not have to be built at the nuclear site, as is the case with conventional, large reactors, but that they instead can be prefabricated in a production facility and thereafter be transported to their intended site. The International Atomic Energy Agency IAEA also thinks that the reactors can be both built and operated separately, and that several units can be interconnected to a greater (modular) unit. [3]

8.1.2 Application areas, advantages, and risks with SMRs

Small modular reactors are proposed to be placed where the needs arise, both in urban regions and in remote and inaccessible locations (see [4, 5, 6], for example). Some small modular reactor systems are even proposed to be mobile. [7, 8] The small modular reactors are proposed to generate electricity, just as current large commercial reactors, but other application areas can be generation of process heat, district heating, hydrogen, and desalination of sea water. [2, 4, 6, 9, 10]

There are a number of publications that highlight arguments in favour of [9, 11, 12] and against [10, 13, 14, 15, 16] SMRs, while other publications try to make a more comprehensive review in order to evaluate the opportunities and challenges with the systems. [6] One may observe that SMRs to a varying degree are based on known and proven technology, but that some SMRs constitute new and thus far untested concepts. Examples of aspects that differ from conventional large-scale nuclear power are the modularisation and that the nuclear power systems are proposed to be spread over a large number of units and also deployed in locations where nuclear power plants previously have not existed. The latter can constitute an increased risk of proliferation of both radioactive and toxic substances, as well as of sensitive materials and technologies. One may also consider whether it may be a challenge to achieve as strong a physical protection around such systems as around conventional large-scale nuclear power plants.

The purpose of this chapter is not to take a stand for or against SMRs. Instead, the Swedish National Council for Nuclear Waste rather wants to direct attention to the wastes from such systems to investigate whether, how and to what extent these issues are being studied. This requires a description of the reactor systems, though, and an insight into how the systems are meant be used.

8.1.3 What does the development need look like?

Today not only small modular reactors based on current light-water technology are being studied, but also high-temperature gas-cooled reactors (so-called HTGRs), molten salt reactors (MSRs) and various metal-cooled concepts.

Primarily the proponents' interest currently lies in the reactors as such, but for SMR technology to be implemented that is not enough. To begin with, social and political acceptance of new nuclear power is required. In addition to designing and constructing a reactor to be operated, considerable work in conjunction with the licensing of the different SMR concepts will also be required. Before that, thorough safety assessments have to be able to show that they comply with nuclear power laws and regulations and that they can be operated in a reliable and safe manner over a full range of operating scenarios. For reactors to be considered for commercial operation, extensive investment capital will also be required, as well as efforts relating to large-scale manufacturing, logistics, operation, safety and maintenance.

With many distributed nuclear power systems scattered across the world, there is also a risk that transports and handling of both nuclear material and operational waste in a broad sense may increase. This leads to a need for developing new systems for the control of nuclear materials and waste, which as far as possible ensure that the new nuclear power systems do not increase the risk that sensitive material or nuclear waste fall into the wrong hands. Furthermore, it has to be analysed how the properties of the fuel are affected during and after irradiation in the reactor (e.g., the content of different radionuclides, radiation levels and decay heat), so that it is possible to develop a safe final storage of the irradiated fuel. Will the waste be recycled, and if so how, or is it to be disposed of in another way? Aspects related to the final storage of the waste from SMR reactors seem easy to forget in this context, when the advantages with a new technology loom large.

That was not least the case during the introduction of conventional nuclear power in Sweden, with the waste from reactors not even having been mentioned in the first Swedish Atomic Energy Act [17]. It was not until the first half of the 1970s, when the first Swedish reactors already were in operation, that the first development projects and studies in the field of waste management were initiated.

In order not to repeat the same development with potential new reactors, the Swedish National Council for Nuclear Waste wants at an early stage to underline how important it is that those researching the systems or advocating their construction, at the same time study how the waste is to be managed and finally stored in a responsible and safe manner.

8.2 Historical background

Small modular reactors have many similarities with previously developed small (but not necessarily modular) reactors. Small reactors, in contrast to what one might imagine, have a long history behind them. Since the 1940s, there have been hundreds of small reactors in the world for different purposes and in different contexts, both military and civilian. For civilian purposes these have often been so-called experimental reactors or research reactors that investigated material properties and reactor principles, in order to then scale up the reactors. This also applies to the Swedish experimental reactors that were constructed at the Royal Institute of Technology and in Ågesta and Studsvik.

In the early 1950s, the US Army initiated a programme [18] to develop small reactors in order to produce heat and electricity at remote military installations. The programme was realised in 1954 and would until 1977 produce eight reactors of various kinds. One of these, PM-2A, was put together of prefabricated parts at the US military base Camp Century on Greenland. When it was started up in October 1960, it was the first reactor not constructed on site. The most known reactor in the programme was MH-1A, though, a mobile pressurised-water reactor on a barge that was started up in 1967 and then used to produce electricity at the Panama Canal until 1977.

More known are the small reactors placed in nuclear submarines already in the 1950s. At the time there was a fleet that comprised many hundreds of vessels from primarily five countries, but the fleet has decreased considerably in numbers since the cold war. Reactors were also placed on aircraft carriers, cruise ships, and icebreakers. [19] There were also plans for nuclear powered aircrafts, but the interest for them decreased as intercontinental missiles and nuclear-armed nuclear submarines replaced the strategic superiority that nuclear powered aircraft had been planned to offer. [20] Furthermore, there were technical challenges, as the shielding required to reduce the dose to the crew weighed down the structure in a way that impeded the flight characteristics. [21] In contrast to the aircraft, the plans for nuclear powered tanks never left the drawing board. In the 1960s, the Soviet Union did develop a mobile reactor with a power of 1.5 MW, though, mounted on the chassis of a T-10 tank and called TES-3 (Transportable Electric Station 3). When it did not succeed, the project was cancelled in 1969. [22]

Small reactors were also discussed as early as in the 1970s as a way to introduce civilian nuclear power to developing countries. The interest was strengthened by the oil crisis and a growing electrification in developing countries, combined with an increased competence in electric power generation. At the same time, criticism of nuclear power as an energy source started to emerge all over the world, and economic considerations rather than technical ones led to commercial nuclear power completely being dominated by medium-sized and large reactors. At the UN body IAEA's 18th yearly conference in 1974, a prominent issue was why there were no smaller reactors for developing economies. [23]

In Sweden, the oil crisis led to ASEA Atom planning the construction of small reactors. Those plans were for two variants of mini reactors for Swedish municipalities, which would produce district heating and electricity, respectively. The reactors were called SECURE and were launched in the late 1970s. [24]

8.2.1 Small modular reactors today

In order to be able to shed light on the nuclear waste issue related to SMRs, we have to be aware of the systems that are under development. This section intends to shed light on where in the world development of SMRs takes place, and what types of reactors and reactor systems are being studied. This has a direct impact on the fuel materials and the fuel types that are intended to be used, and thus also on the waste that will be produced.

More than 70 SMR designs under development are presented in an IAEA publication [25], with the CAREM reactor in Argentina being the SMR design of light-water reactor type that is closest to commissioning. The development of SMRs has recently been conducted with the help of private companies as well as through government efforts. Development needs vary, with the concepts based on light-water cooled reactors being most like today's reactors and thereby having the smallest development needs. It is therefore perhaps not surprising that this type comprises the majority of the SMR designs being developed. Of the SMRs that are light-water cooled, a large part are so-called pressurised water reactors (PWRs), which is the reactor type that is globally dominant today.

There are also SMRs under development, however, which rather can be classified as Generation IV (Gen IV) reactors, or as part of a Gen IV system. These are nuclear systems that are being developed with the goal of overcoming weaknesses with today's nuclear power systems. The hope is that the systems will utilise fuel resources more efficiently, produce less waste, be economically competitive, meet higher safety requirements, and be less attractive for misuse and diversion. The Gen IV technologies selected by the Generation IV International Forum include metal-cooled reactors, molten salt reactors and high-temperature reactors. [78] One of the SMRs based on Gen IV technology and closest to the market, is being developed by China and uses fuel in the form of fuel spheres (a so-called pebble bed reactor). [26, 27] Demonstration reactors are planned to be used for both electricity generation and process heat.

There are also a large number of metal-cooled reactor concepts that use liquid sodium, lead or lead-bismuth as their cooling medium. Those concepts offer several advantages such as small and compact systems and long refuelling intervals, but at the same time, the enrichment of uranium in the fuel is higher than in today's light-water reactors, which has impact on both the non-proliferation issue and fuel production and waste management. [28]

The technology behind the molten salt reactor (which is classified as Gen IV) has not come as far, and at present there are no commercial systems even though development and demonstration have been pursued for several decades. A concept from Canada may possibly get to be the first one to be built. The concept is called IMSR (Integral Molten Salt Reactor) and passed the first step of the pre-licensing process a few years ago. In this system, the fuel is not separate from the cooling medium, and liquid fuel circulates through a graphite-moderated core.

An overview of various countries' interests and plans for construction of SMRs is presented in the section below.

8.2.2 An overview of the development in a number of countries

- In **Canada**, studies on SMRs have been going on for many years, and the country has a leading position in many respects. The so-called "Canadian Small Modular Reactor (SMR) Roadmap Steering Committee" published a document in 2018, a "Roadmap", relating to SMRs and their role in the future. [5] The document indicates three potential markets: as a substitute for coal-generated electricity; for combined generation of electricity and heating in heavy industry; and for the generation of electricity, district heating, and desalination of sea water in remote locations without an existing electrical power grid. A possible application for SMRs may be in the mining industry, which today uses a lot of fossil fuel. Since the report's publication, the Canadian government has announced an "action plan" for the work on developing, demonstrating and establishing SMRs in the country. [29] The Canadian Authority CNSC has at the same time been conducting work comprising pre-licensing processes for in the range of ten different projects. The purpose is not to license the reactors now, but to give the manufacturers feedback on the technology. In 2019 the authority received a first "siting licence application", for a micro-SMR by the company Global First Power. [30] The application relates to a 15 MW gas-cooled reactor called "Micro Modular Reactor" that will generate process heat for a nearby molten salt facility, which in turn will generate electricity and/or heat. [31] It can be added that CNL, Canada's largest research laboratory for nuclear technology, in 2017 received expressions of interest concerning the construction of nineteen different demonstration and/or prototype reactors of an SMR type.

A number of manufacturers (Kairos Power, Moltex Canada, Terrestrial Energy and Ultrasafe Nuclear Corporation) received support from CNL in November 2019 in order to speed up the construction of SMRs in the country. In October 2020, one of the companies, Terrestrial Energy, was awarded additional state funds for the development of the reactor called Integral Molten Salt Reactor (IMSR). In the same month, the company Ontario Power Generation (OPG) announced its intention to collaborate closely with three different manufacturers (GEH's 300 MWe BWRX-300, Terrestrial's 192 MWe Integral Molten Salt Reactor, and X-energy's 80 MWe Xe-100 high temperature SMR) in order to investigate energy supply for remote locations. [30] At the same time, over 100 organisations in civilian society and among indigenous organisations endorsed a petition from the Canadian Environmental Law Association that criticises the development of SMRs in general and state financing for SMRs in particular. [32]

- **China** conducts research and development on SMRs. The development is being pursued towards different milestones such as electricity generation for small grids, district-heat generation, process-heat generation, and desalination. China is financing a number of different programmes aiming to conduct research, develop and demonstrate reactor concepts both on the Generation III and on the Generation IV level. Since the 1970s, one has i.a. been studying gas-cooled high-temperature systems, and the construction of a demonstration facility consisting of modular high-temperature gas-cooled reactors is a high-priority science project. The facility called HTR-PM will consist of two so-called pebble bed reactor modules, which are based on the principle of HTR-10. [33] Since 2010, one has also been studying small and medium-sized pressurised water core systems (ACP100). [34] A demonstration reactor of the ACP100 type was built in Hainan in China in 2019, and furthermore, the National Nuclear Co. has also begun the development of an ACP100 reactor that is intended to serve as a floating nuclear power plant.
- **Russia** has the world's most extensive experience of operating SMRs, with one application area being the propulsion of icebreakers. The flagship reactor RITM-200 of the PWR type is a 50 MW SMR which is already tested, has been installed on six ice-

breakers, and is intended to be installed on two more. [35, 36] There are also other examples of SMRs sited on land as well as off-shore. One noted off-shore reactor is a floating nuclear power plant where the reactor is of the PWR type and is known under the name KLT-40 reactor. [37] The reactor has the purpose of providing electricity to remote locations without infrastructure. As for land-based SMRs, there are plans for an RITM-200 reactor to be placed in the vicinity of an existing diamond mine. It is primarily the state-owned Rosatom that drives the development in the country, and applications such as electricity and hydrogen generation have been highlighted. Rosatom's plan seems to be primarily to provide the domestic market with the new technology, and secondarily to export it to the rest of the world. [38]

- In the **UK**, the government has shown an interest in new nuclear power, including both SMRs and so-called advanced modular reactors. Such technology is a part of a commitment to a green industrial revolution, where the British government identified ten ways of reaching a zero level for their emissions. [39] Reference [40] specifies that support for new research and innovation in the nuclear area over the period 2016–2021 amounted to 480 million pounds, including support for skills development within the regulatory authority to allow for licensing of new nuclear systems. Within the framework of the strategy, the British government launched a multi-stage competition in nuclear innovation in 2016, where developers and manufacturers of nuclear systems were given an opportunity to support the government's development within the nuclear power sector with development of new nuclear concepts. The concepts were based both on new light water reactor technology and on Gen IV technology. The British government's efforts specifically targeted towards SMRs are described in more detail in reference [41], while the efforts on advanced nuclear concepts are described in [42]. The British government has also carried out investigations aimed at developing recommendations for how it, in cooperation with the nuclear power industry and the finance sector, can make financing available for research and development of advanced nuclear systems. [43]

- In the **USA**, the Department of Energy has for several years been collaborating with and financially supporting a number of companies and programmes on the development of SMRs. Since 2020, there is a programme that will provide support for demonstration of different advanced reactor concepts in the USA. [44] In this programme, areas are given attention which – often in the light of existing regulatory requirements adapted to large-scale light water reactors – are in need of particular support. Examples of such areas are nuclear safeguards and nuclear security. [45] At present there are several different SMRs under development. These vary both in terms of size (from tens to hundreds of MW), technology (light water reactors, gas-cooled reactors, metal-cooled reactors and molten salt reactors), purpose (electricity generation, process heat, desalination, industry processes, etc.) and construction. [46] During 2018, hundreds of millions of dollars were allocated to thirteen different projects. In recent years, collaboration has focused on SMRs of the light-water type, and the Department of Energy has joined forces with the private manufacturer NuScale Power [47] and the political interest organisation Utah Associated Municipal Power Systems (UAMPS) in order to build the first SMR reactors of the light-water type at Idaho National Laboratory (INL). In September 2020, NuScale's reactor concept became the first SMR concept ever to be licensed by the United States regulatory authority NRC. [49] At INL, there has also been a newly started innovation centre since 2019 (National Reactor Innovation Center, NRIC) for facilitating the construction of different types of SMRs. Here, the two companies TerraPower and X-Power are at the forefront, and research and development on a number of reactor concepts are under way. Since 2016, there is also a consortium in the USA called SMR Start [50], consisting of industrial partners advancing the commercialisation of several different SMR concepts.
- In **Sweden**, the state company Vattenfall is participating in a feasibility study in cooperation with the (private) Estonian company Fermi Energia, Finnish Fortum, and Belgian Tractebel. [51] The feasibility study aims to investigate the prospects for building SMRs in Estonia. Vattenfall has announced that the purpose of the collaboration is to gather knowledge and build competence regarding SMRs. Currently four different concepts are being an-

alysed – a boiling water reactor (GE/Hitachi), a molten salt reactor capable of using spent nuclear fuel as its fuel (SSR-W300 by Moltex), a pressurised water reactor (NuScale), and a thermal molten salt reactor (Terrestrisk IMSR-400). More information is available in [52]. There are also links to the development in UK, as one of the companies participating in the British Department for Business, Energy & Industrial Strategy's competition on nuclear innovation (with the project SEALER-UK) has its base in Sweden. The company develops a lead-cooled fast reactor with an electrical power output of 55 MW, intended for the electrification of remote communities. [53] Swedish researchers are also participating in research projects related to development for the construction of a lead-cooled research reactor in Oskarshamn [54, 55] and in a project related to establishing a national centre of excellence with a focus on SMR technology. [56]

