Model or Muddle?
Governance and Management of Radioactive Waste in Sweden

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1 Introduction[1]

The governance and management of radioactive waste in Sweden is often seen as a model for the world. Since the 1980s, the radioactive waste company SKB, which is owned by the Swedish nuclear operators and is legally responsible for radioactive management, has internationally encouraged the idea that Sweden "has solved the radioactive waste problem". The government has generally been pleased with this situation and has for many years presented the Swedish legislation as a governance model for other nations to follow. There have indeed been results, largely because Sweden has a financial system which pays for the final disposal of radioactive waste (RW) from nuclear power and for the decommissioning of nuclear reactors. The nuclear industry pays for future costs into a nuclear waste fund but the government is in full control of how resources are spent.

Today, the country has an operating repository for short-lived operational radioactive waste, a centralized temporary storage facility for spent nuclear fuel (SNF), and a ship-based transportation system for RW. Swedish nuclear industry has also managed to identify a site for a long-term repository for SNF.

As we enter the second half of the 2010s, the Swedish nuclear waste governance model no longer appears as efficient as it did before. The "model" is a muddle that has not adequately taken into account the future governance of radioactive waste in Sweden. There are plans to reform the legal system, but it is questionable whether this will be enough to solve the model's fundamental issues. In this chapter we describe how the Swedish system for the governance and management of nuclear wastes developed, consider the problems that have occurred, and ask whether it is it too late for a new model that could provide for an industry-financed, safe management of nuclear waste.

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1 The content of this chapter is partly based on a chapter in Swahn (2011). An attempt to explain the Swedish nuclear policy development as a result of interacting economic interests is given in Kåberger (2002).

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2 The context: A brief review of Swedish radioactive waste governance and management from 1945 to today.

As in other countries that were early nuclear adapters, military interests initially drove the Swedish nuclear programme. With time, it became apparent that it would be easier to develop a nuclear weapons capacity if the programme could be integrated in nuclear energy development. By 1985, there were 12 reactors operating at four nuclear power plant sites. The two reactors at Barsebäck, the fourth site close to Copenhagen and Malmö, were closed in 1999 and 2005, respectively.

While the number of reactors, capacity, and tonnes of radioactive waste are small in relation to those of the major nuclear countries in the world, with 10 GW nuclear power among less than 10 million people Sweden has more nuclear power and more nuclear waste per capita than any other country

2.1 1945-1970: A military-civil nuclear programme

The Swedish military-civil nuclear programme was based on heavy water technology. In 1947, the government created a company called AB Atomenergi that became central to the development of the bomb and nuclear energy programmes. A nuclear research facility was built in the late 1950s at Studsvik on the Baltic coast.[2] The reactor research programme resulted in the construction of a heavy water moderated reactor that delivered hot water for district heating and some electricity to the suburbs of Ågesta, situated South of Stockholm. The construction of the reactor, which was built underground in bedrock, was started in 1957; the reactor began operation in 1964.[3] The main purpose of the reactor was to produce plutonium for nuclear weapons in case the decision was made to start bomb production. The spent nuclear fuel (SNF) from the Ågesta reactor was thus considered to be an asset and not waste. After reprocessing, it could be used to produce plutonium for nuclear weapons or for nuclear fuel in breeder reactors. The high-level radioactive waste (HLW) from the reprocessing was considered

2 AB Atomenergi was responsible for building reactors while bomb construction and radiochemistry development was the responsibility of the Swedish Defence Research Establishment (FOA). Sweden gained knowledge about nuclear technology from the "Atoms For Peace" programme initiated by U.S President Eisenhower in 1953. For an historical account of the development of the Swedish military-civil nuclear programme see Johansson (1986), Jonter (2001; 2002) and Agrell (2002).

3 The Ågesta reactor was closed in 1974 (IAEA 2014).

to be small in quantity and useful for medical purposes.[4] Sweden was planning to build a large reprocessing plant underground in the bedrock in Sannäs on the West coast in the early 1960s. The plant could produce plutonium from SNF from the Ågesta nuclear reactor and from the planned, even larger heavy water reactor being built at Marviken on the Baltic coast south of Stockholm.[5]

By the 1960s, however, the military part of the Swedish civil-military programme was in trouble. Public opinion against Sweden's goal of acquiring nuclear weapons grew. For some years, the programme to construct nuclear weapons was carried out under the auspices of a programme to develop a *defence against* nuclear weapons. By the end of the 1960s, Sweden decided to reject nuclear weapons. Sweden joined the Nuclear Non-proliferation Treaty (NPT) in 1968, which was enforced in 1970. The heavy water reactor programme was abandoned after 12 commercial reactors were operational.

2.2 1970-1980: Environmental wake-up, political intrigue, end of reprocessing, and a referendum on nuclear power

In the 1960s there was a general awakening about environmental issues in Sweden. Rachel Carson's book "Silent Spring," written in 1962, was published in Swedish one year later and was as influential as the Club of Rome report, "Limits to Growth" (Carson 1962; Meadows 1972). The first United Nations Conference on the Human Environment was held in Stockholm in 1972, which showed that environmental issues had also become mainstream in political circles by the early 1970s. This environmental awareness led to more debates on the environmental risks of nuclear power in the 1970s. The problem with RW, which could no longer be claimed to be a minor nuisance, became a major part of the discussion.