- In **Finland**, there is also an interest for SMRs, and the country is about to completely phase out carbon from today's energy system, at the latest in 2029. This is a challenge, mainly for the heating sector where the greatest potential for SMRs is found, according to both VTT [57] and Fortum. [58] EcoSMR (Finnish Ecosystems for Small Modular Reactors) [59] gathers a number of Finnish actors, among others VTT and Lappeenranta University of Technology, in order to investigate the preconditions for requirement specifications, licensing and business opportunities for a potential construction of such reactors in the country. [60] The interest is being justified on the basis of the opportunities to produce low-CO2 electricity, process heat and district heating. VTT has been very active in the project for several years and is investigating the possibilities to introduce SMRs in Finland. They coordinate a European project concerning licensing procedures, carry out several feasibility studies to investigate the potential role of the SMR technology in different energy contexts (see e.g. [61]), develop tools for modelling of SMR physics, and develop concepts for district-heat generation. [62, 63]

- In **France**, nuclear power has had a very strong position for a long time and has been the dominant source of electricity. Since a couple of years ago, there is a national goal for nuclear power in 2035 to account for at most 50 percent of the electricity generation, which is a decrease compared to the current share of about 70 percent of the electricity generation. [64] Research and development of nuclear systems have had a prominent role, and progress is also being made in the field of SMRs. The French Energy Authority has announced plans to develop an SMR that may be on the market before 2030. The plans relate to the so-called Nuward SMR project, with a reactor developed by the nuclear and energy commission CEA, together with the state-controlled EDF, the so-called Naval group and the company TechnicAtome. There are also plans to cooperate with Westinghouse. [65]

A number of other European countries are cautiously interested of SMRs:

- **Poland** is a country that is largely dependent on coal. Recently, plans to replace coal power with nuclear power were announced, and SMRs are being investigated in order to generate both electricity and heat as a complement to the six planned, larger power-generating nuclear power reactors in the country. The clearest interest for SMRs seems to be in producing process heat for industrial purposes, though, and the Polish Energy Department indicates room for a number of reactors of the HTGR type and a demonstration facility and a full-scale facility within a ten-year period. [66]
- Also **Romania** is investigating SMRs, especially NuScale. A declaration of intent has been signed for the purpose of determining if, and in that case how, SMRs may suit the Romanian needs. [67]
- In a corresponding way, also the **Czech Republic** has expressed an interest in SMRs and has signed contracts with both GE Hitachi and NuScale that permit further exchange of technical information. [68] Development of concepts for district heating is also in progress. [69]

- **South Korea** has successfully been developing and exporting nuclear power plants to other countries for a long time. KAERI, Korea Atomic Energy Research Institute, has developed an SMR of the PWR type under the name SMART. [70] Research and development of SMRs in South Korea is not only limited to reactors of the light-water type. Since the issue of handling the domestic waste from the reactors is unresolved, a national transmutation centre was established in 2002 under the name NUTREK. Within the framework of this centre, a number of research and demonstration studies have been conducted, concerning, among other things, transmutation with respect to metal-cooled reactor systems. Based on the experience that has been compiled, a lead-bismuth-cooled SMR with uranium dioxide fuel has now also been proposed, under the name URANUS. [71]
- **Argentina** has been developing research reactors since the 1950s. Since the 1980s, the CAREM project has been under development, which is an SMR project with a focus on the development of small reactors of pressurised-water reactor design. Construction of a prototype reactor, CAREM 25, was begun in 2014 as a step towards developing a commercial reactor. [72]

8.3 Overview of reactors technologies and fuels under development

What the fuel for the reactors looks like, depends on the type of reactor it will be used in. As mentioned above, several reactor technologies are being investigated within the development of SMRs; an overview of these is given in Table 8.1 below.

Table 8.1: Overview of SMR concepts

Technology	Comment	Examples of the concept
Light-water reactor (LWR)	The most widespread commercial technology today. The reactors are of two types: pressurised water reactor (PWR) or boiling water reactor (BWR). PWR is the most common type globally. The fuel consists of uranium rods put together into fuel assemblies.	PWR: ACP100, CAREM, FlexBlue, KLT-40S, NuScale, RITM-200, SMART, SMR-160, Nuward.
High-temperature gas-cooled reactors (HTGRs)	Many countries have shown an interest in the technology, with proposed gas-cooled SMRs using helium as a cooling medium. SMR fuel is suggested to be "pebbles" (fuel spheres the size of billiard balls) or fuel rods.	EM2, GT-MHR, HTR-PM
Metal-cooled reactors	The cooling medium consists of liquid metal such as liquid sodium, lead, or lead-bismuth. The fast neutron spectrum in the reactor allows the reactors to be used both for creating new fuel ("breeding") and for consuming waste products ("burning").	Sodium-cooled: 4S, PRISM
Molten salt reactor (MSR)	Based on a salt melt that circulates in the system. At present being considered e.g. for process heat and energy storage.	IMSR, LFTR, Molten Chloride Fast Reactor, SSR-W

Note: Additional information is available in reference [63].

For each reactor technology, a number of different reactors are being proposed. A majority of the SMRs under development or construction is of the light-water reactor type, where the fuel material consists of enriched uranium dioxide, UO2, similar to the fuel used in light water reactors today. However, the geometric shape of the fuel material (the so-called fuel geometry) may be different than the oblong fuel assemblies consisting of fuel rods that are being employed in nuclear power plants today. Often the degree of enrichment of the fuel is below 5 percent, but it may reach almost 20 percent in some cases where the reactor is to be operated for long operation cycles without refuelling. In view of this, the spent fuel from SMRs of light-water reactor type is expected to have similar characteristics as that from today's light-water reactors, even though some differences may occur due to other degrees of enrichment or fuel geometries.

High-temperature gas-cooled reactors are found in different variants. Many of them use fuel made up of so-called TRISO particles, small particles with a diameter of about 1 mm. The core of TRISO particles usually consists of uranium dioxide, while the outer layers are carbon- or ceramic-based, intended to keep the fission products entrapped also at high temperatures and final burnups. The TRISO particles can be formed into different fuels, such as a larger variant of the present-day fuel pellets used in fuel assemblies (similar to light water reactors fuels) or into round spheres, so-called pebbles, the size of billiard balls. These pebbles cannot be distinguished from each other, and a single core can contain several hundred thousand of them. The fuels are expected to reach a high final burnup, and the refuelling interval varies from continuous refuelling to times of almost 30 years. The spent fuel will have a higher final burnup, since it has a higher enrichment, and a higher decay heat than today's fuel. Furthermore, the pebble fuel marks a significant departure from the fuel geometry that we handle in Sweden today, as the fuel has a different shape (round spheres that cannot be distinguished from each other, rather than ID-marked fuel assemblies with fuel rods). The fuel elements that occur for certain concepts have different properties than the fuel from light-water reactors, but there is already experience with such handling, for instance from gas-cooled reactors (Magnox) in the UK.

Reactors cooled with liquid metal use different types of fuels, with the fissile material being in the form of uranium or plutonium carbides or nitrides (carbides are metal-carbon compounds and nitrides, metal-nitrogen compounds, with high melting points and high mechanical stability). The degree of enrichment in the fuel is higher than for today's light-water reactors and the fissile material may consist of both uranium and plutonium. The refuelling interval varies from around one year to decades, and in some cases no fuel replacements are planned at all as the entire core is replaced or the reactor is expected to have reached its end of life (metal-cooled SMRs without fuel replacements include SVBR-100 and SEALER-UK, (see Table 8.2 below), but there are also other SMRs without planned fuel replacements). The spent fuel will be similar to today's in the sense that it consists of fuel elements, but the fuel's material composition, burnup, decay heat, etc. will differ from that of today's light-water reactor fuel. In addition, the spent fuel will presumably be interim-stored for some time in liquid metal before it is handled for final storage. Although we in Sweden have no experience of handling of such fuels, there is considerable experience for instance in France, which long operated sodium-cooled reactors, and in Russia, which has operated lead-cooled reactors.

Molten salt reactors are the most different from today's light-water reactors in terms of fuel. In these cases, the fuel is liquid and often mixed with a fluoride salt or possibly a chloride salt, and the fissile material may consist of thorium fluoride or uranium(IV) fluoride [74, 75] or of plutonium. [76, 77] A molten salt reactor in operation has a much higher working temperature, about 700 °C, than a conventional light-water reactor, which has a working temperature of about 300 °C. The high working temperature and the salt melt's chemical properties mean that corrosion is a great challenge for the materials that are to be used. The waste from these types of reactors is very different from today's waste. Since many of these concepts have the ability to utilise the long-lived transuranics as fuel (after the transuranium elements have been separated from other waste products in a reprocessing facility), the final waste will mainly consist of short-lived fission products. By contrast, new types of waste will arise, which consist of various types of salts, as well as waste from the chemical reprocessing.

Table 8.2 shows the main fuel properties of a number of the proposed SMR concepts. The table is not complete, since the list of proposed SMR concepts today can be very long. In this context, it can be mentioned that a part of the SMRs in Table 8.2 explicitly claim to be so-called Gen IV reactors. Within these systems there is, for a number of physical reasons, an opportunity to utilise as fuel parts of what today is regarded as long-lived waste. This may then reduce the waste quantities from nuclear power operation, as well as the storage times for the waste. [79] A large number of processes for separation and reuse of different elements are already developed, or are in research and development. Processes are at different levels of maturity, extending: from a low level where the principle of separation and recycling has been demonstrated but further step remain to be carried out before the process can be scaled up to a commercial level; to a high level where the essential process is in commercial operation (e.g. PUREX) and relatively small modifications of the process are under development. A more complete overview of different recycling processes and their levels of maturity can be found in a publication of the OECD/NEA. [80]

8.4 Waste from SMRs

Many SMRs are relatively early in their development phase, in particular, several of the concepts that are based on a technology other than light-water reactor technology. In many cases the design of the reactors and their surrounding facilities for fuel fabrication, reprocessing or recycling, etc. is not finished either, and research is under way to formulate durable material that can sustain the new, challenging environments. Hence, it is difficult today to estimate exactly what the waste streams and volumes may look like, and what properties the wastes will have. In that light, the IAEA believes that it may be more meaningful to make assessments of which types of unique waste streams will be produced, rather than to design the details of the waste disposal already. [108]

Overall, the IAEA states in [108] that for the light-water reactor concepts, the fuel in terms of its form and properties is similar to the one from today's commercial large-scale light-water reactors. Therefore, the waste will likely be possible to be disposed of in a similar manner and with similar processes, even if one in various ways tries to reduce and compact the waste volumes. It is worth noting in this context that nearly all countries today lack a long-term solution for the nuclear waste already existing, and that even countries with plans for final repositories do not expect additional waste from future SMRs within the scope of their ongoing projects.

The overview in [108] shows that the waste from gas-cooled systems in many ways is similar to that from existing gas-cooled systems, with which there is experience. However, there are certain differences in for instance the occurrence of various radionuclides in the different waste forms, which justifies continued research in the field of waste. Regarding waste other than the fuel, its volume can be reduced for instance by dint of the pebble-bed reactors' fuel not being encapsulated. By contrast, for these reactors the disposal of radioactive graphite will be added, which is a new type of waste. [108] We can note in Table 8.2 that the fuel for high-temperature gas-cooled reactors is expected to have a much higher initial enrichment and thereby also higher final burnup and higher decay heat than today's waste from light-water reactors. In addition to this, the fuel cycle will include thorium (Th), which is not being used as fuel to any appreciable extent today. The authors of [109, 110] observe that the final storage of nuclear waste from the high-temperature gas-cooled reactors has been studied since the 1960s, with the intention of separating the fission products and recovering and recycling uranium oxide and thorium oxide and to create new fuel. Which alternative for final storage of waste is to be preferred for an individual country is dependent on a number of different factors. These may e.g. involve which types of waste a facility can receive and what laws, requirements and resources exist concerning the recycling of nuclear waste. Regardless of what the situation looks like, the solution proposals today are schematic and vary from packaging/containment with subsequent direct disposal of the entire core, to complete chemical reprocessing of the spent fuel where fertile and fissile material is recovered and recycled, minor actinides (heavy elements including thorium, uranium and plutonium, and all being radioactive) are separated and fission products are encased in glass (vitrified). Despite extensive research, no well-defined "finished" process for recycling of HTGR fuel exists yet, although major progress has been made on the pilot scale. [109, 110]

Regarding fast reactors, i.e., reactors with a fast (high-energetic) neutron spectrum such as metal-cooled reactors or some molten salt reactor concepts, these generate spent nuclear fuel with a radiotoxicity by a factor of ten higher than today's MOX fuel. [108] This will have effects on the safety around and handling of such material. A fuel handling or recycling facility can reprocess waste to forms that are for instance insoluble in water, but the radiotoxicologic properties remain, as long as the material has not decayed. The largest reduction of radiotoxicity (a factor of 100–1 000) is achieved by transmuting transuranic elements and actinides, for instance in a fast reactor. Transmutation means to transform an element or isotope (variants of the same element but with different atomic masses) to another element by means of irradiation. This would entail that the waste can be new fuel, which reduces both the waste volumes and their storage times. A certain volume of long-lived waste will always remain, but it will be a smaller volume/amount than from the LWR systems. However, the reuse of transuranic elements and actinides requires fuel reprocessing or fuel recycling, which in turn generates new waste streams. What these streams look like depends on the type of fuel to be processed (oxide, nitride, carbide, metallic fuel, etc.). The waste streams also depend on the processing used, such as aqueous reprocessing methods or high-temperature methods that includes salt melts. Reference [108] describes this more thoroughly. This reference further observes that the metal-cooled systems give rise to a new type of waste that is to be categorised as low-level and intermediate-level waste. This waste consists in part of material that in some way has come into contact with the cooling medium (i.e., liquid sodium, lead or lead-bismuth). In these cases, the cooling medium as such will constitute a new and unique type of waste, for which separate waste management processes have to be devised.

The different molten salt reactors that have been proposed use a number of different types of fuels, with both fissile materials (e.g. U-235, which constitutes the fuel for today's nuclear power) and fertile materials (e.g. U-238 which is present in the fuel today but is not fissile) being possible to be used. Some of the molten salt systems are expected to burn the major part of the transuranic elements and the lighter actinides, which (as in the metal-cooled systems) can reduce both the volume and storage time for the spent fuel salt. The waste from the reactor, with its associated reprocessing, would contain fission products which are separated in the reprocessing step. Today there are no processes to safely manage and during long time scales store the frequently corrosive salts, but these have to be developed, as well as solutions for their long-term containment. [108]

8.4.1 What does the need for development in waste management look like?

In the edition "Management of Spent Fuel from Nuclear Power Reactors" of the journal *IAEA Bulletin*, the director of the IAEA's Division of Nuclear Fuel Cycle and Waste Technology speaks out about whether the waste from SMRs will be a challenge to dispose of or not. [111] The representative concludes that a country's ability to dispose of the waste depends on both which SMR concept is meant and the country's previous experience with the final storage of nuclear waste. Countries with already existing nuclear power programmes have proper infrastructure in place since earlier as well as experience with handling nuclear waste, and for such countries waste from SMRs of the light-water reactor type should not pose any further challenge beyond what the final storage of the waste from current nuclear power already does, according to the director. He further asserts that he does not believe that the waste from more advanced SMR concepts such as high-temperature reactors necessarily will be more complicated to dispose of, since the waste to a large extent can be handled in a similar manner to conventional waste from today's nuclear power. On the other hand, he points out that the challenge may all be the greater for countries that have no or little experience from previous nuclear power. The IAEA has also discussed the waste issue in other contexts, for instance in the publication "Technology roadmap for small module reactor deployment". [112] The publication does not aim to give an account of various possibilities and limitations, but emphasises the importance of raising the issue and addressing the necessity of developing systems to dispose of the waste from the reactors.

In the USA, the country's safety authority U.S. Nuclear Regulatory Commission (U.S. NRC) stated already in 2014 that a licensing application for the construction of new nuclear power has to describe how the radioactive waste is to be managed and present plans for final storage of the waste. [113] U.S. NRC also observed that they at the time did not have information on specific waste streams even for SMRs of the light-water reactor type, and that SMRs of more advanced type would require further research in order both to estimate the unique waste streams and to prepare solutions for management and disposal of these. Furthermore, the U.S. NRC believed that both regulations and recommendations would have to be updated. Since then, one concept, NuScale, has passed the U.S. NRC's sixth and last review phase, which means that the company can continue its plans to establish the reactors. Regarding the handling of the spent reactor fuel, the company behind NuScale proposes that it should be stored in a fuel pool for the first five years and then be placed in a dry repository at the facility. That type of final storage is estimated by the company to be safe for up to 100 years. What happens after that is more unclear. The US Department of Energy is responsible for the development of a final repository, thus the responsibility for long-term storage lies beyond the company. The company behind NuScale states that reprocessing of the fuel for MOX fuel production can be an option. [114]

In Canada, which is at the forefront regarding the implementation of SMRs, a report was published in 2018 that relates to an investigation of what is required in order to develop and install SMRs in the country. [115] The report is authored by a working group that handles the very issue of waste, and it identifies both knowledge gaps and possible solutions for waste from SMRs. What becomes clear is that a plan for managing the waste from these reactors has to be developed. SMR developers, together with the responsible waste organisation, must prepare a set of requirements for the waste as well as investigate what waste forms can be accepted. This includes studies of possible methods for fuel characterisation, fuel handling and fuel transports. Continued work is also needed in order to be able to show that the fuel is safe to be placed in a repository based on the plans that the country has today. Generally, there are many question marks concerning how future "small producers" are to handle their low-level and intermediate-level waste, as the responsibility for providing and funding this today rests on the owners of the individual nuclear power plants. Regarding the high-level waste, there are also a number of logistic challenges related to transports of the irradiated cores from remote sites. There is also another study that investigates waste streams from different types of advanced SMRs (high-temperature gas-cooled reactors, molten salt reactors and lead cooled reactors) that are being considered for construction in Canada. The work identifies various types of new waste streams that do not include the fuel itself, and indicates that the expected high burnups in the fuel will result in high activity levels. [116]

The Finnish regulatory authority STUK has also looked into prerequisites for using SMRs in the country, and concludes that the waste from SMRs of the light-water reactor type inherently is very similar to the waste from today's reactors in the country. That means that such waste can probably be handled with similar equipment to that which is already being used or is planned to be used in the country, and that current safety requirements regarding the final repository can be applied. STUK also concludes that there may be advantages with today's centralised waste management. Thus, the regulatory framework and the set of requirements on the waste issue may have to be reconsidered, if facilities in the future come to be distributed or have a size that substantially differs from today's. [4] Systems that are not of the light-water reactor type are not appreciably touched upon in the report, probably because a commercial implementation of them lies further in the future, if it at all will become relevant.

Regarding waste studies for SMR fuel, we are not aware of such having been done in Sweden. The closest we have found are studies carried out by Swedish Nuclear Fuel and Waste Management Co (SKB) which is responsible for the spent nuclear fuel from light water reactors in Sweden. In [117], the company reflects on a number of issues related to the company's application for a final repository for spent nuclear fuel and its extent. This concerns among other issues the impact on the final repository of the introduction of new nuclear power plants (even though waste from new reactors is not covered by SKB's application). [118] SKB states that the uncertainties regarding this are so large regarding the choice of technology and when such an introduction may be considered, that this of necessity will require a separate process for development, review and licensing (in line with Swedish and European legislation, one may add). According to SKB, the existing waste volumes might be reduced if the waste could be used to create MOX fuel. Looking beyond the fact that such a waste processing would be problematic from both an environmental, health and economic perspective, the final repository would be more complex and receive more categories of high-level and long-lived waste. Regarding fast reactors (some SMRs are of this type) and their waste, SKB concludes that such an introduction in Sweden would require large investments in new reprocessing and fuel fabrication facilities. Thus, a final repository for light-water reactor fuel will continue to be needed in the future, and in addition to it, another repository for waste from fast reactors. Although legal aspects are not discussed in the publication, it may be added that in Sweden, a final repository in the sense of the Nuclear Activities Act is precisely a final repository and nothing else. In that light, it is legally not possible to retrieve the fuel without first submitting new licence applications for this under the Act (1984:3) on Nuclear Activities (the Nuclear Activities Act) and the Environmental Code (1998:808). With the way that legislation looks today, that will be a difficult licensing, since the final repository then no longer is a final repository – at least not for all fuel – and the state's responsibility for a final sealed repository may have to be reconsidered.

8.5 Conclusion

SMRs based on a number of different reactor technologies are under development, with concepts based on well-known technology for light water reactors as well as advanced technologies where the fuel and/or cooling medium substantially differ from today's reactors. This raises issues regarding what the waste will look like and to what extent it is possible already now to plan for its specific disposal.

A review of a number of different reactor concepts shows that the waste issue is not forgotten, but not prioritised either. Some reactor concepts are presented along with plans for management and final storage of waste, but the solutions tend to be general and focus on the fact that the waste can be stored or contained, without going into more detail about what this means or how it should be done. For the concepts based on light water reactors, the situation is similar to that of large-scale nuclear power. That is probably due to the fact that many concepts still are early in their development and that it is difficult to present specific plans for waste management when the systems are not mature. At the same time, there are large opportunities at this early stage to impose requirements on, and thereby affect, the basic design of the waste system.

There are countries that invest heavily in the development of SMRs today. In Sweden, too, there is an interest among some researchers and companies in participating in the development. That can be understood by looking into research funds that have been awarded to, for instance, the project SUNRISE from the Swedish Foundation for Strategic Research [54, 55], as well as to the establishment, recently awarded by the Energy Agency, of a Swedish nuclear centre of excellence with a focus on precisely the deployment of SMRs [56]. Also the Swedish Radiation Safety Authority (SSM) indicates that the regulatory authority, in order to promote radiation safety and the competence supply for future society, has to monitor innovations in the nuclear field. [119] Such monitoring can for instance be carried out by the authority following the development of small and advanced modular reactors in other countries, but will not lead to any substantial build-up of domestic competence in the area. Furthermore, opportunities to influence the focus of the research and development are limited. Monitoring of the area is also possible by the regulatory authority making funding available in selected areas.

In such a scenario, the authority could point to needs of research and development in selected fields, such as for instance the waste field.

Table 8.2 Overview of a number of selected SMR concepts being developed

MW(e) or MWe means electrical effect

Name	Comment	Fuel	Enrichment
Light water reactors, PWR			
ACP100 China [81, 33]	PWR. 100 MWe. Preliminary safety report is completed. Preparations for construction and design were initiated in 2019.	Enriched UO_2 fuel rods in 17x17 geometry. 2-year refuelling interval.	4.2 %
CAREM Argentina [72, 82]	PWR. 27 MWe. The project was initiated in the 1980s. The first prototype reactor is under construction and is expected to be commissioned in 2022.	Hexagonal fuel assemblies consisting of enriched UO_2 fuel rods.	<5 %
FlexBlue UK [83]	PWR. 160 MWe or 530 MW. Based on submarine design, is placed on the seabed and controlled from land.	Enriched UO_2 fuel rods in 17x17 geometry. Refuelling with ca. 3-year intervals.	<5 %
KLT-40S Russia [84, 85]	PWR. 35 MWe. Floating nuclear power plant that i.a. can be placed on remote sites. Connected to the electrical power grid for the first time in 2019.	Fuel rod consisting of e.g. (U238 + U235)O2, (U238 + Pu239)O2, (Th232 + U235)O2, (Th232 + U233)O2. Refuelling after 10–12 years.	18.6 %
NuScale USA [48, 86]	PWR. 45 MWe (160 MW). The first licensed SMR in the USA (2020). A facility with 12 modules is planned in Idaho.	Enriched UO_2 fuel rods in 17x17 geometry. Refuelling with ca. 2-year intervals.	< 4.95 %
RITM-200 Russia [85]	PWR. 2x50 MW(e) or 2x175 MW. Primarily intended (and already installed) for propulsion of icebreakers, but can also act as a stationary or floating power plant.	Enriched UO_2 fuel. The whole core is replaced after 60 months.	< 20 %
SMART Korea [70]	PWR. 100 MWe (330 MW). Obtained so-called "Standard Design Approval" by the Korean authority in 2012. The reactor is intended to be exported with the purpose to generate electricity and desalinate sea water.	Enriched UO_2 fuel rods in 17x17 geometry. Refuelling after ca. 3 years.	< 5.0 %

Name	Comment	Fuel	Enrichment
SMR-160 USA [25]	160 MWe underground reactor intended for simultaneous generation of electricity and hydrogen, district heating, or desalinated sea water. Preparation for the licensing process is under way.	Enriched UO_2 fuel rods in 17x17-geometry, which are replaced after 2 years.	4.95 %
Nuward France [25]	PWR. 2x170 MWe. A commercial model is planned for the end of the 2020s.	Enriched UO_2 fuel rods in 17x17 geometry. Refuelling after 2–3 years.	< 5.0 %
Light water reactors, BWR			
BWRX-300 USA and Japan [25, 87]	BWR. 270–290 MWe (870 MW). Licensing activities have been initiated in the USA, with the intention to build the first reactor around 2030.	Enriched UO_2 fuel rods of 92 fuel rods per bundle. MOX fuel (U+Pu) may also be used. Refuelling after 1–2 years.	< 4.95 %
VK-300 Russia [88]	Design based on known VK-50 (in operation since 1965). 2x750 MW or 2x(150–250) MWe. Intended for electricity generation and desalination.	Fuel design based on the one from WWER-1 000 reactors with enriched UO_2 fuel. Refuelling after ca. 1.5 years.	3.6 %
High-temperature gas-cooled reactors			
Energy Multiplier Module (EM^2) USA [25, 89]	Fast reactor intended to be operated with spent nuclear fuel. 265 MW(e) modular reactor.	Hexagonal fuel geometry consisting of uranium carbide. After 30 years the whole core is replaced.	< 15 %
GT-MHR Russia [90]	Evolution of a reactor that was developed jointly by the USA and Russia to eliminate nuclear weapons material. 286 MW(e) per module.	TRISO particles of uranium are formed into pellets and subsequently hexagonal fuel assemblies. Half the core is replaced after about 1.5 years.	< 20 %
HTR-PM China [33, 91, 92, 93]	Pebble-bed reactor. 10 MW test reactor has been in operation at Tsinghua university. The Demonstration reactor HTR-200 (210 MWe) is now being built now in Shidao Bay in Shandong province.	TRISO-coated UO_2 particles are formed into pebbles of 6 cm diameter. HTR-200 will have a core consisting of about 420 000 pebbles. The pebbles are continuously replaced when they have reached their final burnup.	Ca. 8,5 %
Micro Modular Reactor (MMR) Canada [94, 95]	15 MWt. The reactor will generate process heat for a nearby facility, where electricity and possibly heat is to be produced. The reactor undergoes licensing in Canada.	TRISO fuel (UO_2) in pellet form creates a cylindrical silicon carbide matrix. The reactor is expected to operate for 20 years without refuelling.	< 19.75 %

Name	Comment	Fuel	Enrichment
Xe-100 USA [96, 97, 98]	200 MWt. Can operate with load following.	Pebbles consisting of TRISO particles with enriched uranium (High Assay Low Enriched Uranium), but also Pu fuels are being considered (PuO_2, $(Th,U)O_2$, $(Th,Pu)O_2$) for disarmament purposes. Continuous refuelling of fuel.	15.5 %
Metal-cooled reactors			
4S Japan [99, 100]	Sodium-cooled fast reactor of pool type with a power of 10 or 50 MWe. Intended for electrification of remote sites.	Refuelling after 10 years (50 MWe) or 30 years (10 MWe). A number of different fuels can be used, e.g. metallic enriched uranium or plutonium from spent nuclear fuel (17.5–24 %).	<20 % U-235 or 17.5–24 % Pu
PRISM USA [101]	Was originally a 160 MWe sodium-cooled reactor intended to be self-sustained on fuel, but the focus is now on extraction of energy from spent nuclear fuel and burning long-lived radionuclides. The current model is at 311 MWe.	The reactor can be run for different purposes: for burning actinides, for an equilibrium between production and consumption of fuel, for creating more fuel than it consumes, or for burning weapon plutonium. The metallic composition of the fuel varies, as does the refuelling interval (1–2 years). In terms of form, the fuel elements are hexagonal. A pyro-processing facility for fuel recycling is required in the vicinity of the reactors.	Pu, between 11.3 and 17.2 %
SVBR-100 Russia [85]	100 MWe lead–bismuth-cooled reactor of pool type for electrical and process-heat generation. The reactor is based on principles from submarine reactors. A licence for construction and operation is expected before 2025.	The virgin core consists of UO_2 fuel. The whole core is replaced after 8 years, refuelling can take place with $(U\text{-}Pu)O_2$ or (U-Pu)N.	<19.6 %
SEALER/SEALER-UK Sweden [25, 53, 102]	Lead-cooled reactor in different variants. Proposed in the size 3–10 MWe for electricity generation in the Arctic areas, or in the size 55 MWe for connection to the existing electrical power grid.	Plans to use UN fuel in a hexagonal geometry. The reactor will be able to be operated for 10–30 years without refuelling, depending on the application. After that the reactor is considered to have reached its lifespan.	19.75 %
Molten salt reactors (MSR).			
IMSR Canada [103, 104]	Conceptual design finished 2015. Pre-licensing was initiated in 2017. Can generate district heating, hydrogen, industrial heat, etc. in addition to electricity.	Low-enriched uranium fluoride salt circulated through a graphite-moderated core. As the fuel is liquid, there are no fuel assemblies. The fuel in the salt can consist of low-enriched uranium fluoride, plutonium fluoride, thorium fluoride, or a mixture of these. The entire primary system is replaced after 7 years.	<5 %

Name	Comment	Fuel	Enrichment
LFTR USA [25]	250 MWe molten salt reactor that uses thorium fuel and a thermal neutron spectrum to create fuel during operation. The concept requires continuous reprocessing of the molten salt.	Fuel salt with fissile U233 circulates in the "driver" part of the reactor, while a "blanket" part contains fertile Th232 that forms U233. Reprocessing takes place during operation to separate the newly formed U233 and transfer it into the "driver" part.	
Molten Chloride Fast Reactor USA [105, 106]	"Breed and burn" reactor that first creates fissile material (from natural uranium, depleted uranium, or thorium) and then consumes it. Uses a fast neutron spectrum and does not require reprocessing.	Molten chloride salt that is based on U–Pu and Th–U cycles. The design requires refuelling of natural or depleted uranium.	<20 %
Stable Salt Reactor – Wasteburner (SSR-W) UK [107]	Fast reactor. Eight modules together deliver 750 MW (300 MWe). The system is intended to burn spent nuclear fuel and at the same time generate electricity. It can be noted that the same manufacturers also design molten salt reactors for U and Th cycles.	The fuel salt (60 % NaCl, 20 % reactor-grade $PuCl_3$, 20 % UCl_3 and lanthanide trichlorides) is fabricated from spent UO_2 fuel. Fuel refuelling during operation similar to that for CANDU reactors.	Reactor-grade Pu

Note: Note that the table is not at all intended to provide a comprehensive picture. The selection of systems and information stems mainly from [63] but has been supplemented somewhat.

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9 Nuclear waste, the responsibility towards future generations and the non-identity problem

9.1 Introduction

> The nuclear waste issue has other concerns besides bedrock types, groundwater flow, mechanical strength and welding methods. Nuclear energy and nuclear waste issues also relate to moral and ethical values and priorities: – Who is responsible for the safe disposal of the high-level waste? Should we wait for new and better technology to become available in the future? If not, which municipality and landowner should give up a site for a repository? What does the responsibility for future generations require us to do? [1]

These words are taken from the Swedish National Council for Nuclear Waste's state-of-the-art report 2004 (Klr 2004). The chapter was particularly focused on the latter issue of what the responsibility towards future generations means for the management of nuclear waste. Much has happened in this matter over the years that have gone by since then. The issue of responsibility towards future generations has more and more come to be about the climate issue, the global climate goals, and sustainable development. That is true for the public debate, but also the philosophical discussion.