In response to increasing public debate, a government commission was set up in 1972 to come up with a proposal to suggest how Swedish RW was to be managed. In 1976, this AKA commission delivered a report in three volumes

4 There was a general understanding in the 1950s and 1960s that the management and disposal of any waste from nuclear activities could easily be solved in the future by Swedish engineers. At this time there was also sea dumping of radioactive waste barrels, both in the Baltic Sea and along the Swedish west coast.

5 The Marviken reactor was built during the 1960s but was never loaded with nuclear fuel. There were technical problems with the reactor design, but the main reason for not going forward was that the decision had been made to abandon the Swedish heavy water reactor programme. It was too expensive to compete on a commercial market once plutonium for nuclear weapons was no longer needed. The Marviken plant was converted to run on oil until it was shut down in 2009 – the only nuclear reactor in the world to run on fossil fuel.

(AKA 1976). The main proposal was that SNF was to be reprocessed and the remaining waste should be encapsulated in canisters and deposited in tunnels a few hundred metres underground, in a bedrock without any, or with only very few and small, fissures.

With RW now identified as a liability rather than an asset, the problems of long-term RW management also became central in the political debate. Ethical arguments about the waste problems associated with using nuclear energy and discussions about alternative energy futures based on renewable energy became part of the political debate before the 1976 elections. These issues were picked up by the Centre Party and the party's gain in popularity allowed for a change in power to the first non-Social Democratic government in 40 years. The Centre Party shared power with the Liberal and Conservative parties, which were both pro-nuclear. Still, the government was able to pass new legislation through Parliament, namely through the Stipulation Act. The law decreed that no new nuclear reactors could be put into operation unless there was an *absolutely safe* way of managing the final disposal of the nuclear waste (SFS 1977). While the third reactor at the Ringhals NPP was awaiting a licence for operation, the Stipulation Act, which clearly connected RW solutions to the operation of new reactors, gave the waste problems an important political role for a few years. This act also forced the nuclear industry to act quickly; consequently it launched the KBS project to develop a repository concept for high-level reprocessing waste, or SNF. The project was developed in close collaboration with the Swedish Nuclear Fuel Supply Company (SKBF), which the nuclear utilities had created in 1972 to coordinate the Swedish nuclear fuel supply.

The 1977 KBS-1´s report described how vitrified high-level nuclear waste from reprocessing, the industry policy at this time, could be disposed of (KBS 1977). It was approved in a controversial decision by a minority government after the Centre Party government fell, and enabled the operation of the Ringhals 3 reactor.

So, despite the ambitious criteria of the Stipulation Act, new reactors were allowed to become operational. The argument that an absolutely safe way to solve the RW issue had been found was very political. The proof that the KBS-1 method was safe depended on the existence of a crack-free bedrock. However, no such rock was found during the drilling programme for site selection. The argument supporting the decision was that there were no fissures in this part of the Sternö candidate site in southern Sweden, and therefore a crack-free rock existed. Yet, the reason why no fissures were found was that no test drillings were carried out in that particular part of Sternö. Hence, these have been called "political boreholes".

The political "logic" behind the decision to start Ringhals 3 was seen as very provocative by those who had supported the idea that no more RW should be produced until the waste problems were solved.[6]

The Stipulation Act also allowed for direct disposal of SNF without reprocessing. The 1978 KBS-2 report therefore provided a solution for the direct disposal of SNF, similar to the one for vitrified reprocessing waste (KBS 1978). The main difference was that the canister´s material had been changed from titanium to copper.

Because the main focus of the nuclear industry at the time of the Stipulation Act was to reprocess the SNF, reprocessing contracts had been signed with the French company Cogema and the British company BNFL. With the KBS-2´s method there was a possibility for the industry to also claim completely safe disposal for SNF that was not reprocessed. At the same time, it became clear that reprocessing was expensive compared to direct disposal. In addition, the U.S. government, under the Ford and Carter administrations, was working internationally to convince countries to reject reprocessing as a nuclear non-proliferation measure. Even though reprocessing is still legally possible in the Swedish nuclear legislation, by 1980 the industry and official policy was that Sweden would not reprocess SNF.

The political turmoil with regard to nuclear power did not end with the decision to declare the RW problem solved and the starting of new reactors. In the spring of 1979, following the Harrisburg nuclear accident, the nuclear debate became increasingly intense. As a result, the pro-nuclear Social Democratic Party changed its mind to allow for a referendum on nuclear power in 1980. The referendum was also politically manipulated because there was not a clear "yes" or "no" choice. However, the final result of the referendum was that 12 reactors would be allowed to operate. The Swedish Parliament decided that the reactors should be phased-out after 25 years of operation, i.e, by 2010 as the newest reactor (Forsmark 3) came on line in 1985.

2.3 1980-2006: Calm governance in a phase-out scenario

The radioactive waste company SKB continued to develop the KBS concept for final disposal of SNF. In 1983, the KBS-3 report became part of the licensing process for the last two Swedish nuclear reactors, Oskarshamn-3 and Forsmark-3 (SKBF 1983). The KBS-3 report had a more developed discussion of long-term

6 A good description of the political turmoil around the decision to start the Ringhals 3 can be found in Sundqvist (2002). A description from the environmental movement's viewpoint can be found in Åhäll et al. (1988).

safety and relied on the results from the geologic studies that have been done to date.[7]

The last two reactors were licenced in 1984 in accordance with the new Nuclear Activities Act, which replaced previous nuclear legislation including the Stipulation Act. After 1986, Sweden had 12 operating nuclear reactors at four NPPs. The new legislation placed all responsibility for developing and operating RW repositories on the nuclear industry. However, this legislation stipulated, as its only requirement for RW management and final disposal that the nuclear industry, through SKB, would provide a R&D programme every three years for the government to accept.