A basic starting point for much of what has been written about responsibility towards future generations is that there is no difference between our responsibility for currently living people and for people belonging to future generations. If we harm another person in a remote part of the world, we are equally responsible as if we harm our neighbour. And if we harm some human in the future, it is equally bad as if we harm a human today. We may call this the idea of *symmetry of responsibility*.

The idea of symmetry of responsibility is also present in the background both for the climate issue and for the handling of the nuclear waste. In 1995, IAEA (the International Atomic Energy Agency) adopted basic principles for the handling of radioactive waste. [2] According to Principle 5, the waste is to be handled in a way "that will not impose undue burdens on future generations". This thought was developed in IAEA's 1997 *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*. Sweden has acceded to this convention. According to Article 1, the aim of the convention is among other things:

> ... to ensure that during all stages of spent fuel and radioactive waste management there are effective defences against potential hazards so that individuals, society and the environment are protected from harmful effects of ionizing radiation, now and in the future, in such a way that the needs and aspirations of the present generation are met without compromising the ability of future generations to meet their needs and aspirations. [3]

In the quote, no difference is made between the responsibility for currently living people and future generations. Somewhat cynically one may of course wonder if we have to do anything for the future – after all, it hasn't done anything for us! But this lack of symmetry has hardly any *moral* significance. After all, we have obligations to respect and show consideration towards other currently living people whom we do not know nor have any contact with. According to many moral philosophers, however, there are other asymmetries between currently living people and future persons. One of these was the British philosopher Derek Parfit (1942–2017). He was considered one of the most distinguished moral philosophers of the 20th century. In 2016 he visited Stockholm to receive the prestigious Rolf Schock Prize in Philosophy and Logic, awarded by the Royal Swedish Academy of Sciences, "for his ground-breaking contributions concerning personal identity, regard for future generations and analysis of the structure of moral theories". [4] Parfit published only two – albeit extensive – books during his lifetime (*Reasons and Persons*, 1984, and *On What Matters* in three volumes, 2011–2017), but they had a huge impact and have among other things influenced the recent decades' discussion about our moral obligation to take responsibility for climate change.

Parfit was entirely convinced that we have an inevitable responsibility towards future generations and a moral obligation to take measures against climate change. But he also thought that it was not all that easy to formulate a watertight moral theory that explains *why* we have this obligation. The issue has come under extensive and thorough philosophical discussion, in which also Swedish philosophers have been active. Two of these are professors Gustaf Arrhenius and Torbjörn Tännsjö. In a current article, they and Danish professor of ethics Jesper Ryberg review the current discussion and conclude that an acceptable theory about our responsibility towards future generations has not yet been formulated. [5]

9.2 Aim and layout

The *aim* of this chapter is to clarify in what way the present-day ethical discussion has treated the question about the responsibility towards future generations, and what this responsibility means for the nuclear waste question. Apart from the introduction and this presentation of aim and layout, the chapter contains ten different sections. In one section we give a theoretical background of the questions that the chapter will discuss, and we present the so-called non-identity problem. This is followed by a section with a brief analysis of the importance the non-identity problem has for the nuclear waste issue. It is followed by sections where the meaning of the so-called person-affecting principle is clarified and different basic approaches to the principle are explained. Then, an attempt at a solution to the non-identity problem is presented that also offers a robust moral justification for our responsibility towards future generations and the importance of a sustainable and persistent management of the nuclear waste. The chapter is rounded off with conclusions and a summary.

9.3 Theoretical background

In this initial section, we will first give a very brief presentation of some ethical fundamental concepts, and then give a short summary of the problem, namely the non-identity problem.

9.3.1 Ethical theory and method

In the 2004 ethics chapter, the meaning of certain ethical fundamental concepts and theories was described. To begin with, there is a general distinction between descriptive ethics and normative ethics, for example. *Descriptive ethics* can also be called value research and is carried out with the same empirical methods as e.g. in sociology and psychology. *Normative ethics* instead aims to study what is good and right and what one *should* do in certain situations – and why. The difference is important, since prevailing values about what is good and correct not always coincide with that which *actually* is good and correct and what one *should* do.

In the state-of-the-art report 2004, we refer to the American philosopher John Rawls and his book *A Theory of Justice* (1972), where he outlines a theory of how a good and just society should be designed. One of his basic ideas is that only such inequalities (e.g. as to income) should be accepted that favour the most deprived persons in society. But what are reasons for such a rule? Rawls argues that such a general rule can only be justified in interplay with the moral assessments or "intuitions" we have in concrete situations. We react spontaneously when a child is tormented before our eyes, when women are exploited in human trafficking, or when shop owners are forced to pay an organised crime syndicate for a "protection" they have not asked for. Against this background, we can ask the question if there are more general principles that explain these intuitions. Some particularly debated rules are *consequentialist* rules such as utilitarianism, and *deontological* principles such as Immanuel Kant's ethics or the idea of human rights. (We will return to this question later in the chapter.) Often, it turns out that our general principles do not quite "cover" our moral intuitions. If these basis rules do not "match" our moral intuitions, we have to adapt our basis rules – or modify our moral intuitions. Gradually, we hopefully achieve a so-called *reflective equilibrium* – even though we cannot expect this balance to be entirely unwavering.

An interesting question is now how we "get hold of" our moral intuitions. One way can be to formulate concrete dilemmas that pointedly challenge our thinking. Assume, for instance, that you find an expensive clock in the street. What do you do? What should you do? Most would of course reply that the right thing to do is to submit it to a police station or lost property office. This is quite a simple and easily solved example – but all examples are not equally simple. Certain examples instead describe moral dilemmas. They are not as easy to relate to. Here is such an example:

> *A train is about to drive over your sister who lies tied to one track. You have only so much time that you manage to pull a lever so that train will change tracks and thus not drive over your sister. Anyway, then you see that your best friend is tied to the other track. This friend saved you from death very recently. You can only save one of them. What would you do? [6]*

The aim of these and similar (often provoking) examples is actually not to solve the stated dilemma, but to direct the attention to certain, more general philosophical problems. In this chapter, we will address a number of more or less realistic examples, which among other things are about how we are to relate to future persons or generations. These examples sometimes challenge our moral intuitions and the moral rules that we believe these assessments to be based on. What does the interplay between individual assessments and general rules actually look like? Do the rules do justice to the assessments? Is there a reason to modify the basis rules? Should the moral judgements be reconsidered? The aim in the present context is to reach a reflective equilibrium between our moral feelings and certain general rules about our obligations to future humans.

9.4 The non-identity problem

Contemporary philosophical analyses of morality and justice take into consideration a previously overlooked question about the identity of people and how this affects the view on our responsibility towards future persons. The British philosopher Derek Parfit (1942–2017) clarifies this by means of different examples that have become much-debated in ethics. In several of these examples, Parfit proceeds from a genetic view of human identity (central characteristics). A person's central identity is the result of genes from their parents. The genes that decide a person's identity are defined by the woman's egg and the man's sperm with the genes that they have at the time of fertilisation. If the fertilisation had taken place a month earlier or takes place a month later, we get a different person with a different identity. One of Parfit's examples is about a woman who plans to conceive a child but is diagnosed with a health problem with consequences for her future child.

> *A woman longs for a child.* *At a doctor's visit, a woman is informed that she suffers from a temporary health problem. If she gets pregnant during the coming month, the child will get a congenital disease that can lead to a premature death. But if she waits for two months, her health problem will be resolved, and the child will be fully healthy with a normal life. For various reasons, the woman does not want to wait for two months. She therefore decides to have the child immediately. She becomes pregnant, and as the doctor predicted, she conceives a child with a disease that likely will shorten the child's life.*[1]

How should we morally assess the woman's choice? Most persons would perhaps think that the woman acts morally wrong if she chooses to have a child immediately. Parfit thinks so, too. But what would the woman answer to this criticism? She could say the following: "I don't think that I have done anything wrong. My future child will have a good life despite their disease and has all reason in the world to be grateful for existing rather than not existing. If I had waited with my pregnancy, another child without a congenital disease would have been borne. But *that child is not the same child who gets a shorter life than normally due to the congenital disease*. The child I will bear is another person than the one that would have been born if I had waited for two months. In other words, it is not the same child who will be worse off due to my choice to get pregnant now and would have been better off if I had waited two months. No harm is done to my child, because *one can only harm a person if one makes life worse for that particular person*."

Despite this, many of us still react negatively to the woman's choice. She ought to have waited with her pregnancy.[2] At the same time, she does have a point in that the child that she bears is a different child than the one she would have carried two months later. But does this really have any moral importance? Many of us probably think so. But if one can harm a person only if one makes life worse for exactly that person, then one cannot compare the child that she chooses to conceive immediately with the child that might have been conceived after two months. It is in this way the so-called *non-identity problem* arises. The problem consists in that there is a contradic-

[1] This version of the example is taken from [7, 8].
[2] In real life, it might have been insensitive to patronise the woman for her actions.

tion between the woman's conviction that she has not made any moral error and the opposite moral feeling that many of us others have.

9.5 The non-identity problem and the nuclear waste issue

Many may perhaps think that all this is just philosophical hair-splitting that does not have anything to do with real life. It is something which philosophers without any responsibility for concrete practical issues can speculate over. Why should people in general – and even more so, politicians – have to consider such issues? Furthermore, the woman's trouble with her pregnancy and her medical problem are very special and the non-identity problem is limited to very unusual situations. We can leave these issues to philosophical seminar discussions in their academic ivory tower.

But this reaction is premature. When one starts to get a grip on the non-identity problem, it starts to appear all around. It also has to do with burning current issues – for example, with the climate issue. [8] Here we will focus on how the non-identity problem has consequences for energy policy. We start with two new examples that highlight what this involves and what the problem means for the nuclear waste issue. (It should again be stressed that these examples are about unlikely situations and chosen following Derek Parfit's analysis only to highlight philosophical problems.) Here are two new examples about this issue.

> The negligent nuclear waste technician. *In connection with the deposition of nuclear waste, a nuclear waste technician is negligent while controlling a copper canister with spent nuclear fuel. After approximately 10 years, the canister starts to leak radioactivity and many persons suffer radiation injuries. Independent of his conduct, the same people will have been born during the time that has passed up to the accident and the people who are affected by his negligence would not have been affected if he had been more careful.*[3]
>
> Choosing a policy for the management of nuclear waste. *A country faces the choice between two different solutions to take care of the radioactive waste from its nuclear power plants. One alternative is to build a long-term safe geological final repository. A cheaper and quicker alternative is instead to postpone the decision about a final repository by approximately*

[3] The example is retrieved from Derek Parfit [9].

100–200 years and extend an existing interim storage facility and/or build a new one. The country chooses the latter solution with an interim storage, and after hundred years, a natural disaster strikes that causes the interim storage to be flooded. Radioactive material leaks and hundreds of persons suffer radiation injuries.

The most important point is the difference between these two examples. The second example with the choice of energy policy differs from the first example with the negligent nuclear waste technician. *The negligence of the nuclear waste technician does not have large-scale consequences for society*. The choice of energy policy, on the other hand, does. Industrial development leads to social changes, and sometimes even individual industrial projects can have comprehensive and far-reaching social consequences. One example is the establishment of the battery factory Northvolt in Skellefteå. [10] The social consequences of a final-repository project in Östhammar municipality has also been subject to different future studies. [11] Both projects will – if they are completed – lead to a development that influences the development and mobility of the entire population in the concerned regions. Without going into details, one can note that the choice of energy policy is about multi-billion projects with far-reaching social consequences. New industries, jobs and cultural meeting places arise, other people meet, form families and get children.[4] In the first case with the nuclear waste technician, these large social changes do not arise. If he had been more attentive in his work, *the same* people that are affected by his negligence would be spared their suffering. In the other case, the situation becomes different. If the country chooses a final repository, the result is that in a few hundred years, other people will be populating the region than if one chooses an interim storage. With a geological final repository, it is not the same people who avoid harm in a few hundred years as the people who are harmed with an interim storage. If one can harm a person only by making life worse for that particular person, those who are harmed by a leaking interim storage do not get a worse life – *they would simply not have come into being* if one had taken a decision for a geological final repository instead.

[4] See more about the socio-technical perspective in chapter 3.

9.6 The person-affecting principle

Let us consider the non-identity problem in more detail and particularly notice the importance that the so-called *person-affecting principle* has in this context – and how one can relate to this principle. It has been pointed out as the main reason for the non-identity problem's origin. We start with formulating an argument that clarifies the importance of the person-affecting principle. Thereafter, we go through three different basic approaches to this principle. Then we give some reasons against two of these approaches. Finally, we present the American philosopher Elizabeth Harman's version of the third basic approach. She argues the person- affecting principle is acceptable but does not lead to the conclusion that an energy-policy choice which entails that persons will be harmed by radioactive emissions is morally right.

9.7 The importance of the person-affecting principle

Irrespective of one's energy-policy opinion, everyone might agree on the following:

1. It is morally wrong to harm future persons.

   From (1), we deduce a more detailed evaluation:

2. There are moral reasons against the energy-policy choice according to the example, since this choice means that future persons are harmed.

   The following so-called person-affecting principle is also assumed to be true:

3. An energy policy harms future persons only if these persons come to be worse off than they would have been if the energy policy had not been realised.[5]

All these three statements seem self-evident – at least at first glance. That is also true for (3), the person-affecting principle. It is based on a more general principle, namely that *one causes a person harm*

[5] One can conceive of a weaker and a stronger version of (3). A stronger version means that an action harms another human only if it makes life worse for them. Here, we assume the stronger version and return to the weaker one below.

only if one makes life worse for that person. It has been problematised in philosophical ethics and we will soon return to this.[6]

When scrutinising these three statements, one may discover a logical problem. If (3) is true, then (2) must be false (or vice versa). Why? The reason is the following: The future persons who are affected by a leaking interim storage in a few hundred years, are *not* harmed in the sense that these persons are worse off than if another energy policy had been realised. If another energy policy had been chosen, *these people would not have existed at all!* They exist due to a certain energy-policy choice. In our example, this choice leads to a nuclear waste accident, but – and this is important – despite this accident, they still might be able to have lives that are worth living, live in good relationships to their fellow humans, and experience many joys in life. For this reason, no future persons would be able to blame us for having chosen an interim storage instead of a final repository. On the contrary, they should thank us for their existence! Therefore, no moral error has been committed. Even so, most have of us a definite moral conviction that the chosen energy-policy is wrong.

9.8 Three basic approaches to the person-affecting principle

The person-affecting principle is a key issue in the philosophical debate about the responsibility towards future generations. Space allows only a brief analysis of the discussion. Three different basic approaches can be distinguished.

According to the *first* approach, the person-affecting principle should be accepted. It means that the woman wishing for a child does not make any moral error if she chooses to become pregnant immediately instead of waiting two months to be on the safe side and giving birth to a healthy child. If one takes the example with the energy-policy choice as a starting point, the result is similar. If one decides for an interim storage and future persons are affected by a nuclear waste accident, still no moral error has been committed. Another energy policy would mean that they that are affected would not have been born at all. "*... one can only harm a person if one makes life worse for that person.*"

[6] The argument above is taken from [8a].

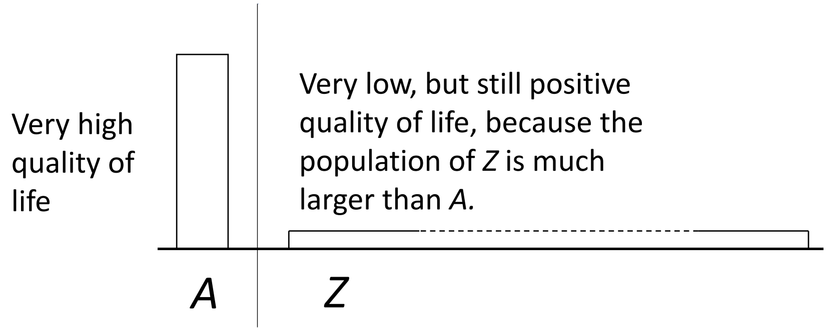
The other approach is based on substituting the principle with an impersonal rule that does not aim at specific persons but instead is about overarching and desirable conditions. Utilitarianism is the most prominent example. An action is morally right if it promotes well-being (or happiness, life quality or benefit) for as many as possible. The strength of utilitarianism is that it avoids the non-identity problem and at the same time gives a basis for taking a position e.g. on energy policy. Provided that the security issues are solved, one should choose a geological final repository and thereby avoid the risks with an interim storage. The reason is that it promotes the well-being of people better than other alternatives – at least better than the alternative with an interim storage.