In 1995, the Äspö Hard Rock Laboratory was inaugurated near the Oskarshamn NPP and a number of experiments were started involving copper and clay, including a full-scale demonstration project with full-size copper canisters in the underground research site.

The siting process for a repository for SNF – the most long lived RW with a safety case necessary for hundreds of thousands or even millions of years – was not as easy. A voluntary process finally allowed the RW company SKB to start site investigations in 2000 at a site just south of the Forsmark NPP and at a site just adjacent to the Oskarshamn NPP.

As the twenty-first century arrived, the Swedish model seemed to be thriving. The economics, siting, repository design, and technology – all seemed fine. What could go wrong?

2.4 2000-2014: Moving towards a collapse of the Swedish model?

At the beginning of the 2000s it was clear that there were a large number of issues that were of great concern. These were raised by regulators and the Swedish Council for Nuclear Waste, but also by the academic community and the environmental movement. There was some concern about how the company would deal with threats to the repository during repeated glaciations – ice ages – that could threaten the artificial barrier system that now, without the illusion of crack-free bedrock, was seen as critical in isolating the waste from humans and the environment. The government was informed about these concerns, however since the legislation deemed the industry responsible for any necessary extra work, all the government could do in its decisions on the programme was to ask for some complementary work. It was the industry's risk if it did not do enough, because any work that was lacking or insufficient would not be reviewed until

7 In the rest of this chapter this will be called simply the KBS method or KBS concept.

the application for a licence. These were issues that the company had to deal with properly in its upcoming application for a licence.

The government that came into power in Sweden in 2006 included a very pro-nuclear party and changed the law in 2009 to allow the construction of new NPPs. This means that Sweden moved from a situation where nuclear power was seen as a technology to be phased out, with a finite amount of waste, to a situation where the future amount of RW is uncertain. As demonstrated in the early period, waste management regulation is not only a matter of managing an unavoidable limited problem. Again, the future production of waste may influence how RW should be managed.

In 2009, SKB finally chose an area south of the Forsmark NPP as the site for the repository for SNF. An encapsulation plant, for placing the SNF in copper canisters, was to be built at the Oskarshamn NPP. The siting choice was surprising to many, as the geology was very different at the two investigated sites. The experiments at the Äspö Hard Rock laboratory were seen as positive experiences and inspired confidence in how copper canisters and clay behaved in the bedrock near the Oskarshamn NPP. SKB, however, decided not to use the recommended criteria for the functioning of these barrier systems for final site selection. Instead the company returned, at this final stage, to using criteria involving fissures in the rock. The mean distance between major fissures was higher in Forsmark than in Oskarshamn. Thus, Forsmark was chosen mainly because it had a "crack-free" rock. In March 2011, SKB handed in its application to build a SNF repository in Forsmark to the Environmental Court and the Swedish Radiation Safety Authority (SSM). The application will be reviewed in parallel by both bodies. As of September 2014, the process was still ongoing and it was not yet decided which additional requirements SKB must fulfil in order to complete the application and review its merits. There were many requests for additional changes on a large number of issues, from SSM, from the Swedish Council for Nuclear Waste, and also from members of the environmental movement. SKB has given SSM additional tasks, but the company's interaction with the environmental court has not been so successful. The large volume of demands for amendments and the time it is taking SKB to answer, as well as its refusal to acknowledge many demands, has prompted the environmental court to make a ruling between January and October 2015 on whether a "process hindrance" exists. If such a ruling is made, SKB may be forced to make further amendments. Ultimately, a "process hindrance" could mean that the licence application will be rejected.

Perhaps the major issue that has led to this situation is the scientific controversy that emerged in 2007 regarding copper corrosion in a repository environment. Researchers from the Royal Institute of Technology in Stockholm have published a number of scientific articles questioning SKB's view that copper in an environment without oxygen in gas form – as is the situation in a repository – corrodes very slowly. The researchers have shown that water corrodes copper even if oxygen is not available (Szakálos 2007; Hultquist 2009; Hultquist 2011; Hultquist 2013). If this is the case, the SKB safety case for the KBS method will have to be questioned. SKB is fighting the issue, but as of June 2014 the controversy had not been resolved and SSM is continually demanding more information from SKB. For the environmental court, it is certainly unreasonable to have to try and judge a case mired in scientific controversy. The court is so far mainly waiting for the results of interaction between SKB and SSM.

3 Overview of the nuclear power programme and radioactive waste volumes

The Swedish nuclear programme includes 13 commercial reactors listed in the IAEA Power Reactor Information System (IAEA/PRIS 2014). In 2014, 10 of these 13 reactors were operational. They are located at three NPPs, Oskarshamn with three reactors, Ringhals with four and Forsmark with three. The two reactors at the Barsebäck NPP, close to Copenhagen and Malmö, were closed in 1999 and 2005. All other reactors are being refurbished to ensure increased safety and life-time extension.

The average production cost for electricity from the three reactors at the Oskarshamn nuclear power plant, OKG, over the last five years is significantly higher than the electricity market price for the coming 10 years. In January 2014, OKG announced that it was preparing to file an application to put the oldest reactor on the site, Oskarshamn 1, out of operation. The company's rationale for this was that it was expecting demands for safety upgrades as a result of evaluations of the Fukushima accident that would be too expensive to carry out. Oskarshamn 2, the second oldest reactor, is under major modernisation that is expected to take about one year. In June 2014, OKG told the power market that there was no longer a start date scheduled.

The nuclear legislation was changed in 2009 to allow the construction of new nuclear reactors if old ones were shut down. Since the summer of 2012, the state-owned electricity company Vattenfall announced that it was considering building one or two reactors at the Ringhals NPP on the West coast. There is an "application" in the early stages to force the regulator SSM to start working on the regulations for new-build. A decision to build a new reactor is expected soon. There is presently an overcapacity in Sweden, as wind power generation has been expanding rapidly in the last 10 years. The life-time extensions of the present reactors are said by the industry to ensure operations for 50 or even 60 years. Finally, it would not be possible to transfer the investment to a new nuclear reactor in Sweden without clear and broad political support for nuclear new-build, one that would probably require subsidies and financial guarantees. This is not the situation in Sweden today, and may be difficult to achieve in the future.

3. 1 Radioactive waste from NPPs[8]

The RW from the Swedish NPPs, including the initial small Ågesta reactor that is considered part of Sweden's commercial nuclear programme, is primarily stored in the intermediate storage facility Clab. There is a total of 5,740 tonnes of SNF in the facility; 5,695 tonnes come from the nuclear power reactors, 20.2 tonnes from the Ågesta nuclear reactor, 2.4 tonnes is spent fuel from tests which were done at the Hot Cell Laboratory at Studsvik, and 22.5 tonnes is German spent MOX fuel traded for Swedish fuel exported to France in transferred reprocessing contracts from the 1970s.[9] In addition, there were 556 tonnes of SNF in the cooling pools at the 10 operating reactors on December 31, 2013. In the cores of the operating reactors there is approximately an additional 1,000 tonnes of fuel that will become SNF. The total amount of SNF to dispose of will be about 12,000 tonnes if the existing Swedish reactors are in operation for the 50 to 60 years that the industry is presently planning for.

The repository for short-lived operational waste, SFR, contains 34,953 m^3 of short-lived low- and intermediate-level radioactive waste from the operations of the NPPs. Some of this waste is also from medical and industrial sources. It is expected that about a total of 53,000 m^3 of this type of short-lived waste will be produced from reactor operations.[10] The operation of Clab and the planned encapsulation facility for SNF is expected to add another 400 m^3. In addition,

8 These and the following figures are taken from the Swedish Ministry of the Environment (2014).

9 The reprocessing contracts that had been signed with France were transferred to Germany; 28 tonnes of German spent MOX fuel was transported to Sweden and still awaits final disposal. The British contracts were never broken and 140 tonnes of Swedish SNF was reprocessed at Sellafield. The high-level reprocessed waste was not returned to Sweden and in the spring of 2014 it was made known that the plutonium would also be transferred to British ownershipThe Hot Cell Laboratory at the Studsvik facility has been in operation since the late 1950s and has, for many years, been operating as a commercial test facility for nuclear fuel. The facility is now owned by Studsvik Nuclear AB. The fuel rods are moved to Clab after the tests and are stored in special steel containers with the same form factor as spent fuel assemblies. Studsvik Nuclear AB has a permit to also store foreign SNF that has been tested in Clab and will be disposed of along with the Swedish SNF.

10 The data from the rest of this section comes from SKB (2013).

73,000 m^3 of short-lived decommissioning waste from the nuclear reactors is expected. This waste is to be stored in a new facility, SFR 2, which SKB wants to build as an expansion of the SFR facility. The decommissioning of Clab and the planned encapsulation facility for SNF is expected to add another 3,400 m^3 of waste to SFR2 as well.

It is also expected that the decommissioning of the NPPs will produce 3,700 m^3 of long-lived intermediate level waste (SFL). A new facility for this waste has to be built, but the method and the siting for this construction have still not been decided on. The NPPs at Ringhals, Forsmark, and Oskarshamn, as well as the Studsvik nuclear facility, also have shallow land burial facilities for very low-level waste. In total, Sweden is expected to have approximately 12,000 tonnes of SNF, 154,000 m^3 of short-lived, and 15,500 m^3 of long-lived intermediate nuclear waste to dispose of at the end of the nuclear era, unless there are new plant constructions.

3.2 Historic radioactive waste

Most of the historic waste from the early Swedish military-civil programme was reconditioned, put into new containers in the 1990s, and then stored underground at the Studsvik facility.[11] The SNF from the Ågesta reactor is in Clab, but there is still 40 kg of spent fuel from the R-1 research reactor in Sweden. Most of the fuel from the reactor, 4.8 tonnes, was exported in 1997 to the United Kingdom for reprocessing, but a small amount that was considered too damaged to move remains in Sweden.[12] This fuel is metallic uranium and cannot be disposed of using the KBS method. It is possible that this SNF will be put in a future

11 There are 7,750 containers in this facility. Judging mainly from documentation, the containers at the Studsvik site could contain too much long-lived RW, which should be deposited in SFR. A programme was carried out to try and ascertain in more detail what was in each container. It found that the documentation of the containers was not accurate. There were liquids in 20-30% of the containers though no liquids should have been in them. There was mercury in some containers and some containers contained fissile material that was not accounted for in the safeguard registers. In the original reconditioning process 2,844 canisters were considered only to contain short-lived waste and were placed in 75 containers that were then deposited in SFR. These containers with the canisters now have to be retrieved because the documentation apparently is not good enough to classify the canisters as only containing short-lived wastes. A new facility for reconditioning and classifying the “historic” waste in the canisters is planned for the Studsvik site. Sweden kept 3.3 kg of separated plutonium from different sources in the military-civil programme stored in a vault at the Studsvik research facility for many years. The plutonium was exported to the United States in March 2012 as part of the U.S. Global Threat Reduction Initiative.