The *third* approach simply questions whether (2) and (3) are as incompatible as it seems. One could at least maintain a version of the person-affecting principle *without therefore denying (2)*, i.e., that a certain energy policy is morally wrong if it harms future persons. From the view that the person-affecting principle in some form is true, it is not necessary to deduce that it is incompatible with (2).

9.9 How should one assess the different basic approaches to the person-affecting principle?

Of the three different basis approaches, there are evident problems with the two first ones. The first approach accepts the person-affecting principle according to (3). Thereby, one collides head-on with our moral intuition that an energy policy that risks harming future persons in around 100–200 years is morally wrong. There are those who think that we cannot avoid this dissonance and that we therefore, in this respect, must revise our moral thinking. Something similar applies also to the second approach, which entails that one simply dismisses the principle and replaces it with e.g. an utilitarian rule. Unfortunately, this approach leads to new problems. One of these is what Parfit calls the *repugnant conclusion*. Let us assume two societies A and Z. In society A, there is a small number of people who on average have a very high level of happiness. Society Z consists of a much larger number of people who are not as happy at all, but who collectively still achieve a higher level of happiness than society A. Therefore, according to utilitarianism we should prefer society Z to society A. This is the repugnant conclusion. The large number of people in Z results in Z obtaining a collective level of happiness that is higher than the much smaller society A with very high quality of life.

Figure 9.1 The repugnant conclusion – according to utilitarianism, society Z is better than society A [5]



The figure shows the repugnant conclusion – according to utilitarianism, society Z is better than society A [5].

How should we respond to the repugnant conclusion? The best would of course be that we found some alternative to utilitarianism that did not entail a repugnant conclusion. Parfit calls this solution theory X. Several candidates for X have been suggested, and in his doctoral thesis, Gustaf Arrhenius conducted a review of the state of discussion 20 years ago. [13] His prognosis for finding a timely and sustainable solution was pessimistic. The development since then has proven him right; a consensus about what X could look like has not been reached.

In the section about our responsibility towards future generations in the *Swedish National Council for Nuclear Waste's state-of-the-art report 2004*, the starting point is taken in a theory of justice. It is a combination of a strong theory (in the short term for nearby generations) and a weaker variant (also for generations later on). The weaker theory of justice implies that "we have a moral obligation to use the natural resources in such a way that not only people living now, but also future human generations can meet their basic needs."[7] A problem with this theory of justice is that it includes a utilitarian component. We should act in such a way that we fairly satisfy basic human needs. The need for a happy life is one example which according to utilitarianism we should seek as much as possible. Therefore, this theory of justice does not avoid the repugnant conclusion.

9.10 Harman's solution

The third basic approach means that one maintains the person-affecting principle. The principle is admittedly not comprehensive and may need to be modified. In that case, it need not be incompatible with (2), i.e., that a certain energy policy is morally wrong if it harms future persons. There are several specialisations of this view. [12a] We will particularly focus on the American philosopher Elizabeth Harman's argument. [8] [8]

Harman accepts the starting point of the non-identity problem. It is true that the persons who would be harmed if one chooses an interim storage today, are not the very people who come to exist if one chooses a geological final repository. She also accepts the person-affecting principle and dismisses all impersonal principles in the form of e.g. utilitarianism. She writes: "There is harm in non-identity cases, and this harm explains the wrongness of actions." [8b]

Harman takes as her starting point an example that does not seem relevant in the context, but which turns out be significant and clarifies an important point. The purpose of the example is to highlight how an action assumes a weighting of reasons for and against:

> *A physician cuts a hole in my abdomen to remove my swollen appendix. Cutting open the abdomen cause me pain (when I recover); but if the surgery had not been carried out, I would have suffered greater pain and died very soon. [8c]*

The physician is right to execute the surgery. The patient is not harmed; rather, she is healed. But that is a simplified description of the situation. The actual procedure does harm the patient and is a

[7] The stronger principle of justice implies that "[w]e have an obligation to utilise or consume natural resources in such a way that later human generations can be expected to achieve an equivalent quality of life to that we have ourselves." [1a]

[8] Harman's solution to the non-identity problem is based on an example that partly differs from the one we have been starting from in this context, but the difference is not important.

reason *against* surgery. But there is also reason *for* carrying out the procedure. The patient would have suffered and died if the procedure had not been carried out. And this reason *for* weighs heavier than the reason *against*. The surgery is therefore morally acceptable – not to say, necessary.

Against this background, we can return to the example with the choice of energy policy. According to the example, the decision to choose an interim storage instead of a geological final repository has the consequence that a number of people will suffer radiation damage in – let us say – 200 years. The nuclear waste decision today causes suffering, death, physical injury and handicap later on. This is a reason *against* the decision. The decision is morally wrong since it – indirectly – causes harm. There is thus reason to refrain from such a decision. There is admittedly also a reason *for* the decision: we want to get rid of the nuclear waste problem and at least find a temporary solution while awaiting a final disposal in around 100–200 years. But this is hardly an argument that outweighs the harm that results from such a decision. Therefore, the decision is still morally wrong.

There is an objection against this line of reasoning. The decision to build an interim storage admittedly harms a number of persons in the future, but it is also something positive for them. Everything that they will experience in terms of joy, community, enjoyment, all this they would miss out on with another decision; for the decision is – as we have observed several times – a precondition for their being born at all. This is a reason *for* the decision, but it is not a *sufficient reason*. While there are these positive consequences, there are also, as was just stressed, the negative ones. The same future people who get to experience much good in life, will also to be affected by radiation injuries. At the time of the decision, we do not know which and how many will be harmed, but we can hardly be unaware that an accident is possible and perhaps more probable than if we had chosen a geological final repository.

Harman's argument results in the following two conclusions. *First*, an action harms a person if the action causes suffering, death, physical injury or handicap, *even if they would not have existed if the action had not been carried out*. The italicised clause does not conflict with the person-affecting principle (albeit in a weaker form than (3) above under 9,7). [8] An action harms a person if it makes life worse for just this person *even if they would not have existed if the action* *had not been carried out*.[9] Here is another example: a careless driver injures a woman who plans to become pregnant. As a consequence of the accident, the pregnancy is postponed. Later on, she bears a child who gets worse preconditions in life as a consequence of the woman's injury. The child would not have existed if the accident had not happened. The action is still morally wrong not only because the woman has been harmed, but also because the child gets worse preconditions in life.

Secondly, we have an obligation not to harm if a harm cannot be outweighed by larger advantages for the one who is harmed. This obligation also applies "when there is an alternative where parallel advantages can be achieved without parallel harm". [8] This means that a surgery is morally wrong if a patient can recover in another way than through a surgical procedure. It also means that a solution of the nuclear waste problem is morally wrong if we can protect ourselves and future generations without harming – or risking to harm – any persons.[10]

9.11 Ethical conclusions

In our view, the conclusion becomes that one should maintain a person-affecting principle – that an action harms a person if it makes life worse for that person. We harm an individual if the action causes suffering, death, physical injury or handicap, even *if they would not have existed if the action had not been carried out*. And we are morally obliged not to harm other persons if there are no major advantages for the concerned persons and these outweigh the harm, or if there are alternative actions that achieve these advantages without harm. This is – put briefly – one of the most important moral grounds for our responsibility towards future generations. (In the state-of-the-art report 2004 [1], we also consider if there are other moral grounds.).

As has been stressed earlier, the chosen examples are made-up and chosen following Parfit's analysis in order to highlight philosophical problems with our responsibility towards future genera-

[9] See more in the chapter on the Aarhus Convention, chapter 4.

[10] Gustaf Arrhenius has written an article that treats different objections against the principle. [12b] Reproducing and responding to this special discussion would take us too far afield. Here, it suffices to note that Arrhenius in a summary of the article admits that certain designs of the person-affecting principle (so-called soft comparativism) can have advantages over the impersonal basic approach.

tions. If we leave the fictitious world of the examples and instead turn to our current situation, we can ask the question *what importance the stated moral ground for our responsibility towards future generations has for the proposal regarding a final repository for the Swedish nuclear waste*. The question has two replies.

The first reply is about that the moral ground precludes every form of devaluation of our responsibility towards future generations relative to our responsibility for currently living people. Only because a human – or a generation of humans – lives further or a long time in the future, our responsibility for these humans does not decrease (insofar as they are affected by our actions today).

The second reply is about what demands this puts on our actions and particularly on a final-repository decision. *We are obliged not to harm unless the harmful action has major advantages that outweigh the harm, and if there are alternative actions that achieve these advantages without harming*. In theory, these requirements are unambiguous. They mean – put briefly – that a final-repository decision must be taken with regard to fundamental radiation protection requirement. These are established in the Swedish Radiation Safety Authority's (SSM's) regulations and are the point of departure for the Swedish Nuclear Fuel and Waste Management Co's (SKB's) final repository application. That way we protect future people against suffering, premature death, physical injury or handicap. In practice, the situation is of course much more complicated. It is subject to the review process that the final-repository application has gone through and will go through in a future stepwise licensing process. Morality does not float above this reality; it is woven into these processes, which also hold uncertainties regarding future scenarios. Moral reflection constitutes an inevitable part of the scientific and policy work in the management of the spent nuclear fuel. Or as a Swedish philosopher, Sven Ove Hansson, once expressed it: morality is not only a spice on the food, but part of the actual dish.

9.12 Summary

The aim of this chapter has been to clarify in what way the current discussion of fairness and morality can highlight what the responsibility towards future generations entails for the nuclear waste issue.

This discussion has substantially been based on the British philosopher Derek Parfit's thinking and on what he calls the non-identity problem. The problem arises when we do not pay attention to the existence of a morally important asymmetry between our responsibility for currently existing persons and future persons. Large-scale technology decisions such as a choice of energy policy that completely other people are born in the future than if such a decision is not taken. There are those who from this draw the conclusion that we do not have responsibility towards future generations in the same way as we have responsibility for currently living and identifiable humans. This comes into conflict with basic moral intuitions, for instance, that it is morally wrong to expose future generations to radioactive risks. We can either live with this inconsistency, or we can seek to formulate moral principles that correspond to our moral intuitions and that at the same time can form a basis of measures for an active responsibility towards future generations.

A closer analysis of the importance of the non-identity problem for the nuclear waste issue shows the central role that the so-called person-affecting principle plays. That principle means that an action can harm a person only if the action makes it worse for that person. The principle seems completely self-evident but on closer inspection turns out to have several problems. Three solutions to these problems are discussed. According to the *first* one, the person-affecting principle is maintained even if it leads, among other things, to a relativization of our responsibility towards future persons, and the importance of safe and sustainable handling of the nuclear waste. The *second* solution wants to replace the principle with an impersonal rule of a utilitarian character. The problem is that this morality principle leads to a repugnant conclusion, and it has been difficult to find a solution to this problem. A *third* solution – stated by the American philosopher Elizabeth Harman – entails modifying the person-affecting principle but at the same time questioning if that really has to lead to a relativization of our responsibility towards future persons. Harman tries to show that on the contrary, our responsibility gets a sustainable moral justification. An action harms a person if the action causes suffering, death, physical injury or handicap, *even if they would not have existed if the action had not been carried out*. We are morally obliged not to harm other persons if there are no major advantages that outweigh that harm or if there are alternative actions that achieve these advantages without harm.

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PART 2

10 The Swedish National Council for Nuclear Waste's work and the nuclear waste field

10.1 The Council's work in 2020 and 2021

10.1.1 The current terms of reference

The Swedish National Council for Nuclear Waste's (the Council) activities are regulated and steered by instructions in its directives. According to the 2018 supplementary directives, the Council shall every other year publish and report the work of the preceding two years and its independent assessment of the current state of knowledge in the field of nuclear waste, which is what is done in this report for the years 2020 and 2021. [1]

According to the to the directives, the Swedish National Council for Nuclear Waste shall investigate and shed light on issues relating to the management and final storage of nuclear waste and spent nuclear fuel, and the decommissioning and dismantling of nuclear facilities. The Council shall also advise the Government in these matters. Other important target groups are concerned authorities, the nuclear power industry, municipalities, interested organisations and politicians, as well as mass media. The Council works with and for its target groups in various ways including via publications, meetings, seminars and via its website. [2] The Council's mission is valid through 31 December 2022 and can then be extended at most five years at a time.

10.1.2 Publications and communications

In accordance with its directives, the Swedish National Council for Nuclear Waste shall publish a state-of-the-art report every other year. The Council shall also, in a separate pronouncement, publish its own assessment of the reactor owners' research programme (RD&D programme) that is presented every three years. Both the Council's publications are published in the series Statens Offentliga Utredningar (SOU, Public Studies of the State). The Council's mission also includes responding to documents circulated for comment by the Government and various regulatory authorities. Information on the Council's publications that have been published during the years 2020 and 2021 is found below. (All are available for download on the Council's website [3]).

State-of-the-art reports 2020 and 2022

In February 2020, the Council published the state-of-the-art report SOU 2020:9 *Step by step – Where are we now? Where are we going?* [4] The report's chapters shed light on different issues based on the Council's inter-disciplinary perspective.

A prerequisite for the project of constructing and operating a final repository for spent nuclear fuel to succeed is that appropriate competence exists within the fields of nuclear power and nuclear waste. The initial chapter "Long-term competence management within the nuclear waste field in seven European countries with commercial nuclear power plants", describes a survey regarding the state of competence and the national strategies in Sweden and six European countries with a commercial nuclear power.

The chapter "Stepwise licensing and beyond – process and reflections" has to do with the different phases of the stepwise licensing and up to the final closure. The Council writes that there are uncertainties regarding how the existing regulation can be adapted to the special conditions that apply for the construction and operation of a final repository for spent nuclear fuel.

The chapter "Modern2020 – the state of the art in monitoring" gives an overview of the state-of-the-art on the basis of the international research project concerning monitoring, Modern2020.

Questions relating to the canister and long-term safety are addressed in the chapter "Development of barriers – the state-of-the-art regarding the integrity of the copper canister".

The chapter "Nuclear waste and the public" describes an investigation that the Council has carried out of the public's perception to and knowledge of the Swedish nuclear waste.

Some initiatives regarding information and knowledge preservation are described in the chapter "Remembering a final repository".

Furthermore, there is the chapter "Nuclear waste and good technology", which is a synthesis of the previous chapters.

The Council presented the state-of-the-art report from the year 2020 to Minister of the Environment, Isabella Lövin, in February 2020. Due to the corona pandemic, however, the planned seminar about the state-of-the-art report could not be held. The Council therefore published on its website, six information leaflets during the summer and autumn of 2020, which describe the different chapters of the state-of-the-art report. [3]

During the years 2020 and in 2021, the Council's members have been working on the present state-of-the-art report 2022.

Publication and handover of the Swedish National Council for Nuclear Waste's Review of SKB's RD&D Programme 2019

Every three years, the reactor owners, through Swedish Nuclear Fuel and Waste Management Co (SKB), publish their research programme. The Swedish Radiation Safety Authority (SSM) reviews the programme and after public consultation, comments from other actors are included in SSM's pronouncement and review report. [5] SKB published its latest research programme in September 2019. On 30 June 2020, the Council submitted to the Government its assessment of the research programme: SOU 2020:39 *The Swedish National Council for Nuclear Waste's Review of SKB's RD&D Programme 2019*. [6] In conjunction with this, also an information leaflet was published with the Council's recommendations in brief. [3] The Council asserts that comprehensiveness, openness and transparency are important for the sake of safety. One of the Council's recommendations to the Government in its review is that research, development and demonstration (RD&D) are presented in the RD&D programmes in the future, both for non-licensed activities and for licensed activities. An open RD&D process is a democratic issue at the same time as it contributes to a broadening of the level of knowledge.

Responses/pronouncements and communications

The Council has in the years 2020 and 2021 responded to a number of documents circulated for comment from the Government, SSM and the National Debt Office. During the period, the Council has also sent communications to various actors/authorities (all in Swedish). What was sent and to which actors and organisations is mentioned below. The pronouncements and communications include responses to documents circulated for comment and questions relating to the final repository for spent nuclear fuel, maintenance of competence, the nuclear waste fees, and SSM's new regulations. The pronouncements below (in italics), and all other communications, are published on the Council's website.

Responses to the Ministry of the Environment on the final repository for spent nuclear fuel

The Council has responded to two documents circulated for comments from the Ministry of the Environment relating to the content in SKB's application for a final repository for spent nuclear fuel and supplementary material for the application (October 2021, June 2020). See more on these documents circulated for comment below under the overview of the field of nuclear waste (section 10.2).

After the reactor owners had warned about the interim storage facility (Clab) soon reaching its maximum storage capacity, the Council (March 2021) sent a communication about the possibility to separate the application for an extension of the capacity in Clab from an application for the final repository for spent nuclear fuel. In July 2021, the Council was sent this issue for comment. The Government took a decision on licence for extension of Clab separately from the licence application for a final repository for spent nuclear fuel, on 26 August 2021, see more below under the overview of the field of nuclear waste (section 10.2).

- *Kärnavfallsrådets svar på Remiss angående kopparkorrosion och gjutjärn när det gäller Ärenden om tillåtlighet enligt miljöbalken och tillstånd enligt lagen om kärnteknisk verksamhet till anläggningar i ett sammanhängande system för slutförvaring av använt kärnbränsle och kärnavfall* [The Council's response to Document circulated for comment regarding copper corrosion and cast iron when it comes to Cases on permissibility under the Environmental Code and a licence under the Nuclear Activities Act for facilities in a connected system for final storage of spent nuclear fuel and nuclear waste] (October 2021). Read more about this pronouncement below.
- The Council also sent in a communication to the Government regarding that the final repository for spent nuclear fuel is to be examined in separate legal processes under two different laws (March 2021). The communication discusses i.a. the question whether the Government can break out the licence application on increasing the capacity in Clab from the overall application.
- *Kärnavfallsrådets yttrande gällande "Ärenden om tillåtlighet enligt miljöbalken och tillstånd enligt lagen om kärnteknisk verksamhet till anläggningar i ett sammanhängande system för slutförvaring av använt kärnbränsle och kärnavfall"* [The Council's pronouncement regarding "Cases on permissibility under the Environmental Code and a licence under the Nuclear Activities Act for facilities in a connected system for final storage of spent nuclear fuel and nuclear waste"] (July 2021).
- *Kärnavfallsrådets yttrande angående Komplettering i regeringens ärenden angående Svensk Kärnbränslehantering AB:s ansökningar om tillstånd till anläggningar i ett sammanhängande system för slutförvaring av använt kärnbränsle och kärnavfall* [The Council's comments on the supplement in Government's matters concerning Swedish Nuclear Fuel and Waste Management Co's applications for licences to facilities in a connected system for final storage of spent nuclear fuel and nuclear waste] (June 2020).

Miscellaneous to the Ministry of the Environment

The Council has also sent the following pronouncements (in italics) and other correspondences to the Ministry of the Environment:

- *Kärnavfallsrådets svar angående remiss av promemorian ”Ändrade förutsättningar för att betala ut medel från kärnavfallsfonden”* [The Council's response regarding document circulated for comment on the memorandum "Changed circumstances for paying out money from the Nuclear Waste Fund"] (September 2021).
- Kärnavfallsrådets synpunkter på Svensk Kärnbränslehantering AB:s bemötande av Strålsäkerhetsmyndighetens granskningsrapport och Kärnavfallsrådets yttrande över Fud-program 2019 [The Council's comments on the Swedish Nuclear Fuel and Waste Management Co's reply to the Swedish Radiation Safety Authority's review report and the Council's review of the RD&D Programme 2019] (November 2020).
- *Kärnavfallsrådets yttrande angående en ny och uppdaterad förordning om ansvar och ersättning vid radiologiska olyckor* [The Council's pronouncement regarding a new and updated ordinance on responsibility and compensation in the event of radiological accidents] (October 2020).
- In October 2020, the Council sent a communication to the Ministry of the Environment concerning future competence management.

Responses to the Swedish National Debt Office (RKG)[1]

(In section 10.2 below on the nuclear waste field, there is more information about RKG's proposals for nuclear waste fees.) The Council has during the period sent the following pronouncements to RKG:

- *Kärnavfallsrådets yttrande gällande Remiss av Riksgäldens förslag på kärnavfallsavgifter, finansierings- och kompletteringsbelopp för 2022–2023* [The Council's pronouncement regarding the document circulated for comment on the Swedish National Debt Office's proposal for nuclear waste fees, financing and the supplementary amount for 2022–2023] (August 2021).

[1] https://www.riksgalden.se/en/our-operations/financing-of-nuclear-waste-management/ (hämtad 2022-08-19).

- *Kärnavfallsrådets yttrande gällande Riksgäldens remiss angående Riksgäldens beräkningsmodell för kompletteringsbelopp* [The Council's pronouncement regarding the Swedish National Debt Office's document circulated for comment regarding the National Debt Office's computational model for the supplementary amount] (May 2021).
- *Kärnavfallsrådets remissvar angående Riksgäldens förslag på kärnavfallsavgifter, finansieringsbelopp och kompletteringsbelopp för 2021* [The Council's response to document circulated for comment regarding the Swedish National Debt Office's proposal for nuclear waste fees, financing amount and supplementary amount for 2021] (August 2020).

Responses to the Swedish Radiation Safety Authority (SSM)

The Council has responded to documents circulated for comment regarding SSM's updated regulations, the draft for a National plan, as well as a national strategy for competence management (about which the Council previously sent a correspondence, see also correspondence regarding competence, to the Ministry of the Environment above).

- *Kärnavfallsrådets remissvar angående Strålsäkerhetsmyndighetens förslag om nationell strategi för Sveriges kompetensförsörjning inom strålsäkerhetsområdet* [The Council's response to document circulated for comment concerning the Swedish Radiation Safety Authority's proposal regarding a national strategy for Sweden's competence management within the radiation safety field] (November 2021).
- *Kärnavfallsrådets remissvar angående Strålsäkerhetsmyndighetens förslag till föreskrifter om omhändertagande av kärntekniskt avfall* [The Council's response to document circulated for comment concerning the Swedish Radiation Safety Authority's proposed regulations for management and final storage of nuclear waste] (April 2021).
- *Kärnavfallsrådets remissvar angående Strålsäkerhetsmyndighetens förslag till föreskrifter om konstruktion och drift av kärnkraftreaktorer samt värdering och redovisning av strålsäkerhet för kärn-*

kraftsreaktorer [The Council's response to document circulated for comment concerning the Swedish Radiation Safety Authority's proposed regulations for construction and operation of nuclear reactors as well as evaluation and reporting of radiological safety for nuclear power reactors] (February 2021).

- *Kärnavfallsrådets synpunkter på Strålsäkerhetsmyndighetens (SSM) utkast av rapporten Nationell Plan för ansvarsfull och säker hantering av använt kärnbränsle och radioaktivt avfall (Nationell plan)* [The Council's comments on the Swedish Radiation Safety Authority's (SSM's) draft of the report National Plan for the responsible and safe management of spent nuclear fuel and radioactive waste (National plan)] (February 2021).

Responses to other actors

- The Council's response regarding the nuclear power municipalities' cooperation body's communication (KSO) (May 2021).

10.1.3 Seminars and meetings

In accordance with the directives, the Council shall investigate and shed light on important issues in the nuclear waste field, for example by holding hearings and seminars.

Due to the corona pandemic, the Council has only carried out one open seminar in 2020 and 2021. On 30 November 2021 the Council arranged a seminar concerning cast iron, the material that is used for the copper canister insert. In order to increase dissemination, the seminar was recorded and published on the Council homepage. [7, 8]

Hannu Hänninen (expert in the Council) and Ville Björklund, both from Aalto University, held a presentation (in English) on the "Effects of embrittlement mechanisms on mechanical performance of nodular cast iron". Hasse Fredriksson, KTH, held the presentation "An optimal casting process – for optimal properties". Bo Strömberg, SSM, gave a "A look back on the Swedish Radiation Safety Authority's review of the nodular cast iron insert". SKB was invited to have a presentation and/or participate in the seminar but declined.

All meetings with other actors during the two years have been carried out digitally instead of physically due to the corona pandemic. The Council has held coordination meetings with the Ministry of the Environment and the Swedish Radiation Safety Authority (SSM).

In December 2020, the Council conducted a digital round table meeting with the municipalities of Östhammar and Oskarshamn. In March 2021, a digital round table meeting was carried out with representatives of environmental organisations (NGOs) active in the nuclear waste field.

On 28 April 2021, representatives from the Council participated in a meeting with the former Minister of the Environment and Climate, Per Bolund. The purpose of the meeting was to present the Council and its responsibilities. Questions concerning the future, competence management and information preservation were discussed, among other matters.

On 24 August 2021, representatives of the Council had a meeting with the Ministry of the Environment and the Prime Minister's Office and among other things presented the Council's proposals for conditions and canister issues.

10.1.4 Global perspective

In accordance with the directives, the Council shall keep track of other countries' programmes for final storage in terms of the management of nuclear waste and spent nuclear fuel. The Council should also monitor and, where necessary, participate in the work of international organisations on the nuclear waste issue. Due to the corona pandemic, the Council did not participate in place in any international meetings or conferences over the years 2020 and 2021.

The Council monitors and participates in a couple of international working groups in the OECD/NEA (Nuclear Energy Agency). In the working group Forum on Stakeholder Confidence (FSC), Sweden is represented by the Council, together with SSM and SKB. The Council is participating in a working group on Information, Data and Knowledge Management (IDKM), where also SKB, SSM, the

National Archives and representatives from municipalities have participated on behalf of Sweden.[2]

The Council is keeping track of various areas, some examples are listed below.

Decommissioning and dismantling

According to the directives, the Council shall investigate and shed light on issues relating to the management and final storage of nuclear waste and spent nuclear fuel, and the decommissioning and dismantling of nuclear facilities.

In previous years, the Council has visited different countries for example to follow these issues, but due to the corona pandemic, this has not been possible in 2020–2021. A study visit for Barsebäck was scheduled but had to be postponed. The Council has added general information on decommissioning and dismantling on its website (in Swedish).

Reaching out to young adults

In Almedalen 2019, the Council organised the seminar "Vad tänker de unga om kärnavfallet – och vad vill de veta? [What do young people think about nuclear waste – and what do they want to know?]". Before the corona pandemic the Council had plans to continue the work with reaching out to young adults via for instance lunch seminars at universities, about nuclear waste. A seminar at Chalmers was scheduled in the spring of 2020, but it had to be postponed.

In some countries, it is an issue receiving considerable attention that younger people who are to take over the nuclear waste issues in the future have to know that those issues exist. For instance, in the autumn of 2021, the OECD/NEA FSC group (Nuclear Energy Agency, Forum of Stakeholder Confidence) published the brochure "Intergenerational connections in radioactive waste management: Involving children and youth", where one can read about the initiatives that have been taken in several countries. [9]

[2] Read more about IDKM in [4].

Information preservation

Above, the working group IDKM is mentioned, whose focus includes how it is possible to handle the preservation of information and knowledge for a very long time. In the years 2020 and 2021, IDKM has had a number of digital meetings which the Council has attended.

The Council has several times pointed out that information preservation is an important issue, and in its letter of appropriation 2021, SSM was given the task to give an account of how different methods for information and knowledge on the final repository for spent nuclear fuel can be ensured over a long period of time. In October 2021, SSM published the report SSM 2021:24 *Metoder för överföring av information och kunskap om slutförvar för radioaktivt avfall* [Methods for transfer of information and knowledge of the final repository for radioactive waste]. [10] In the report, SSM gives an account of the strategies and methods that are described in international collaborations and the work that has been carried out within the field in Sweden and in other countries.

10.2 The nuclear waste field in Sweden in 2020–2021

10.2.1 The licensing process for the final repository for spent nuclear fuel

The Government's decisions on permissibility and a licence for a final repository for spent nuclear fuel that were taken the 27 January 2022 [11, 12] arrived in the absolute final phase of the work on this state-of-the-art report. The Council has therefore not had the decisions as a basis in the early and over all planning and writing process. The comments on government decisions included in e.g. chapter 1 here, were possible to include at the final stages of preparing the state-of-the-art report.

Below follows general information on the government decisions and what has happened in the process, from 2020 up to 27 January 2022.

The decisions on 27 January 2022 and the continued process

The decisions were possible to take after SKB´s application, under the Environmental Code (1998:808), was supported by the municipal council of Oskarshamn in 2018 and the municipal council of Östhammar in October 2020, based on the so-called right of veto in the Environmental Code. The Government set one condition for permissibility under the Environmental Code and five for a licence under the Nuclear Activities Act, see more about the decisions in Chapter 2 in the present report.

Now that the Government has given permissibility under the Environmental Code, the court will hold a second main hearing and give a licence in accordance with the Government's decision. The court also decides on conditions under the Environmental Code in addition to the one the Government put forth in January 2022.

After the Government now having given a licence under the Act (1984:3) on Nuclear Activities (the Nuclear Activities Act) and decided on five conditions, making additional conditions for the activity is being delegated to SSM. The conditions that SSM announces are based both on the Nuclear Activities Act and on the Radiation Protection Act.

According to the conditions now set by the Government, a stepwise licensing process under the Nuclear Activities Act starts. In the stepwise licensing process SKB needs approval by SSM prior to the construction, prior to trial operation and prior to standard operation of the final repository. According to SKB's calculations, the entire project up to the time of closure, will take about 70 years.

Information on the process up to a decision

The nuclear waste issue has during the period been more topical in the public debate than in previous years. During 2020 and 2021, a number of interpellation debates[3] have been held in the Swedish Parliament on final storage of spent nuclear fuel, and the issue has attracted attention in daily newspapers.

[3] Interpellations are a type of questions that are debated in the chamber. The member poses the interpellation in writing to a minister in the Government and receives answers both in writing and verbally by the minister, who comes to the chamber. Debates are documented in the chamber's minutes.

Below some aspects are briefly described that were part in the Government's examination:

- two referrals to the public
- one referral to SSM and the Council regarding canister issues
- Espoo consultation in 2021
- separation and approval of the application for extension of Clab.

Two referrals to the public – response dates June 2020 and January 2022

SKB submitted its applications under the Environmental Code and the Nuclear Activities Act in 2011. After preparing the applications, the Land and Environment Court and SSM submitted their respective pronouncements to the Government in January 2018. After that, it has been up to the Government to make decisions on the applications. SKB submitted supplementary information in April 2019, which were circulated for comment and responded to by a number of authorities and other actors during the autumn of 2019. [13] The Government announced the supplements, and also the public had an opportunity to submit opinions in June 2020. [14]

The Government once more announced the application in December 2021 so that the public would have another opportunity to submit their views prior to the Government's decisions on 27 January 2022. New material was included in the announcement, as the Government had received more consultation responses. Among other things, SSM and the Council received a document for comment from the Government in the autumn of 2021, regarding canister issues, which is described below.

Documents circulated for comment on uncertainties about the cast iron's properties and the copper canister's ability to isolate the nuclear waste in the long term

On 23 September 2021 the Government sent a referral, with two supporting documents, to the Council and to SSM, to receive comments on the remaining uncertainties when it comes to the properties of the cast iron and to the copper canister's ability to isolate the nuclear waste in the long term. *One* of the supporting documents was an article from the scientific journal *Corrosion Science* 184, 2021, which describes how metallic copper of the type that is intended to be used in the copper canisters for the final repository can corrode in the presence of sulfur compounds. [15] The *other* supporting document was a Finnish master's thesis on new Finnish research on the properties of cast iron. [16]

The Government also requested comments on the so-called LOT tests at the Äspö Hard Rock Laboratory. (Regarding the discussion concerning LOT tests, see e.g. [17, 18]).