12 Ownership of the plutonium from the reprocessed R-1 fuel is to be transferred to the United Kingdom, along with with the plutonium fromSwedish SF reprocessed in Sellafield.

repository for intermediate-level, long-lived radioactive waste. The SNF from the other research reactors was returned to the fuel source in the United States.

The amount of historic low-level RW from the early military-civil programme, together with the operational short-lived waste from the present Studsvik Nuclear AB activities, is expected to reach 11,500 m3. Decommissioning waste from all the facilities will add an additional 13,000 m3 of short-lived waste.

Long-lived intermediate-level RW from the early military-civil programme, together with operational waste of the same type from the present Studsvik Nuclear AB activities, is expected to reach 11,800 m^3.

4 Overview of operating and planned radioactive waste facilities

At present, the nuclear industry is planning three new final repositories in Sweden, in addition to the existing SFR and Clab facilities.

4.1 Centralised intermediate storage facility for SNF (Clab)

In 1985 the centralized intermediate storage site for spent fuel (Clab) started operations at the site of the Oskarshamn NPP on the South-East Baltic coast. A special ship had been commissioned to move both short-lived operational RW to the SFR facility in Forsmark and SNF to the Clab facility at the Oskarshamn NPP. The storage is in a pool about 30 metres underground in granite bedrock. This facility was expanded and a second pool was put into service in 2008. Currently, the SNF inventory in Clab is about 5,800 tonnes. The present storage capacity is 8,000 tonnes. If a licence to build a repository for SNF is not granted, it is possible to store some SNF in Clab. It would also be possible to expand the facility with a third storage pool or build a facility for dry storage. According to the nuclear industry, if necessary, the SNF can be stored safely in the pools for at least 100 years.

4.2 Repositories for short-lived operating radioactive waste, SFR and SFR 2

By 1988, the nuclear industry had built a repository for short-lived operational RW from the nuclear power reactors. It was the first of its kind in the world. The repository, called SFR, was situated 50 metres under the sea-bed outside the Forsmark NPP on the Baltic coast north of Stockholm. This repository is for operational waste from the NPPs, but each year 10-20 m^3 of waste from hospitals, industry and research is also deposited. The storage capacity is approximately 63,000 m^2, of which 35,000 m^3 is used.

In the early 2000s, it was discovered that the RW that had been deposited in SFR had excessive long-lived radioactive elements, most significantly carbon-14 and plutonium. The regulators therefore forced SKB to conduct a new safety analysis. Because the safety case for SFR included a release of radioactivity from the repository into the Baltic Sea, it was not easy to get an acceptable result from this analysis. SKB and the regulator have been under public criticism for the safety case ever since.[13]

Another problem for SFR is that the repository is deteriorating faster than initially foreseen. Waste containers are corroding faster than anticipated and the concrete, including steel reinforcements, is breaking apart. There is an inflow of water into parts of the operating repository that is hindering operations. In 2005, it was discovered that there were stray electric currents from the direct current transmission line going from Forsmark to the Finnish side of the Baltic. These stray currents passed through the SFR repository and it is not yet clear if they have been causing corrosion problems or if there are other causes for the corrosion.[14] These SFR issues are a problem for SKB, which is currently preparing an application for a licence to expand SFR with a new addition, SFR 2. The new expansion will be a little deeper than the original repository in order to make it safer, at 120 m below sea level. The original SFR will also be reviewed along with the new facility; it remains to be seen whether the old and new repositories, which are both part of the safety case with a deliberate release of radioactivity into a recipient, will be accepted in accordance with the modern Swedish nuclear and environmental legislation. The total waste volume needed for both repositories is about 200,000 m^3.

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13 The repository was designed according to the environmental standards of the late 1970s, as dilution into a recipient was still considered to be an acceptable part of a safety case for a new facility as long as the releases were below certain limits.

14 In June 2005, a leak was discovered from corroding drums that had been deposited in SFR. The radioactive material was caught in the drainage system. The drainage water has since that time been collected and delivered to the Forsmark NPP for further treatment. The repository roof has also been covered to decrease the inflow of water.

4.3 Planned repository and encapsulation facility for SNF

Since the 1970s the Swedish nuclear industry has been planning to build a repository for SNF using the KBS method. The 1983 KBS-3 report looked in greater detail at the theoretical understanding of corrosion processes and the required thickness of the copper canister. Although no recommendation for the thickness of the copper in the canister wall was given, a decision was later made that a thickness of 5 cm would be sufficient. This assumption is still in effect today. The KBS-3 report was the last report in this series and the proposed disposal method is sometimes called the KBS-3 method.

An analysis of the KBS method was carried out in two projects, SKB 91, around 1990, and SR-97, in the second half of the 1990s (SKB 1992; SKB 1999). The SKB 91 report was important in that it shifted the focus of the safety case from the importance of a crack-free bedrock to the importance of the artificial barriers of copper and clay. This allowed SKB to move over into a voluntary siting process. It was assumed that there was a sufficient amount of suitable bedrock for a repository and this assumption played an important role in the subsequent siting process.

The SNF will be put into a cast iron insert and then encapsulated within a 5 cm thick copper canister. The canisters are then to be lowered into bored holes in mined tunnels at a depth of about 500 metres in granite bedrock. A bentonite clay buffer will be placed around the copper. The deposition tunnels are then filled with more clay.