Below are summaries of the Council's responses (see above, pronouncement of October 2021) to the three parts of the referral [19]:

- According to the Council, the paper in *Corrosion Science* does not contain any new findings regarding stress corrosion cracking under repository conditions that alter the state of knowledge regarding the assessment of the copper canister's long-term integrity. Furthermore, the Council proposes to the Government to stipulate as a condition in the event of permissibility for operation of a final repository for spent nuclear fuel, that SKB carries out new experiments to specifically study copper corrosion under repository conditions.
- Master's thesis: The Finnish research provides new knowledge on the properties of the cast iron. However, there are still uncertainties regarding the cast iron's properties in relation to the copper canister's ability to encase the nuclear waste in the long term. At the present time it is not possible to quantify these as small or significant.
- The LOT tests: The results from the LOT tests with regard to copper corrosion do not provide new knowledge regarding the long-term integrity of the copper canisters under repository conditions. The reason lies in weaknesses in the study design with respect to the durability of the copper canisters.

The Government's decision on increasing storage capacity in Clab (the central interim storage facility for spent nuclear fuel)

The Government took a decision on permissibility under the Environmental Code and a licence under the Nuclear Activities Act for increasing the storage in Clab to 11 000 tonnes of spent nuclear fuel, on 26 August 2021. [20]

The background is that SKB has a licence to store 8 000 tonnes of spent nuclear fuel and reactor core components in Clab, and that the reactor owners have warned that the interim storage facility will reach these 8 000 tonnes in 2023. According to SKB, it is possible to increase the storage in existing pools to 11 000 tonnes of spent nuclear fuel by means of relatively simple measures in the facility. [21]

SKB has emphasised that Clab is part of a connected system for managing and final storage of the nuclear waste. A request for an increased storage capacity in Clab was not included when SKB submitted its application in 2011, though, but was added in 2015. [22]

The Council sent a communication in the spring of 2021 on it being possible for the Government to separate the licence application to increase the capacity in Clab from the application of the remaining repository system. [23] During the summer of 2021, the Government circulated a document for comment on views about issuing a permit for an extension of Clab in a separate decision. Thereafter, the Government took a decision on 26 August on allowing an increased storage capacity of 11 000 tonnes of spent nuclear fuel and core components. After the Government's decision, the case was handed back to SSM and the Land and Environment Court for further handling.

In January 2022, the Land and Environment Court announced a timetable for further licensing of an increased storage capacity. A main hearing on conditions was held 24–25 May 2022 in Oskarshamn. [24] The court's granted a licence on June 22nd 2022.[4]

SKB had an information meeting with SSM in October 2021 on the continued licensing under the Nuclear Activities Act. [25]

[4] https://www.domstol.se/nacka-tingsratt/nyheter/2022/06/tillstand-har-lamnats-till-utokad-lagring-av-anvant-karnbransle/ (hämtad 2022-08-09).

Consultations under the Espoo Convention 2021

The Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention), is an environmental protection convention addressing that countries in Europe, Canada and the USA are to cooperate and avoid transboundary environmental effects. There are in accordance with the convention requirements that neighbouring countries and the public must be notified if there are plans for activities "likely to cause a significant adverse transboundary impact". [26] In Sweden, the Swedish Environmental Protection Agency is responsible for holding these consultations with other countries.

The Swedish Environmental Protection Agency held a first written "Espoo consultation“ in 2008 concerning a final repository for spent nuclear fuel. After the Land and Environment Court's and SSM's announcements of the applications, SKB was able to continue with the "Espoo consultation“ 2016. [27]

As SKB supplemented its application for the final repository for spent nuclear fuel in April 2019, the Swedish Environmental Protection Agency held a new Espoo consultation in the spring of 2021, after a question from the Government whether one was needed. The consultation was held with Poland and Germany, since these were the only countries that expressed a wish to continue receiving any new documentation related to the case. [28] Neither the authorities in Poland nor Germany received any comments and they had no comments themselves. The Swedish Environmental Protection Agency thus considered the supplementary "Espoo consultation“ to be concluded. [29]

10.2.2 The licensing process for a Final repository for short-lived low- and intermediate-level waste (SFR)

The Government took decisions on permissibility under the Environmental Code and a licence under the Nuclear Activities Act on 22 December 2021 for an extended Final repository for short-lived low-level and intermediate-level waste, SFR. [30, 31]

The background is that more space is needed for i.a. the final storage of decommissioning waste, and SKB submitted its applications under the Environmental Code and the Nuclear Activities Act in

2014. After the Land and Environment Court and SSM had prepared the applications, the authorities submitted their respective pronouncements to the Government in the end of 2019, in which both recommended the approval of the applications.

On 27 April 2021, also the municipal council in the municipality of Östhammar took the decision to recommend the approval of the extension of SFR in Forsmark.

10.2.3 Other activities and inputs

RD&D Programme 2019

After pronouncements were submitted by SSM and the Council, see above, the Government decided to approve SKB's research programme *RD&D Programme 2019* in December 2020. [32]

The Swedish National Debt Office's proposals for nuclear waste fees

The reactor owners pay nuclear waste fees, and their joint company SKB, based on its assumptions, calculates the future costs for the handling and final storage of nuclear waste and decommissioning of reactors. [33] The National Debt Office (RKG) has since 2018 been responsible for providing proposals for nuclear waste fees (this was previously done by SSM), based on SKB's calculations. The Government then takes a decision on the fees. Normally, the fees are determined for a three-year period. (You can read more about the financing system on a new subpage on the National Council for Nuclear Waste's website [34]. In Swedish)

The financing legislation was changed in 2017 and RKG has developed the methods such that the calculations will correspond to the new provisions. The authority's work on a new computational model for the supplementary amount was delayed due to the corona pandemic. RKG chose to provide proposals for fees for only 2021, which the Government accepted 2020-12-10. In the spring of 2021, the new computational model was circulated for comment. After the circulation, RKG submitted a proposal in September 2021 for fees for the years 2022–2023, with the supplementary amount having been increased considerably based on the new model. [35] On 27 January 2022 the Government took a decision on the fees according to RKG's recommendations. [36]

The state's ultimate responsibility

The Nuclear Activities Act and the Environmental Code have been updated with respect to the state's responsibility after closure of the final repository. The law changes began to apply on 1 November 2020. [37]

SSM's updated regulations

The Swedish Radiation Safety Authority is working on revising its regulations. During 2021, the authority has after referral, published the following regulations [38]:

SSMFS 2021:7	*Strålsäkerhetsmyndighetens föreskrifter om omhändertagande av kärntekniskt avfall* [The Swedish Radiation Safety Authority's regulations concerning the management and final storage of nuclear waste]
SSMFS 2021:6	*Strålsäkerhetsmyndighetens föreskrifter och allmänna råd om drift av kärnkraftsreaktorer* [The Swedish Radiation Safety Authority's regulations and general guidelines concerning the operation of nuclear power reactors]
SSMFS 2021:5	*Strålsäkerhetsmyndighetens föreskrifter och allmänna råd om värdering och redovisning av strålsäkerhet för kärnkraftsreaktorer* [The Swedish Radiation Safety Authority's regulations and general guidelines on evaluation and reporting of radiation safety for nuclear power reactors]

SSMFS 2021:4	*Strålsäkerhetsmyndighetens föreskrifter och allmänna råd om konstruktion av kärnkraftsreaktorer* [The Swedish Radiation Safety Authority's regulations and general guidelines concerning the construction of nuclear power reactors]
SSMFS 2021:1	*Strålsäkerhetsmyndighetens föreskrifter om avgifter vid riksmätplatsen för joniserande strålning och radonlaboratoriet* [The Swedish Radiation Safety Authority's regulations concerning the fees at riksmätplatsen for ionising radiation and radon laboratory]

Financing for environmental organisations

In the years 2020 and 2021, environmental organisations were able to apply for state funding for work with nuclear waste final storage issues by way of SSM. This is also true for 2022. [39]

An investigation was appointed in 2021 with the aim to revise the possibility of a long-term funding of the participation of municipalities and non-profit environmental organisations in matters concerning the assessment of a final repository for spent nuclear fuel and radioactive waste, and for other work to follow the nuclear waste issue. [40]

Updated National Plan published

After referral, SSM has published 2021:15 *Nationell Plan: Ansvarsfull och säker hantering av använt kärnbränsle och radioaktivt avfall i Sverige.* [National Plan: Responsible and safe management of spent nuclear fuel and radioactive waste in Sweden.] [41]

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Committee terms of reference 1992:72

Scientific committee charged with the task of investigating questions concerning nuclear waste and the decommissioning and dismantling of nuclear facilities etc.

Decision at Government meeting of 27 May 1992.

Conducted by the head of the Ministry of the Environment and Natural Resources, Minister Johansson.

My proposal

I propose that a special scientific committee be appointed charged with the task of investigating questions concerning nuclear waste and the decommissioning and dismantling of nuclear facilities and of giving advice in these matters to the Government and certain public authorities.

Background

In Gov. Bill 1991/92:99 regarding certain appropriation matters for the budget year 1992/93 and changes in the national organization in the nuclear waste field, the Government proposed that the National Board for Spent Nuclear Fuel be abolished as a separate agency and that its activities be transferred to the Swedish Nuclear Power Inspectorate. The Bill proposed that the scientific council – KASAM

– tied to the National Board for Spent Nuclear Fuel be given a more independent position and be tied directly to the Ministry of the Environment and Natural Resources as a commission instead of being administratively tied to an authority.

The Government (1991/92:NU22, rskr. 226) has decided in favour of the Government's proposal for a changed national organization in the nuclear waste field.

Thus, a special scientific committee charged with the task of investigating questions concerning nuclear waste and the decommissioning and dismantling of nuclear facilities and of giving advice in these matters to the Government and certain public authorities should be appointed.

Task

The committee should

- every three years, starting in 1992, submit by not later than 1 June a special report describing its independent assessment of the state of the art in the nuclear waste field.
- not later than nine months after the point in time specified in Section 25 of the Ordinance (1984:14) on Nuclear Activities, submit a report describing its independent assessment of the programme for the comprehensive research and development work and other measures which the holder of a license to own or operate a nuclear reactor shall prepare or have prepared according to Section 12 of the Act (1984:3) of the Act on Nuclear Activities.

The committee should also offer advice in matters relating to nuclear waste to the Swedish Nuclear Power Inspectorate and the Swedish Radiation Protection Authority when requested to do so.

Whenever necessary and economically feasible, the committee should undertake foreign travel to study facilities and activity in the nuclear waste field and arrange seminars on general topics in nuclear waste management.

The committee should comply with the Government's instructions to state committees and special investigators as regards the thrust of its proposals (Dir. 1984:5) and the EU aspects of the investigations (Dir. 1988:43).

The committee should consist of a chairman and at most ten other members. It should also be allowed to engage outsiders for special assignment whenever necessary and economically feasible.

Chairman, members, experts, consultants, secretary and other assistants should be appointed for a defined term.

The committee's task shall be regarded as completed when the Government has made a decision on the license application for a final repository for spent nuclear fuel and high-level nuclear waste in Sweden.

Petition

With reference to the above, I petition that the Government authorize the head of the Ministry of the Environment and Natural Resources

- to appoint a special scientific committee – subject to the Committee Ordinance (1976:119) – with not more than eleven members charged with the task of investigating questions concerning nuclear waste and the decommissioning and dismantling of nuclear facilities and of giving advice in these matters to the Government and certain public authorities,
- to appoint chairman, members, experts, consultants, secretary and other assistants.

I further petition that the Government order that the costs be charged to appropriations under the fourteenth title "Commissions etc.".

Decision

The Government concurs with the rapporteur's suggestions and approves his petition.

Committee terms of reference 2009:31

Supplementary terms of reference for the Swedish National Council for Nuclear Waste (M 1992:A)

Decision at Government meeting of 8 April 2009

Summary of task

The Swedish National Council for Nuclear Waste was established by a decision at a Government meeting on 27 May 1992 (dir. 1992:72). The Swedish National Council for Nuclear Waste shall investigate and shed light on matters relating to nuclear waste and decommissioning and dismantling of nuclear facilities etc. and give advice to the Government in these matters. Aside from the Government, important target groups for the Swedish National Council for Nuclear Waste are also concerned public authorities, the nuclear power industry, municipalities, interested organizations, politicians and the mass media.

The Swedish National Council for Nuclear Waste shall possess broad scientific qualifications in natural science, technology, the social sciences and the humanities.

The task of the Council shall be regarded as completed when the Government has decided on a final repository for spent nuclear fuel and high-level nuclear waste in Sweden.

These terms of reference replace the terms of reference from 27 May 1992.

Task

The Swedish National Council for Nuclear Waste shall assess the Swedish Nuclear Fuel and Waste Management Co's research, development and demonstration programmes (RD&D programmes), applications and other reports of relevance for the final disposal of nuclear waste. The Council shall – not later than nine months after the Swedish Nuclear Fuel and Waste Management Co has submitted its RD&D programme in compliance with Section 12 of the Act (1984:3) on Nuclear Activities – submit its independent assessment of the research and development activities and the other measures described in the programme. The Council shall also follow the work being done on decommissioning and dismantling of nuclear facilities.

In the month of February every year, starting in 2010, the Council shall submit a report on its independent assessment of the state of the art in the nuclear waste field.

The Council shall investigate and shed light on important issues in the nuclear waste field, for example by holding hearings and seminars, so that it can make well-founded recommendations to the Government.

The Council shall also keep track of other countries' programmes for management and disposal of nuclear waste and spent nuclear fuel. The Council should also follow and, where necessary, participate in the work of international organizations on the nuclear waste issue.

These terms of reference replace the terms of reference from 27 May 1992 (dir. 1992:72).

Organization

The Swedish National Council for Nuclear Waste shall consist of a chairman and not more than ten other members (one of whom also acts as deputy chairman). The members shall have broad scientific qualifications in fields related to the nuclear waste issue. It can engage outsiders for special assignments whenever necessary and economically feasible. Chairman, members, experts, consultants, secretary and other assistants shall be appointed for a defined term.

Timetable

The task of the Council shall be regarded as completed when the Government has decided on a final repository for spent nuclear fuel and high-level nuclear waste in Sweden.

(Ministry of the Environment)

Committee terms of reference 2018:18

Supplementary terms of reference for the Swedish National Council for Nuclear Waste (M 1992:A)

Decision at Government meeting of 01 March 2018

Amendment of task and timeframe

The Swedish National Council for Nuclear Waste was established by a decision at a Government meeting on 27 May 1992 (dir. 1992:72) replaced by the supplementary terms of reference (2009:31).

From the beginning of 2018, the Swedish National Council for Nuclear Waste shall review the work of the previous years and submit a report on its independent assessment of the state of the art in the nuclear waste field every other year, instead of every year.

The task of the Swedish National Council for Nuclear Waste shall be time limited until the 31 December 2022. After this, the task may be extended by a maximum of five years at a time.

These terms of reference replace the terms of reference from 08 April 2009.

Task

The Swedish National Council for Nuclear Waste shall investigate and shed light on matters relating to management of nuclear waste and decommissioning and dismantling of nuclear facilities. The Council shall give advice to the Government in these matters. Aside from the Government, important target groups for the Swedish

National Council for Nuclear Waste are also concerned public authorities, the nuclear power industry, municipalities, interested organizations, politicians and the mass media.

The Swedish National Council for Nuclear Waste shall possess broad scientific qualifications in natural science, technology, the social sciences and the humanities.

The Swedish National Council for Nuclear Waste shall assess the Swedish Nuclear Fuel and Waste Management Co's research, development and demonstration programmes (RD&D programmes), applications and other reports of relevance for the final disposal of nuclear waste. The Council shall – not later than nine months after the Swedish Nuclear Fuel and Waste Management Co has submitted its RD&D programme in compliance with Section 12 of the Act (1984:3) on Nuclear Activities – submit its independent assessment of the research and development activities and the other measures described in the programme. The Council shall also follow the work being done on decommissioning and dismantling of nuclear facilities.