The safety case of the KBS method relies on the integrity of the copper canister and the bentonite clay buffer. The copper canister should be corrosion resistant in the repository environment which, when completed, should contain water but no molecular oxygen. Biological and chemical processes are supposed to consume the oxygen after the deposition holes are sealed. The bentonite clay buffer absorbs water from the surrounding bedrock and swells. The water-saturated clay should prevent the movement of ground water and corrosive substances in the water in the vicinity of the copper surface. Thus, for the safety case to be valid, the clay has to swell and protect the copper. In addition, the safety case has to ensure that the repository will not be affected by mechanical and chemical changes that could take place during repeated ice ages.

On March 16' 2011, SKB filed an application for a licence to build and operate a SNF repository south of the Forsmark NPP. The application also included an encapsulation plant to be built as an addition to Clab at the Oskarshamn NPP.

4.4 Planned repository for long-lived intermediate-level radioactive waste (SFL)

A new, final repository for long-lived intermediate-level radioactive waste is also planned, but these plans are vague. The regulator and the government have criticised the industry for its lack of planning, but it is generally believed that the industry wants to build SFL as an extension with a few more tunnels once the licence is granted for a repository for SNF. At a depth of 500 metres, SFL would not need much encapsulation or buffering to make it safe.

5 The Swedish concept for radioactive waste governance and the legal framework

The Swedish state takes the ultimate responsibility for the management of RW, but differently from many other countries, has tried to shift this responsibility to industry, including historic, pre-commercial RW, management and final disposal, as well as for the financing of all activities and regulation. The Swedish concept for RW governance places the entire responsibility for RW governance on the owners and operators of the NPPs. The nuclear industry, in turn, has transferred this responsibility to their co-owned radioactive waste company SKB. The waste company has been tasked with developing and operating all nuclear waste facilities. The company also has to develop new waste management solutions and final repositories, as well as manage the decommissioning of nuclear facilities.

The main legislation regulating the industry's work on nuclear waste is the Nuclear Activities Act (SFS 1984a) and the Nuclear Activities Ordinance (SFS 1984b). These regulate the way in which applications for licences should be reviewed. In addition to the Nuclear Activities Act and Ordinance, there are a Radiation Protection Act and an Ordinance that set up requirements for radiation protection and, in the case of repositories, the criteria for long-term release of radiation (SFS 1988a, SFS 1988b).

The nuclear power operators are also obligated to carry out a R&D programme every three years which is to be reviewed by the regulator(s) and the Swedish Council for Nuclear Waste, the government's scientific advisory board. These programmes are sent out for public comment. Each programme has to be approved by the government, which can also require additional work on certain issues. The government decides if the programme is sufficient to allow further operation of the nuclear power reactors. These so-called "Fud" programmes essentially represent the only way that the industry's efforts in RW management can be influenced by the state.[15] The government can make requests that the industry has to answer, but since the only way to really make the industry do what the government wants is to stop the nuclear reactors, this mechanism seems very blunt. No government so far has refused to give a go-ahead to the programme. In practice, the system has allowed the industry to do as it wants. Independent researchers, critical of SKB, cannot use funding from the nuclear waste fund because it can only be used by the industry. There are no economic incentives offered to trace any problems with the plans. Any problems with the RW programmes must be identified and dealt with by the licence reviewers. This is true for both selection of method and siting processes.[16] It is all done by the industry, which then has to try and get the necessary permit. The present Fud programme was started in 2013 and the government will make a decision regarding the programme in late 2014.

The Swedish concept for governance of RW is dependent on a strong regulator. In the middle of the 2000s, the government and parliament decided to reform the regulatory system by joining the two regulators, SKI and SSI. The new regulator, the "Swedish Radiation Safety Authority" (SSM), was created in 2008. SKI and SSI had very different cultures. During the 1980s and 1990s the main regulator SKI, which analysed the safety of the barrier systems and reviews of the RW department, was "captured" by the industry; they did little to challenge the industry's work. The secondary regulator SSI was more critical on many issues but did not have direct access to the government in the Fud process.[17] SKI could filter criticism from SSI in the reports reaching the government. Political interest in RW issues during the last two decades of the last century was low. Successive governments, therefore, were happy to agree with the regulator that everything was acceptable. As a result, nuclear industries around the world hailed the Swedish model for radioactive waste governance.

The new regulator SSM put immediately in 2008 new effort into analysing the financial system. A separate department for financial control was created and

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15 SKB issued R&D reports every three years, from 1986 onwards, describing a programme for management and final disposal of all RW as well as for the decommissioning of all reactors and other nuclear facilities. The reports got the name "Fud report" – the D stands for demonstration – and the latest report is the Fud-13. The reports are available in English at the SKB web site http://www.skb.se.

16 One of the authors described how the economic incentives made all involved parties interested in hiding, rather than discovering, problems in the early phase of the programme. This resulted in significant cost escalations later, when the industry was no longer able to provide the funds required (Kåberger 1992).

17 SSI had a responsibility for long-term safety with regards to the release of radioactive elements. It took this issue very seriously and has had a more open culture. SSI also followed the development of the environmental legislation closely and recognized the importance of investigating siting and choice of method.

it was soon discovered that the cost estimates that SKB had been giving over the years were not correct. The financial collapse of 2008 caused large problems for the nuclear waste fund. It became clear that there was a big risk that the fund would be insufficient to cover costs.

A problem with the Swedish system of governance has been that crucial problems have been swept under the carpet. Not until an application for a licence for a spent fuel repository has come under review has the regulator had the power to force the industry to explain issues that may be problematic. This opportunity for questioning is much too late for the system to be effective.

The governance system might have been able to continue to muddle through had the regulatory system not been reorganized in 2008. But the new regulator, SSM, has taken many critical issues raised historically by the previous Swedish Radiation Protection Institute (SSI) under its wing and has tried to build a culture of integrity regarding interactions with industry. The licence applications are now reviewed with a greater focus on problems that might previously have remained unaddressed. This includes implications for applications that are being reviewed by SSM at a level that SKB may not have anticipated when preparing the applications.

5.1 The Environmental Code and licencing procedures

Sweden adopted a separate Environmental Code in the late 1990s, which was a step in the wrong direction for the nuclear industry (SFS 1998). Nuclear activities have to undergo review also under this act, and applications for licences are reviewed both by the nuclear regulator and the Environmental Court. The Nuclear Activities Act and the Radiation Protection Act have been changed and have the same or similar effect regarding the general principles that are in the Environmental Act, including the use of the precautionary principle, the use of the best available technology, and the need to show that the best method and site have been chosen.

The importance of the Environmental Code with regard to other laws should not be underestimated. There is on-going work to integrate the Nuclear Activities Act and the Radiation Protection Act into one chapter in the Environmental Code. Presently, licences for nuclear waste repositories are reviewed by both the regulator and the court according to the different acts, albeit with careful coordination. In the future it will be the main responsibility of the Environmental Court to manage the review.

The current review of the licence application to construct a SNF repository in Forsmark shows how the present legislation with a parallel review by SSM and the Environmental Court has made things difficult for SKB. The company has for decades avoided working on alternative methods for siting, as well as any issues that could be problematic for the industry´s methods. The regulator and other actors in the review process have not had an opportunity to address all of these issues.

Comments have been made by a number of parties, including the nearby communities, the Swedish Council for Nuclear Waste, and the environmental movement. The regulator also reports to the court. There are a number of issues where more facts and analysis are requested.[18] If and when the application is found to be complete, it will be officially announced and then reviewed on its merits. Finally, the regulator and the court will give their recommendations regarding the application to the government, which has the final say.

It is not certain, however, if the government will get the chance to decide on the licence application. The nuclear waste company SKB is very reluctant to do more work to address the issues that have been raised. The licence application was submitted in March 2011 and SKB announced in September 2014 that the company would supply more information in January 2015. Still, the Environmental Court would then have to decide on the additional work which is requested by the different parties for the review. If such a work would show that the safety case would not hold together, the review process may have to be halted.

5.2 Transparency and public participation

In 1980, the referendum on nuclear power and the political decision to put a final date on the use of the Swedish nuclear reactors led to a sudden loss of political interest in nuclear power, but, the referendum opened up a broader discussion on nuclear waste issues. With a final date set for the production of nuclear waste, it became possible to know what waste amounts would be produced in the Swedish nuclear programme. There was also an understanding of what facilities would be needed. This allowed a financial system to be developed to pay for the disposal of waste and the decommissioning of the nuclear reactors.

The fact that a private company created by the nuclear industry is in charge of nuclear waste issues could be seen as an additional problem for the transparency of radioactive waste governance. There is a freedom of information

18 The issues include: a) problems with the barrier systems of copper and clay, especially in the dry rock at Forsmark; b) issues with the siting in Forsmark; c) safeguards and the need for long-term surveillance; and d) a lack of investigation of alternatives, including using deep boreholes for the final deposition of SNF. See also Swahn (1992) and Swahn (1995).

system in Sweden when it comes to authorities and the government, but a private company, like SKB, has no obligation to show material other than what it wants to become public. This makes it difficult, even for the regulator, to get information about problems that may have already been documented by the company.

Transparency and public participation are, however, important in order to increase the safety of nuclear facilities (IAEA 2006). Historically, transparency and public participation in Sweden has developed well. Sweden has also implemented the Aarhus Convention in its environmental legislation (UN 1998). The Environmental Act and the Nuclear Activities Act both include the need for formal consultations with a broad range of stakeholders before the submission of a licence application. The aim of the consultation process is to bring onboard issues that have to be dealt with in the environmental impact statement, which is a part of the application. From 2003 onward, SKB has carried out a consultation process according to Swedish nuclear and environmental legislation in preparation for a licence application for a repository for SNF. The legal aim of this process was to get input that could improve the environmental impact report in the company's application. SKB held a large number of meetings until spring 2010. Sweden has already implemented Art.10 on Transparency and Public Participation of the 2011 Euratom Radioactive Waste Directive, and thus the regulator, who is responsible for developing the Swedish national programme on RW, will have to consult with stakeholders.

In the field of Swedish RW management there is even support for environmental organisations to take part in the consultation processes. Since 2005, some environmental organisations have received support from the nuclear waste fund. Three organisations now receive a total of €0.39m per year (§§ 32-33 in SFS 2008).

6 The financing system

In accordance with the polluter pays principle, the Swedish nuclear industry is responsible for the costs of management and for the final disposal of radioactive waste. Before the referendum on nuclear power in 1980, the costs of waste management were the responsibility of the industry and were supposedly handled by internal accounts with sufficient money. When Sweden was revising its nuclear legislation at the beginning of the 1980s, a piece of financial legislation was introduced. By the mid-1980s, a financial system for the management and disposal of radioactive wastes and the decommissioning of the reactors was also established. A nuclear waste fund, controlled by the government, was in place and the nuclear industry was paying a fee per kWh of nuclear electricity produced into the fund. A special legislation forced the industry to also pay a smaller fee for the management and final disposal of the historic wastes from the military-civil past.