In the month of February every other year, starting in 2018, the Council shall submit a report on its independent assessment of the state of the art in the nuclear waste field over the last two years.

The Council shall investigate and shed light on important issues in the nuclear waste field, for example by holding hearings and seminars, so that it can make well-founded recommendations to the Government.

The Council shall also keep track of other countries' programmes for management and disposal of nuclear waste and spent nuclear fuel. The Council should also follow and, where necessary, participate in the work of international organizations on the nuclear waste issue.

The task of the Swedish National Council for Nuclear Waste shall continue until the 31 December 2022. After this, the task may be extended by a maximum of five years at a time.

Organization

The Swedish National Council for Nuclear Waste shall consist of a chairperson and not more than ten other members (one of whom also acts as deputy chairperson). The members shall have broad scientific qualifications in fields related to the nuclear waste issue. It can engage outsiders for special assignments whenever necessary and economically feasible. Chairperson, members, experts, consultants, secretary and other assistants shall be appointed for a defined term.

(Ministry of the Environment and Energy)

Appendix 4

Reduction-oxidation (electron transfer) reactions and the chemistry of the chemistry of metal oxide surfaces in contact with water

Introduction redox reactions

Corrosion of metals is a reduction-oxidation reaction (redox reaction) there electrons are transferred from one chemical compound to another. This means that one compound releases electrons (reduction agent) and oxidizes, and the other compound accepts these electrons (oxidation agent) and reduces. In order to a redox reaction to be allowed from thermodynamic point of view, the oxidation agent in a redox-pair must have a higher standard electrode potential, e_o, than the reducing agent. This can be illustrated by astandard electrode potential line showing the allowed redox reactions and those which are not. This is shown in Scheme 1, see below, where we give an example of a redox-pair relevant for discussion of copper corrosion. Scheme 1 shows a redox-pair ("oxidation agent/reduction agent") consisting of an element in two different oxidation states in contact with each other. When the oxidation agent in a redox-pair reacts with the reduction agent in another redox-pair, the reduction agent in the other is transferred to the corresponding oxidation agent.

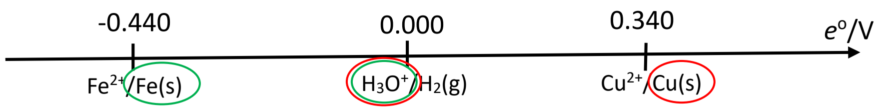
In order for a chemical reaction to take place, the following three criteria must be fulfilled:

1. it must be thermodynamically allowed (at equilibrium more of the products are present than of the reactants),

2. the reaction rate must be sufficient to allow chemical analysis of the products,

3. all required chemicals must be available, and in contact with each other.

The oxidation state of an element is determined by the number of electrons in comparison to the number in the pure element. As an example, an element in a compound with two electrons more than in the pure element has the oxidation state minus two (-II), and when it has two electrons less than the pure element the oxidation state is plus two (+II). The oxidation state is written with Roman numerals. The standard electrode potential of redox-pair is measured *versus* the redox-pair $H_3O^+(aq)/H_2(g)$, where hydrogen in the oxonium ion, $H_3O^+(aq)$, has the oxidation number +I, is oxidation agent, and gaseous hydrogen (pure element), $H_2(g)$, oxidation number 0, is reducing agent. The absolute values of standard electrode potentials cannot be determined, while the difference between two redox-pairs can be determined very accurately. In order to form a the standard electrode potential scale, the redox-pair $H_3O^+(aq)/H_2(g)$, the normal hydrogen electrode (NHE), is defined as 0.0000 V. All other standard electrode potentials are measured *versus* NHE, which can be made visible by a standard electrode potential line as shown in Scheme 1. The standard electrode potentials used in this chapter are from ref. 1. Scheme 1 shows that oxonium ions, present in strong acids as hydrochloric acid, react with metallic iron, (Fe), and iron(II) ions (Fe^{z}) and hydrogen gas is formed, while no reaction takes place between oxonium ions and metallic copper.

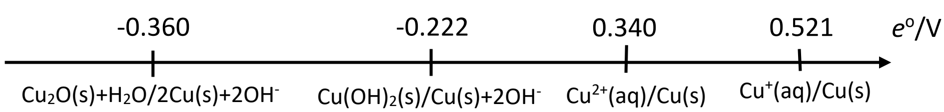


Scheme 1. This standard electrode potential line shows that oxidant H_3O^+ (non-oxidizing acid as hydrochloric acid) is a sufficient strong oxidant to oxidize metallic iron to iron(II) ions, and the oxonium ion is reduced to hydrogen gas in a thermodynamically allowed redox reaction; allowed reaction is shown by green rings around the reactants. On the other hand, oxonium ions are not able to oxidize metallic copper as the redox-pair has Cu^{2+}/Cu(s) has higher e^o-value than H_3O^+/H_2(g) ; not allowed reaction is shown by red rings around the reactants.

When metallic copper is oxidized the copper product formed is the one with the lowest e^o-value. As shown in the Scheme 2, copper(I) oxide (cuprous oxide), Cu_2O, is formed when hydroxide ions, OH-, are present which is the case in neutral and alkaline aqueous solution due to the auto-protololysis of water ($2H_2O \rightleftharpoons H_3O^+ + OH^-$, this equilibrium is strongly shifted to the left, but giving concentrations of H_3O^+ and OH^- of 10^{-7} mole/liter). From the standard electrode potentials it can be seen that the most stable oxidation product of metallic copper is copper(I) oxide, Cu_2O(s), followed by copper(II) hydroxide, $Cu(OH)_2$(s), which can reform to CuO(s), copper(II) oxide, by release of water. The formation of both copper(I) oxide and copper(II) hydroxide, require the presence of hydroxide ions. In acidic aqueous solution the oxidation product is hydrated copper(II) ions. The copper(I) ion can only exist in aqueous solution in extremely dilute aqueous solution, ca. 10^{-5} mole/liter, as it disproportionate to copper(II) ions and metallic copper.

$2\,Cu^+(aq) \rightleftharpoons Cu^{2+}(aq) + Cu(s);\quad K=[Cu^{2+}]/[Cu^+]^2=1.3\cdot10^6\ M^{-1}$

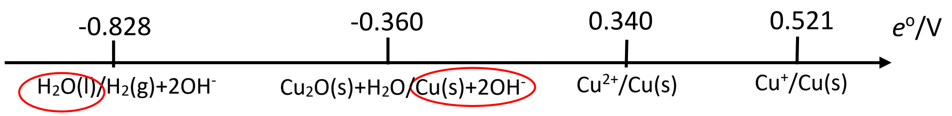
Thus, the concentration of copper(II) divided by the concentration of copper(I) squared has a constant value, in this case $1.3\cdot10^6\ M^{-1}$.



Scheme 2. Standard electrode potentials of some half-cells containing metallic copper.

Copper corrosion – oxidation of metallic copper

For the reaction under debate, metallic copper reacts with pure anoxic water, water is oxidant, it is reduced itself to hydrogen gas, H_2(g), and hydroxide ions, OH^-(aq), are formed as well; the elements in OH^- and H_2O have not changed oxidation state, metallic copper is reducing agent, it is oxidized itself to solid copper(I) oxide, Cu_2O(s). The standard electrode potential line below shows that pure water is a too weak oxidation agent to oxidize metallic copper.



Scheme 3. Standard electrode potentials of the half cells $H_2O(l)/H_2(g)+2OH^-(aq)$ and some containing copper metal. This scheme shows that water is too weak oxidant to oxidize metallic copper as the standard electrode potential of $H_2O(l)/H_2(g)+2OH^-(aq)$ is lower than the lowest for oxidation of copper $Cu(s)+2OH^-(aq)$, and no reaction can take place.

The redox-pair reactions, or half-cells reactions, are normally written in the form of reduction reaction, accepting electrons

$2\ H_2O(l) + 2\ e^- \rightleftharpoons H_2(g) + 2\ OH^-(aq)$ $\qquad e°_{H_2O} = -0.8277$ V

$Cu_2O(s) + H_2O(l) + 2\ e^- \rightleftharpoons 2\ Cu(s) + 2\ OH^-(aq)$ $\qquad e°_{Cu} = -0.360$ V

By combing these two half-cell reactions the following reaction is obtained

$$\cancel{2}\ H_2O(l) + \cancel{2\ e^-} + 2\ Cu(s) + \cancel{2\ OH^-(aq)} \rightleftharpoons H_2(g) + \cancel{2\ OH^-(aq)} + Cu_2O(s) + \cancel{H_2O(l)} + \cancel{2\ e^-}$$

The same chemical species on both sides of the reaction formula take out each other and it remains the required reaction, thus

$2\ Cu(s) + H_2O(l) \rightleftharpoons Cu_2O(s) + H_2(g)$ $\qquad K = p_{H_2}$ (atm) ; p_{H_2} (atm) is the partial pressure of $H_2(g)$

Note that pure solid compounds and solvent has be definition the activity 1.00 and therefore not included in the expression of the equilibrium constant. The equilibrium constant for this reaction can be calculated by the following formula

$\log K = n\cdot(e°_{H_2O} - e°_{Cu})/R\cdot T\cdot F^{-1}$,

where n is the number electrons in the process, 2 in this case, and $R\cdot T\cdot F^{-1} = 0.05916$ V

$\log K = 2\cdot(-0.828-(-0.360))/0.05916 \rightarrow \log K = -15.1 \rightarrow K = 1.5\cdot10^{-15}$ atm

This shows that the equilibrium $2\ Cu(s) + H_2O(l) \rightleftharpoons Cu_2O(s) + H_2(g)$ is shifted very far to the left and that the amounts of $Cu_2O(s)$ and $H_2(g)$ formed are extremely small. This shows also that water cannot alone oxidize metallic copper to copper(I) oxide, the most stable form of the copper(I) and copper(II) oxides and hydroxides presently known (see potential line above). In order to corrode (oxidize) metallic copper in pure water either a significantly more stable copper oxide or hydroxide, denoted H_xCuO_y in standard electrode potential line in the scheme below, and/or a significantly stronger oxidant than water is formed as an intermediate formed on copper surfaces in contact with water. One controversial issue in this matter is therefore, which is the oxidation agent in the copper-water system able to oxidize metallic copper or which is the compound sufficiently stable to allow pure water to oxide metallic copper,

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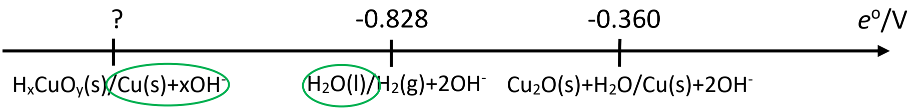
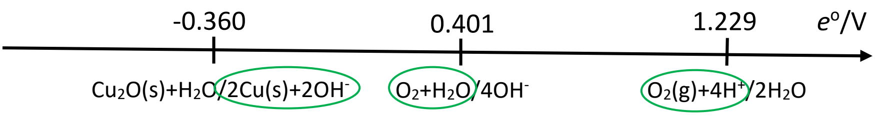
$$2\,Cu(s) + 2\,H_2O \rightleftharpoons 2\,H_xCuO_y(s) + H_2(g).$$



Scheme 4. Standard electrode potentials of the half cells $H_2O(l)/H_2(g)+2OH^-(aq)$ and a hypothetical copper compound $H_xCuO_y/Cu(s)+2OH^-(aq)$ must have standard electrode potential lower than that of water for allowing water to oxidize copper metal.

In presence of oxygen is metallic copper readily oxidized to copper(I) oxide, especially at acidic conditions, see below.



Scheme 5. Standard electrode potentials of the half cells $Cu_2O(s)+H_2O/Cu(s)+2OH^-(aq)$ and $O_2(g)+4H^+/2H_2O(l)$ or $O_2(g)+H_2O/4OH^-(aq)$ shows that copper metal is readily oxidized by oxygen to form solid copper(I) oxide.

Chemistry of metal oxide surfaces in contact with water

As the copper corrosion takes place at the surface of a metal, which in most cases is covered with a thin layer of metal oxide, it is of utmost importance to understand the chemistry in the interface metal oxide-water. Metal oxides surfaces in contact with liquid water or water vapor are hydrated, i.e. they are generally covered with surface hydroxyl groups. [2] They are formed by metal ions in the surface bind water molecules which are split so that one hydrogen atom in the bound water molecules is transferred to the oxide ion in the surface according to Figure 1.

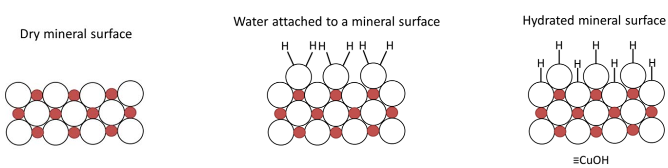


Figure 1. Hydration process of metal oxide surfaces.

It is important to note that the OH group is regarded as a surface complex and not as a compound attached to the surface. This surface complex, normally denoted ≡CuOH in the case of hydrated copper oxide surface, can act as both acid and base as it has the ability to take up and release protons as any ordinary acids or bases. A hydrated metal oxide in aqueous solution act as two-protonic acid; {} denotes surface concentration in a suspension, [] concentration in the aqueous phase, and ^{s} that a solid surface is included in the equilibrium. This illustrated in Figure 1. This means that the hydrated metal oxide surface is charged depending on the pH in the aqueous solution. The surface is positively charged in acidic solutions and negatively charged in alkaline solution, and the pH value, where the number positive and negative charges are equal, is regarded as point of zero charge, pH_{PZC}.

$\equiv CuOH_2^+ + H_2O \rightleftharpoons \equiv CuOH + H_3O^+$; $K_{a1}^s = \{\equiv CuOH\}[H_3O+]/\{\equiv CuOH_2^+\}$

$\equiv CuOH_2^+ + H_2O \rightleftharpoons \equiv CuOH + H_3O^+$; $K_{a2}^s = \{\equiv CuOH\}[H_3O+]/\{\equiv CuOH_2^+\}$

$pH_{PZC} = (pK_{a1}^s + pK_{a2}^s)/2$

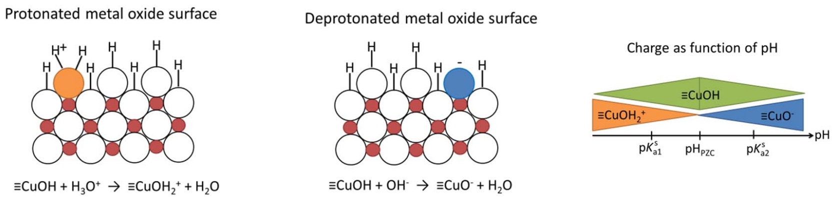


Figure 2. Protonated copper oxide surface, $\equiv CuOH_2^+$ (left panel), deprotonated copper oxide surface (middle panel), and the charge of the surface of a copper oxide surface as function of the pH value of the aqueous solution (right panel).

The pH_{PZC} of copper(II) oxide is ca. 9.5 which means that a copper(II) oxide surface in neutral aqueous solution has a positive charge. Any pH_{PZC} value for copper(I) oxide has not been reported.

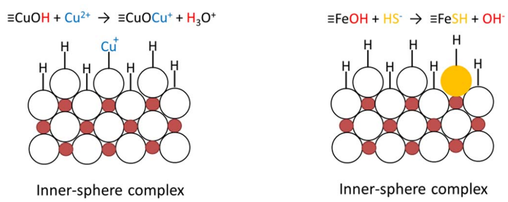


Figure 3. Metal ions, e.g. copper(II) ions, may bind to a hydrated copper oxide surface, and a bound protons are released (left panel). Negatively charged ions, e.g. hydrogen sulfide ions, may bind to a hydrated copper oxide surface, and a bound hydroxide ions are released (right panel).

References

1. Handbook of Chemistry and Physics, Ed. Haynes, W. M., CRC Press, Boca Raton, Florida, USA, p. 5-79–5-88.
2. Stumm, W. *Chemistry of the Solid-Water Interface – Processes at the Mineral-Water and Particle – Water Interface in Natural Systems*. John Wiley & Sons, New York, 1992, Chap. 2, ISBN 0-471-57672-7.