It has been observed that these economic conditions make it unlikely that environmental risks will be discovered. The implementer will have to pay for measures to reduce the risks that are discovered, but not the damages of risks that are realized sometime in the future (Kåberger 1993).

In 1993, the Nuclear Power Inspectorate published a report from projects where stakeholders, including environmental citizen groups and researchers, had discussed scenarios for the future waste management process. In this report, it was suggested that the risk of a lack of funds in the coming decades might also result in environmental risks more significant than those of the current programmes (SKI 1993).

The principles behind the financial system are the same today, but the Nuclear Waste Financial Act and Ordinance was also revised in 2006 (SFS 2006, SFS 2008). The Nuclear Waste Financial Act and Ordinance requires the reactor operators to provide estimates of the cost for RW management and final disposal, as well as for decommissioning the nuclear reactors. The regulator SSM then reviews the estimates and recommends a fee per kWh to the government for the nuclear electricity that is produced. Second, the level of additional financial securities is recommended. The government then decides on the fee, which is paid into a nuclear waste fund, and on the financial securities required. The fund's present investment policies allow foremost placement in Swedish government bonds. The financial resources in the nuclear waste fund are controlled by the government. Historically, the fee and securities were revised and changed every year, but it is now a three-year process coordinated with the review of the industry's R&D programme and governmental decision on the programme. The regulator is now reviewing the fees and securities for the next three-year period, from 2015-2017. The decision about the new fees and securities will be made by the government in late autumn 2014.

Historically, the fee was close to 0.1€ cent. The nuclear waste fee was raised by the government for the period 2012 to 2014 to only €0.22 per kWh, despite the regulator's recommended fee of €0.33 (Swedish Ministry of the Environment 2011). For the year 2015, the regulator has recommended a fee of 0.4 €-cent (SSM 2014).

Since the new regulator was created in 2008, the resources allotted for the regulation on financial issues were increased several times. This has allowed the regulator to examine the financial information from SKB more closely. Apparently, previous estimates for costs were too low, especially as at the end of the last century long-term interest rates became lower. The contribution from interest on accumulated funds now appears to be less than before. Taken together, the resulting analysis is that there may be €3 to €5bn lacking in the fund. In 2011, the government asked the regulator to investigate a way to reduce the risk the state will take if it has to pay for the industry's costs in the future. This was done in cooperation with the Swedish National Debt Office and the Swedish Nuclear Waste Fund Authority. The initial assessment of the fee paid by the nuclear power companies might have to be raised from the present 0.22€ cent to between 0.66€ cent and 1.1€ cent per kWh.

This strategy, however, would not necessarily work. The production costs of the NPPs in Sweden are nowadays high compared to electricity prices. Successful development of renewable electricity from wind and biomass has "out-competed" expensive electricity generation and lowered electricity prices, not only in Sweden but also in Denmark and Germany. In addition, a large new-build of wind power in Sweden is producing a surplus of electricity on the Nordic market. As a result, the average production costs of the last five years for some nuclear reactors are above the electricity prices in the futures market for the coming 10 years. Increasing the fee may thus contribute to the NPPs being closed immediately, and mean no income for the waste management fund.

In the final report of the review, published in spring 2013, the regulator tried to "solve" this problem through creative, new principles for the legislation. First, a longer lifetime for the reactors and for fee-paying was assumed. Second, the authority proposed that the fund should be allowed to invest in shares and other more risky financial instruments, as this could yield a higher rate of return. Third, the real rate of return should be expected to increase in the future, even though this is evidently not the case. The regulator´s solution to the industry's problems has been criticized in the consultation review of the proposals. Even the National Debt Office that took part in this process did not have a final say in the recommendations made by the report and has questioned the ideas presented by SSM to dissuade a fee increase. The office instead suggested a more serious consideration of the issues involved. The government now has to decide how to go forward before introducing new legislation.

The companies who own the nuclear reactors in Sweden are drained by low electricity prices and bad assets. The competitiveness of the reactors themselves may disappear if fees for waste management are raised enough to cover expected costs. In this situation, Sweden is not unique. However, because of the openness in the public administration it may be the first country where the collapse of the waste finance system becomes clearly visible.

7 Conclusions: Time for a new model?

It appears that much of the success story of the Swedish model is disintegrating and its financial system is in disarray. A final scrutiny of the filed application shows that the quality of the research on the KBS method, as well as the actual safety of the KBS method, appear to be less impressive than its international reputation has postured for the last 30 years. A licence for a repository for SNF in Forsmark according to the submitted application cannot be taken for granted. The safety case for the existing repository for short-lived waste in Forsmark can be questioned. It may be time for a new, or at least revised, model for RW management in Sweden. Such a model could include:

- Explicit opportunities for the regulator and the government to force the industry to carry out, or use the wage management fund to finance, research required to support the licence application reviews.
- Allow the use of reserves from the nuclear waste fund for R&D independent of the nuclear industry, in order to allow better critical evaluation of the industry's work.
- Force the industry to organise research on RW management so that it is transparent and under the auspices of freedom of information, similar to that of the Swedish authorities.

Finally, the financial system should be revised in order to reduce the risk of future generations having to pay for the costs that today's nuclear operators are supposed to pay.

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